

PREPARING PUBLIC HEALTH OFFICIALS FOR CLIMATE CHANGE: A DECISION SUPPORT TOOL

A Report for:

California's Fourth Climate Change Assessment

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Edmund G. Brown, Jr., *Governor*

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PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. It includes research to develop rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report and online tool advance the understanding of what types of heat waves pose public health risks for communities across California and examines how the frequency and severity of local heat waves are expected to change over time due to climate change.

ABSTRACT

California is facing a warmer climate over the next century. Evidence already exists that severe heat events pose considerable health risks, and new evidence shows that the character of those heat events is changing. Heat events are becoming progressively more humid, lasting longer than average, and occurring in areas not as accustomed to extreme heat. From a public health perspective, the lack of clear heat wave definition can cause confusion when planning around new heat extremes. In the face of a changing climate, this paper finds that definitions based on aspects of human health may offer a more accurate basis for planning and preparedness. Planners and practitioners in the fields of public health and urban design will increasingly need to incorporate changing patterns of extreme heat into long-term planning. Our aim is to equip them with a baseline from which to judge the influence of climate change on heat vulnerability in their local area. We find less-stringent, health-informed heat wave thresholds may better represent heat sensitive populations. Utilizing a simple statistical framework, we generate over 63 unique, health-informed heat thresholds tailored to California's diverse tapestry of climates and demographics. Using these thresholds as a baseline, we then generate probabilistic climate projections to evaluate how the signatures (e.g., severity, frequency, duration, and timing) of heat-health events are changing. Census tract-level vulnerability maps are also provided to help identify existing areas of need. We conclude that long-term heat adaptation efforts are particularly urgent in coastal, agricultural, and increasingly urbanized regions of California where sensitive populations will face, on average, longer and increasingly severe heat-health events. This document provides a description of the methods, findings, and limitations behind the building of an online interactive tool, the California Heat Assessment Tool (CHAT) (<http://www.cal-heat.org>). The aim of the tool is to support the inclusion of extreme heat considerations into long-term policy and planning decisions throughout California. Given the multi-faceted nature of heat vulnerability, we also hope that this tool will empower local practitioners to better communicate the urgency of this issue to build much needed support for improved planning and adaptation solutions.

Keywords: Heat waves, climate change, heat vulnerability, decision-support, vulnerable communities, heat-health events, thresholds, planning

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HIGHLIGHTS

- The California Heat Assessment Tool (CHAT) equips California planners and public health officials with a baseline from which to judge the influence of climate change on heat vulnerability.
- Tool users can locate areas of high relative change and social vulnerability to find similarly heat vulnerable neighborhoods in their local area.
- When compared to more standard heat wave definitions (Maximum temperature reaches climatological and seasonal 95th percentile for 2 continuous days), we found that definitions tailored to public health impacts among the vulnerable occurred 184% more often and were associated with 18% more heat-related emergency department visits.
- We found that the appropriate heat wave definition for vulnerable subgroups may be up to 6-8 degrees Fahrenheit lower than the general population in some areas.
- After applying climate projections to these definitions, which we call Heat-Health Events (HHEs), we found increases in the severity, duration, and shifts in timing of HHEs throughout the century and under all emission pathway scenarios.
- We found a significant uptick in the number of late season (September, October) HHEs for many regions.
- The duration of the average HHE could increase by up to two weeks in some parts of the Central Valley by mid-century.
- In the North Sierra region, mid-summer HHEs could occur four to ten times more often by mid-century.
- In addition to more frequent and longer HHEs, public health risk is expected to increase due to increasingly warm nights (limiting the opportunity for physiological recovery and prolonging the period for which negative health outcomes can occur), and the presence of Urban Heat Islands, both of which pose serious risk to households without air conditioning.
- Low-income urban areas that we also projected to experience significant increases in the frequency and severity of heat waves could suffer disproportionately. A few of these areas include the San Francisco Bay Area (East Oakland, Vallejo, East Palo Alto), Los Angeles (Compton), and Central Valley (Palmdale and Sanger).

- **WEB LINKS**

The tool can be accessed in its entirety at www.cal-heat.org, available Spring, 2018.

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1: Introduction

California is facing a warmer climate over the next century. More frequent and severe heat events will pose considerable health risks to our communities and to vulnerable populations. There is growing evidence that the character of heat waves in California is also changing. Heat events are becoming progressively more humid, lasting longer, and occurring in areas not accustomed to heat waves. Based on current climate change projections, a typical California summer in 2100 is predicted to be 4-5° F warmer than today (CAT, 2013). In California cities, increasingly frequent and severe extreme heat events could cause two to three times more heat-related deaths by mid-century (UCS, 2006), and heat-related mortality for those over the age of 65 could increase ten-fold by the 2090s (Sheridan, 2012). While some studies have shown a lower rate of heat-related mortality in recent years, in part due to higher prevalence of air conditioners and implementation of heat awareness and mitigation programs (Gasparrini et al., 2015; Bobb et al., 2014; Hondula et al., 2015), more severe and prevalent heat waves will expose California residents, particularly vulnerable groups, to health risks. Climate change will also challenge the efficacy of traditional intervention strategies, and local agencies may struggle to effectively mitigate heat-health impacts.

Meanwhile, local agencies are struggling to effectively address and mitigate the public health impacts of extreme heat. Despite the improvement of heat forecast and warning systems in California, as well as knowledge of interventions, extreme heat continues to affect many people across the state. Within this context, California recently began the state's Fourth Climate Change Assessment,¹ a state-mandated research program to assess climate change impacts in California. Better understanding the public health impacts of climate change is one of the state's identified priorities. This research project was undertaken as part of California's Fourth Climate Change Assessment, with intent to build a decision-support tool informed by decision makers tasked with reducing the long-term public health impacts of extreme heat.

The first phase of the project included an extensive literature review, a survey of over 100 local health and emergency preparedness stakeholders, and key informant interviews. We examined interview and survey responses – and later conferred with expert practitioners – and concluded that the greatest strides towards reducing heat-related health risks could be made through interventions planned well ahead of time, such as long-term changes in the urban design and social programs, as opposed to short-term risk reduction strategies during the alert and emergency response phases. We concluded that a decision support tool would be most useful if it helped informed mid- and long-term interventions to reduce the public health impacts of extreme heat. During this process, we identified three information and technology gaps that could be addressed through our modeling and research:

¹ California produces periodic scientific assessments on the potential impacts of climate change in California and reports potential adaptation responses. Required by [Executive Order #S-03-05](#), these assessments influence legislation and inform policy makers. For more information on California's previous climate change assessments please visit: http://www.climatechange.ca.gov/climate_action_team/reports/climate_assessments.html.

- (1) the lack of a unified heat index tailored to local climate and population histories which could inform when heat-health impacts begin to occur;
- (2) the lack of widely accessible social vulnerability maps tailored to heat vulnerability;
- (3) an underutilization of similar climate and population mapping tools among public health professionals.

Our aim was to address, though not solve, each of these challenges in three ways:

- (1) apply a framework to establish local heat-health event (HHE) thresholds, which can also serve as a baseline for climate projections and adaptation planning,
- (2) map heat-specific social and environmental variables alongside a composite measure of heat vulnerability, and
- (3) develop an interactive, user-friendly tool that enables users to assess current and future levels of heat vulnerability and help them identify areas or neighborhoods where long-term interventions will be most impactful.

This document will discuss the methods to items (1) and (2), while the online tool (3) can be accessed at www.cal-heat.org.

1.1 Intended Audience

The results of this research and the online tool are designed to **inform long-term heat-related planning decisions as opposed to short-term extreme heat response**. The target user group for this information includes practitioners in local departments – such as sustainability, housing, transportation, urban planning, and public health – that focus on integrating climate change hazards, such as extreme heat, into local planning processes.²

The contents of this paper include a background and a detailed description of the methods undertaken by authors to develop the online tool, found at www.cal-heat.org.

² Planning processes include climate action plans, climate adaptation and preparedness plans, extreme heat plans, hazard mitigation plans and general plans, among others.

2: Literature Review and User Needs Assessment

When planning for extreme heat, decision makers currently face many challenges. Findings from our literature review and User Needs Assessment (UNA)³ identified three critical barriers that may continue to limit decision-makers' ability to adequately plan and prepare for more extreme heat: 1) A lack of resources and capacity to adequately serve all vulnerable populations, 2) difficulty identifying and effectively communicating with all individuals vulnerable to extreme heat, and 3) the current reliance on population and health neutral heat alert/ warning thresholds. Our results also pointed to the difficulty in prioritizing extreme heat as a public health planning issue among many other competing priorities, even in regions with a recent history of dangerous extreme heat events.

2.1 Heat and Health in California

Climate change threatens health in a myriad of ways, including increases in vector- and water-borne diseases, decreases in air and water quality, and impacts from more extreme weather events such as droughts, floods, and hurricanes. One of the most apparent health risks stemming from climate change is increasingly frequent and longer periods of more severe extreme heat (Balbus *et al.* 2016). The relationship between human health and extreme heat is well-established (Astrom *et al.*, 2003), and there is strong evidence to suggest that climate change will increase the global number of heat-related deaths (Hales *et al.*, 2014). In the United States, heat is responsible for more deaths than any other natural hazard (NOAA, 2016), and is responsible for the majority of weather-related emergency department visits in the United States (Knowlton *et al.*, 2011). Among natural disasters in California, heat is responsible for the most deaths in the last 30 years. Other natural disasters in recent history, such as the 1989 Loma Prieta and the 1994 Northridge earthquakes, and the 2003 Southern California Firestorms each resulted in 20-70 deaths (Cal OES Contingency Plan for Excessive Heat Emergencies, 2014), whereas the 2006 heat wave killed more than 600 people and resulted in over 1,200 hospitalizations, 16,000 emergency department visits, and nearly \$5.4 billion in costs (Knowlton *et al.* 2009).

Current climate change projections for California show that a typical summer is predicted to be 4-5 F warmer by 2100 than today (Heat Adaptation Workgroup, a subcommittee of the Public Health Workgroup, 2013). Increasing average temperatures (Stocker *et al.* 2013) also increase the frequency and severity of extreme heat events (Pierce, D. W. 2012). Extreme heat days are predicted to increase from currently approximately ten a year to 25-50 by 2050, (Pierce, D. W. 2012), resulting in as many as two to three times more heat-related deaths by mid-century in

³ The UNA consisted of approximately 30 phone interviews and an online survey of over 110 public health and emergency preparedness stakeholders and practitioners representing 43 California counties, and was conducted in early 2017. The UNA consisted of individual and group semi-structure interviews and an online survey of over 100 public health and emergency preparedness stakeholders which was distributed through our contacts at the California Office of Emergency Services (Cal OES), the California Conference of Local Health Officials (CCLHO), Public Health Nursing Directors of California and the County Health Executives Association of California (CHEAC). Survey questions were informed by individual interviews and presentations and discussions with public health groups across the state. Following analysis of the survey results, our team conducted approximately 20 additional individual interviews with stakeholders from local and state agencies involved in responding to extreme heat events.

California cities (Luers *et al.* 2006). The 2006 heat wave was abnormally humid, with very high nighttime temperatures that hindered physiological recovery at night, a trend that is expected to worsen in the future (Gershunov, Cayan, and Iacobellis 2009).

2.1.1 Vulnerable Groups and Regions in California

The changing character of heat waves in California will not affect all regions equally. While the state is, on average, warming, the highest relative temperature changes are predicted to occur along California's coasts where most of the state's population is clustered (Pierce, D. W. 2012). These coastal populations have shown to be more sensitive to heat events in part due to their lack of acclimation to extreme heat and humidity conditions (Gershunov and Guirguis 2012). As evidenced by the 2006 heat wave, central coast communities accounted for the highest rate of heat-related illnesses (Knowlton *et al.*, 2009). These populations, which are not acclimated to such heat events, are more vulnerable to the same temperatures than populations in hotter regions, which experience heat events more regularly. In 2006, sensitivity to heat, or the threshold at which heat illnesses began to appear—in the Central Valley 33°C -42°C and for Coastal regions: 27°C-36°C (Gershunov and Guirguis 2012) —drove differential outcomes across geographies. The prevalence of air conditioning in coastal areas of California is also much lower than historically warmer inland regions.

Income is also an important indicator of heat vulnerability. Nearly 90 percent of all victims of the 2006 heat wave lived in socio-economically deprived areas⁴ (Trent 2007). Latino/Hispanic groups along the North and Central Coast were particularly affected (Knowlton *et al.*, 2009), possibly due to occupational exposure of crop workers where “effects tend to occur during outdoor labor as a result of accumulated heat load over a longer time period with little opportunity for rest” (Li *et al.*, 2015). Although California workers have experienced severe heat-related illness and death during heat waves in recent years, reports are believed to be under-reported and not well captured in existing data retrieval programs (Centers for Disease Control and Prevention, 2016). Other groups have also been found to be more susceptible to heat-related illnesses, such as infants and young children (Schwartz, 2005), athletes (Vanos *et al.*, 2010), people with pre-existing illnesses (Barrow and Clark 1998; Stafoggia *et al.* 2006), pregnant women (Basu *et al.*, 2016), and the homeless (Bassil and Cole, 2010).

Perhaps no other demographic group has received as much related academic inquiry as the elderly, who suffer high rates of health complications during extreme heat (Bunker *et al.*, 2016). During the 1995 Chicago heat wave, elderly individuals living alone represented a significant portion of the deceased (Klinenberg 2003). In California, individuals over the age of 65 were found to be particularly affected during the 2006 heat wave, comprising 52 percent of all heat-related hospitalizations, although they only represent 11 percent of the state's population. On average, across all counties, the 65 and over age group is expected to grow by 145 percent by 2020 (California Department of Finance, 2014), and heat-related mortality among the elderly could increase greater than ten-fold by the 2090s (Sheridan, 2011).

Urbanization, together with the growing development of commercial and residential spaces that are largely impervious (such as cement, asphalt, roof cover, etc.), produces a positive feedback loop, increasing temperature and exposing more individuals to the additive risk of

⁴ Defined as more than 50 percent of the population in their zip code living below the Federal Poverty Threshold.

urban heat island (UHI) effects. In some contexts, strong spatial correlations exist between the built environment, socioeconomic vulnerability, and heat mortality (Ujeto, 2012), implying that communities of color and low-income populations are disproportionately exposed to heat island risk factors. As is so often the case, disadvantaged communities tend to disproportionately suffer and have fewer resources to cope.

2.1.2 Mechanisms and Phenomena Affecting Health

Humidity

An important part of the human body's self-regulation of temperature is to cool itself through sweating. Humidity limits the body's ability to cool; therefore, humidity coupled with a heat wave poses an increased health risk, especially when coupled with stagnant air masses. Several California regions, including the Central Valley and the North Coast, are thus more likely to present high risk for heat illness because of the occurrence of high humidity, alongside high heat and stagnant air mass (Gershunov and Guirguis, 2012). Humidity and pockets of stagnant warm air are uncharacteristic in most of the state's climate, but more humid, nighttime-dominated heat waves have been observed over the last 60 years and are predicted to intensify over the coming century (Pierce *et al.*, 2012). The heat wave that struck California in 2006, which killed more than 600 people and resulted in over 1,200 hospitalizations and 16,000 emergency-department visits (Knowlton *et al.*, 2009), was abnormally humid, with very high nighttime temperatures that hindered physiological recovery at night. These trends are expected to worsen in the future (Gershunov *et al.*, 2009). Coastal, foothill, and mountainous communities, not accustomed to dealing with the combination of heat and humidity, are particularly susceptible.

Nighttime Temperature

During warm seasons, lower nighttime temperatures can offer humans respite and recovery. Heat waves may be accompanied by nighttime extremes, higher in urban areas, as compared with proximate rural areas, due to the urban heat island (UHI) effect. Nighttime temperatures have also been shown to contribute to excess morbidity and mortality (Hémon and Jouglé 2003; Grizea *et al.* 2005), limiting the opportunity for physiological recovery and prolonging the period of time for which heat-related illnesses can occur. The physical mechanisms causing daytime and nighttime heat waves may differ and relative warming is often stronger at night than during the day (Easterling *et al.* 1997; Vose, Easterling, and Gleason 2005). Consistent with most global models, nighttime temperatures are also trending upwards in California (Lobell, Bonfils, and Duffy, 2007). High nighttime temperatures also increase energy demand, as residents are more likely to increase their use of air conditioning (AC). Temporary increases in energy consumption can lead to power outages (Alawar, Bosze, and Nutt, 2005), limiting the utility of air conditioning as a cooling adaptation strategy and affecting those dependent on electrified life-supporting machines such as ventilators or electric powered oxygen machines (Klinger *et al.*, 2014).

The Urban Heat Island Effect (UHI)

The Urban Heat Island effect is a routinely observed phenomenon whereby urban areas exhibit higher temperatures than nearby rural or suburban areas, especially at night. Cities with more impervious surfaces (including cement, asphalt, roof cover, etc.) tend to be hotter than nearby rural areas. Impervious surfaces dominate land cover in urban landscapes and amplify the severity and duration of heat waves within cities. Heat islands are typically less intense in drier

climates (Zhao et al., 2014), although this is not true for all cities (Kenward et al., 2014). Urbanization, in conjunction with rising temperatures, appears to increase heat more than climate change due to global carbon emissions alone, increasing rural-urban temperature differentials.

Poor Air Quality

The health impacts of poor air quality are also worsened by increases in temperature. Air pollution has been shown to exacerbate heat-related morbidity and mortality in some instances when anomalies in high temperature and air quality (particulate matter and ozone) are correlated (Fischer, Brunekreef, and Lebrecht, 2004; Gosling et al., 2009; Stedman, 2004; Touloumi et al., 1997; Katsouyanni et al., 2001). The same weather conditions can increase concentrations of particulate matter (PM). This effect is pronounced in urban settings where pollutants from emissions are more prevalent. Unlike particulate matter from emissions-based sources, ozone is not released into the air directly, but instead forms under the presence of heat and sunlight through a combination of nitrogen oxides (NO_x), volatile organic compounds (VOCs), and carbon monoxide. Even though emissions of these pollutants are decreasing, ozone dependence on temperature indicates that increasingly hotter summers have the potential to elevate average ozone concentrations. (It is worth noting that variables related to air quality were not used as criteria for developing HHE definitions.)

2.2 Heat Thresholds

There is no universal definition of what constitutes a heat wave, and definitions are sensitive to scale and context. Some definitions are based on climatic conditions (e.g. duration of high temperatures, anomalies from a baseline, high temperatures exceeding the 95th percentile of past decades' warm months) and may be augmented with seasonality and humidity. The principal entity for defining, tracking, and issuing heat wave warnings is the National Weather Service (NWS). Historically, the most common definition employed by NWS defined a heat wave as two consecutive days where the daytime high and nighttime low heat index exceeds a specific statistical or absolute threshold. Thresholds can vary by region and climate, and often utilize heat stress thresholds (e.g., 80° and 105°F) specific to the human body's ability to thermoregulate (Robinson et al., 2001). It was under this criterion in which NWS issued only six heat alerts from 2000 to 2009 in California, despite evidence showing that heat events resulting in negative health outcomes occurred 19 times over this period (Guirguis et al., 2014). A new supplementary heat product from NWS, the experimental HeatRisk forecast, identifies multiple thresholds based on local climatology, some of which are temperatures below historical alert levels in order to provide guidance for vulnerable groups and practitioners.

There is still no consistent definition or method for identifying heat wave thresholds, specifically with regards to impacts on human health. To assess the severity of an extreme heat independent of its impact on people could be dangerous, and definitions based on aspects of human health may offer a more accurate basis for planning and preparedness. There is strong supporting evidence in California (Guirguis et al., 2014), and across the wider United States (Smith et al., 2013), that heat-health relationships are often correlated at temperatures well below the prevailing definition used in local warning systems, and definitions tailored to public health may provide a more adequate basis for long-term-planning.

2.2.1 Heat Criteria and Thresholds

Beginning in the 1990s, NWS used multiple heat index thresholds (i.e., 80°, 85°, 90°, 95°, 100°, 105°, 110° F) when determining whether to issue an alert depending on time of season and locale. These absolute, climate-focused thresholds are still operational in some regions, and communities living in cooler climates not physiologically or technologically acclimated to extreme heat will subsequently suffer, as oncoming heat waves may not trigger an alert yet still generate significant heat-health impacts (Basu and Malig, 2011). NWS' climate-focused thresholds generally consider the duration, and severity of nighttime and daytime temperatures. Excessive heat warnings, watches, and advisories are often based on local climatological conditions guided by local expert opinion about the relative probability and extent of oncoming heat waves. For example, many California NWS offices will initiate alert procedures when the daytime heat index exceeds 105°-110° F for at least two consecutive days, but thresholds may vary slightly depending on the local climate and the expert judgment of station meteorologists, rather than that of a public health expert or epidemiologist.

Other threshold definitions are based on the human response to heat. These are developed by assigning relationships between temperature and morbidity or mortality (known as heat "exposure-response" relationships (CDC, 2014)) to establish the temperature at which negative health outcomes occur, otherwise known as "thresholds," or more aptly, "trigger points" (Pettiti et al., 2016). Alerts and intervention measures might be activated when thresholds are exceeded or one or multiple trigger points are reached. Using exposure-response relationships to define local heat thresholds helps to identify health events that may begin to occur well before a climatological threshold, or even a statistical threshold for mortality or morbidity, is crossed.

Guirguis et al., (2014) defined heat waves in such a manner by utilizing multiple regression analysis to assess correlations between daily maximum temperature (Tmax) and patient discharge (PD) data over a 15-day window, allowing them to identify the temperature threshold at which a local population was affected by past heat waves in California. Similar investigations (Hess et al., 2014) have found such relationships are evident in both urban and rural contexts. Greene et al. (2011) conversely used multiple meteorological variable conditions such as visibility, dew point, air temperature, cloud cover, and wind speed and direction to assign air mass types and set thresholds for mortality. Similarly, Kalkstein (2011) examined multiple meteorological variables to evaluate different air mass types and measure the relative departure from historical and recent norms. Pettiti et al., (2016) in their investigation of temperature-mortality and -morbidity relationships in Maricopa County, Arizona, instead focused on better articulating the multiple classes of outcomes resulting from exposure to extreme temperature: minimum risk temperatures, increasing risk temperatures, and excess risk temperatures, which represent different "trigger points" at which heat-health intervention measures might be activated. While each of these approaches varies slightly in their evaluation goals, heat waves are defined and thresholds are set according to the historical health response to heat and other interacting variables in a particular region.

Across California, NWS tracks potential heat threats and issues warnings and alerts anytime between 12 hours and 7 days in advance. Seasonal readiness is based on monthly and 90-day outlooks provided by NOAA's Climate Prediction Center (CPC) to issue general temperature outlooks for regions and the probability that a region will, on average, experience above, below, or equal chances of temperature anomalies for the outlook period. If a threshold is exceeded within the outlook period, then local agencies are alerted by regional staff at NWS and informed

about the approximate timing, magnitude, and spatial extent of the oncoming heat wave. Outside of the state's largest cities, NWS warnings and alerts constitute the entirety of information provided to local stakeholders. Based on our direct communication with NWS staff and local NWS information recipients, it does not appear that these alerts include estimates of the expected heat-attributable health effects, which may have led to missed warning or false positives in the past. For many, especially those working in rural counties, no additional information is provided, and identification of heat vulnerable individuals and groups is the responsibility of local agencies.

Heat reduction efforts remain a local affair, and tailored intervention strategies necessitate local heat wave thresholds. Supplemented with census tract-level heat vulnerability maps, our aim is to equip California planners and public health officials with a baseline from which to judge the influence of climate change on heat vulnerability. To accomplish this, we present a simple statistical framework for identifying HHE signatures locally followed by a future climate analysis of heat waves in California through the end of the century.

3: Approach

The literature review and user needs assessment demonstrated that the utilization of health neutral baselines for heat waves, such as temperature exceedance of the 95th percentile, induces false negatives and underestimates health risks for the most sensitive. These health-neutral thresholds, when used as a baseline for understanding degrees of change in the future climate, can make it difficult to discern the level of future impacts from a public health perspective. As city, county, and state planners think through policies and programs that can address heat related risks, they must first understand what heat thresholds will be dangerous for the populations who live in affected areas. We call these thresholds baselines. Unless these baselines are people focused, meaning they evaluate heat risks from a public health perspective, then existing risk thresholds may lead to misinformed long-term planning.

To address this concern and support the integration of climate projections and heat-health concerns into long-term preparedness and urban planning, we developed a set of statistically-based, health-informed thresholds for what constitutes a heat-health event (HHE) at each census tract across California⁵. This framework and new dataset is intended to serve as a baseline for heat adaptation planning efforts when integrating climate change.

First, we analyze historical medical and weather data to identify the conditions at which excess emergency room visits commonly occur. We identify the local characteristics of each HHE in terms of temperature and duration signatures as well as the associated rate of visits to the local emergency department (ED). This constitutes the baseline for a new set of definitions for HHEs in California (*Chapter 3.1*). We consolidate local areas with similar heat and humidity characteristics into heat wave zones (HWZ), roughly the size of a medium-sized city (*Appendix*

⁵ Methods for how census tracts were assigned to Heat Wave Zones can be found in Appendix A. The health-informed thresholds were based on medical and meteorological data at the Heat Wave Zone level and disaggregated to census tract based on this mapping. This is to provide spatial granularity congruent to the level of detail we can provide for the socioeconomic data and is a more meaningful designation to users; furthermore, medical data is not available at the census tract level, necessitating the development of Heat Wave Zones.

A). Because vulnerable populations (infants, elderly, certain racial groups) are typically more sensitive to excess heat, we identify two sets of HHE definitions for each HWZ, one for lower risk individuals (General cohort) and for higher risk individuals (Vulnerable cohort). Furthermore, acclimation of the human body evolves over the summer, such that we find heat has different impacts on health in the same area from month to month. Accordingly, we delineate our HHE definitions to reflect acclimation of local population by month, grouped in three seasons with similar characteristics: April-May (AM), June-July-August (JJA), and September-October (SO) (*Chapter 3.2*).

Next, we use this baseline to project changes in temperature, timing, and duration of future HHEs using downscaled climate models. We analyze climate projections daily for the entire 2011-2099 period for the summer and shoulder months, identifying consecutive days that meet the definition for a local HHE developed with historical data (Table 1).

Chapter 3 provides a detailed description of the technical approach, data, and limitations, and Chapter 4 presents the key findings from this analysis, by region and by population type, across California.

3.1 Heat-Health Events (HHEs)

A heat-health event (HHE) can be characterized by a set of meteorological conditions occurring over a period of days that, historically, has been associated with significant negative public health impacts. These events exceed thresholds of human response to heat, as defined by the heat-health (i.e., exposure-response) relationships at which negative health outcomes occur (CDC, 2014). An HHE definition can be made up of different climate metrics, such as temperature, duration, and humidity. Previous studies have explored the sensitivity of heat-health relationships to event duration, lag, metric type, and temperature threshold (Barnett et al. 2012; Barnett et al. 2010). Other studies have reported the added effect of heat wave events compared to the effects of individual days that reach extreme temperatures (Anderson and Bell 2011; Gasparrini and Armstrong 2011; Hajat et al. 2010).

When baselines are established at a health neutral statistical threshold (such as the 98th percentile), or in some cases, a health neutral absolute threshold, it may underestimate health risks where the urban heat island (UHI) effect, low acclimation, and high heat sensitivity persist. These health neutral thresholds, when used as a baseline for understanding degrees of change in the future climate, can make it difficult to discern the level of future impacts from a public health perspective. On the other hand, health-informed temperature thresholds, when used as a baseline for understanding degrees of change in the future climate, may help avoid false negatives and better accounts for vulnerable, unacclimated, and seasonally sensitive populations.

Our analysis leverages a statistical framework developed by Vaidyanathan et al. (2017), which was designed to identify heat events within the context of adverse health outcomes. Using a customized distributed lag non-linear model (DLNM) to estimate the effect of different heat wave characteristics over a period of days, we generated several HHE definitions specific to month, region, and cohort. By evaluating the outcome associated with different definitions, we can more readily identify the thresholds at which negative health effects begin to occur. The result is a series of HHE signatures for each area, month, and two generalized population types across the state of California. The statistical framework used to identify HHE signatures is

designed so that it can be easily replicated or supplemented with new or more granular data such as finer geographical scales or specific diagnoses codes (Figure 1).

3.1.1 Defining Historical Heat-Health Events

Meteorological data:

We used a gridded meteorological dataset interpolated from station-data for the years 1984-2013. These data were obtained from the PRISM Climate Group (<http://www.prism.oregonstate.edu/>) and data were extracted for only California. We extracted minimum temperature (Tmin), maximum temperature (Tmax), minimum vapor pressure deficit (vpdmin), and maximum vapor pressure deficit (vpdmax) at a daily time-step and at a resolution of 4 kilometers. To generate relative humidity, from vapor pressure deficit, we first derived an absolute humidity measure. We then calculated relative humidity after spatial aggregation to heat wave zone (See *Appendix A and B*).

Heat-Health Event variables

We considered daily Tmax, Tmin, and daily average temperature (Tavg) with relative thresholds at various intensity levels, including 80th, 85th, 90th, 95th, 98th, and 99th percentile values, as well average temperature +2 standard deviations. We computed these percentiles using daily data for the summer months (MJJAS) between 1984-2013. Definitions were also classified based on minimum duration, and must have lasted at least 2, 3, or 4 consecutive days. For each daily percentile metric and duration requirement, we tested a total of 63 distinct definitions (3 climate metrics x 3 duration periods x 7 percentile/ st. dev) (Table 1). For each zone, daily heat metrics were classified using a binary true (1) or false (0) designation and then grouped according to the specific percentile/ duration variant. Qualifying events (that is, each percentile/ duration/ heat metric variant), were classified in context of their zone and date of occurrence (e.g., Fresno, July 24th and 25th, 2006).

Table 1. Variables used to construct 63 unique HHE definitions. The 'x' connotes definitions selected for analysis and asterisk (*) connotes those used only for the General cohort (all ages, all races) and two asterisks () connotes those only used for the Vulnerable cohort (ages 65 and over, 5 and under, and all non-white individuals).**

Daily heat metric	Duration (days)	Relative Threshold						
		P80	P85	P90	P95	P98	P99	Mean + 2 std dev
Tmax								
	≥2	x**	x	x	x	x	x	x
	≥3	x	x**	x	x	x	x*	x
	≥4	x	x	x	x	x*	x*	x
Tmin								

	≥ 2	x	x	x	x	x	x	x
	≥ 3	x	x	x	x	x	x	x
	≥ 4	x	x	x	x	x	x	x
Tmax and Tmin								
	≥ 2	x	x	x	x	x	x	
	≥ 3	x	x	x	x	x	x*	
	≥ 4	x	x	x	x	x*	x*	

Emergency Department visitation data:

We obtained emergency department (ED) data from the California Office of Statewide Health and Planning (OSHPD) for the years 2005-2013, covering the summer months (MJJAS). The identification of heat-related visits through specific diagnosis codes was not possible because of data suppression rules. Instead, we extracted all emergency department visits, delineated by date of visit, patient's zip code, age, and race. Due to suppression-level rules and low daily ED counts in less populated and less racially diverse zones, we summed ED counts for vulnerable age groups (individuals between the ages of 0 and 4 and those over the age of 65) and all non-white individuals, which together constitute the Vulnerable cohort. While ED visitation rates are typically higher for this group, the total number of ED visits is relatively small for many areas throughout the state. As a result, we forwent a monthly analysis for the Vulnerable cohort and generated HHE signatures for the entire summer season (MJJAS). Additionally, any days when the suppression level rule was not met for any cohort were excluded from the analysis.

Spatial scales of data used for HHE definitions

Using data from varied sources necessitated spatial aggregations in order to use medical data to inform the creation of HHE definitions. Because of data suppression levels for medical data usage, we created Heat Wave Zones (HWZ) as an aggregation of zip code tabulation areas (ZCTAs) (see Appendix A and B). Medical data on ED visits were summed across ZCTAs belonging to a single HWZ, retaining the delineations of race and age described above that used to compile the vulnerable cohort. The general cohort was defined from the total number of ED visits, irrespective of race or age. For each HWZ, we are left with daily ED visits for the general cohort and vulnerable cohort. All meteorological variables were aggregated⁶ to this level to match the spatial granularity of the medical data used. Consequently, all HHE definitions are made at the HWZ level, corresponding to up-sampled medical data and aggregated meteorological data.

Evaluating HHE definitions using ED visits:

We estimated ED visits during extreme heat days (for all 63-distinct percentile/ duration/ heat metric variants) and ED visits in the absence of extreme heat. That is, we calculated the difference in ED visits during each HHE variant and compared with non-heat wave days within

⁶ Temperature variables were averaged over the spatial area defined by a HWZ. Derivation and aggregation of relative humidity data at the HWZ spatial scale is detailed in Appendix B.

the same month (Figure 3). To evaluate effect size during and following each of the 63 definitions, a customized Distributed Lag Non-Linear Model (DLNM) was developed using Python (Version 2.7.13) and the NumPy package, adapted from the DLNM R package detailed by Gasparrini, A. (2011).

To formulate a baseline for comparison for average ED visitation rates during summer days when temperatures were statistically normal by a measure of temperature, we calculated the average number of ED visits during non-HHE days, or those days between the 25th and 75th percentile according to the distribution of tmax and tmin between 1984 and 2013, for each area of analysis. Each cohort (i.e., Vulnerable and General cohort) was assigned an average number of ED visits to represent visitation levels during normal, non-HHE days (e.g., days when temperatures fell between 25th-75th percentile₁₉₈₄₋₂₀₁₃). We then averaged the number of ED visits over all 63 qualifying variants for each area and cohort, including the average number of ED visits with no lag (i.e., no offset), 1-, 2-, 3-, and 4-day extended effects (ExE).

Table 2: Exposure offsets. Adapted from Vaidyanathan et al. (2017)

--Extreme Heat Event--									
Day 1	.	.	.	Day 32	Day 33	34	35	36	37 . . Day 120
--No Lag (Lag0)--									
---1-day extended effect (ExE1)-									
-----2-day extended effect (ExE2)--									
-----3-day extended effect (ExE3)--									
-----4-day extended effect (ExE4)--									

ED visits during HHE days were then compared to visitation levels during non-HHE days, taking account of the duration and month of the event for comparability. The difference in ED visits between HHE and non-HHE days was used to estimate the effect size of particular HHEs. Relative risk (RR) was then calculated after incorporating population size. The calculation of RR assumes that populations remain constant over the period, and the number of persons cancels out the numerator and denominator. The RR calculation is subsequently a simple ratio of ED visits during HHE days (A_1) over the reference period (A_0): $RR = A_1 / A_0$. The 95% confidence are calculated according to Altman, (1991): $\exp(\ln(RR) \pm 1.96 \times SE\{\ln(RR)\})$.

Health impacts could have occurred at any point during the duration of the heat event, and up to four days following the event (Table 2). Normal ED visits were evaluated on a monthly basis for the General cohort and for the entire season for the Vulnerable cohort, due to low sample size.

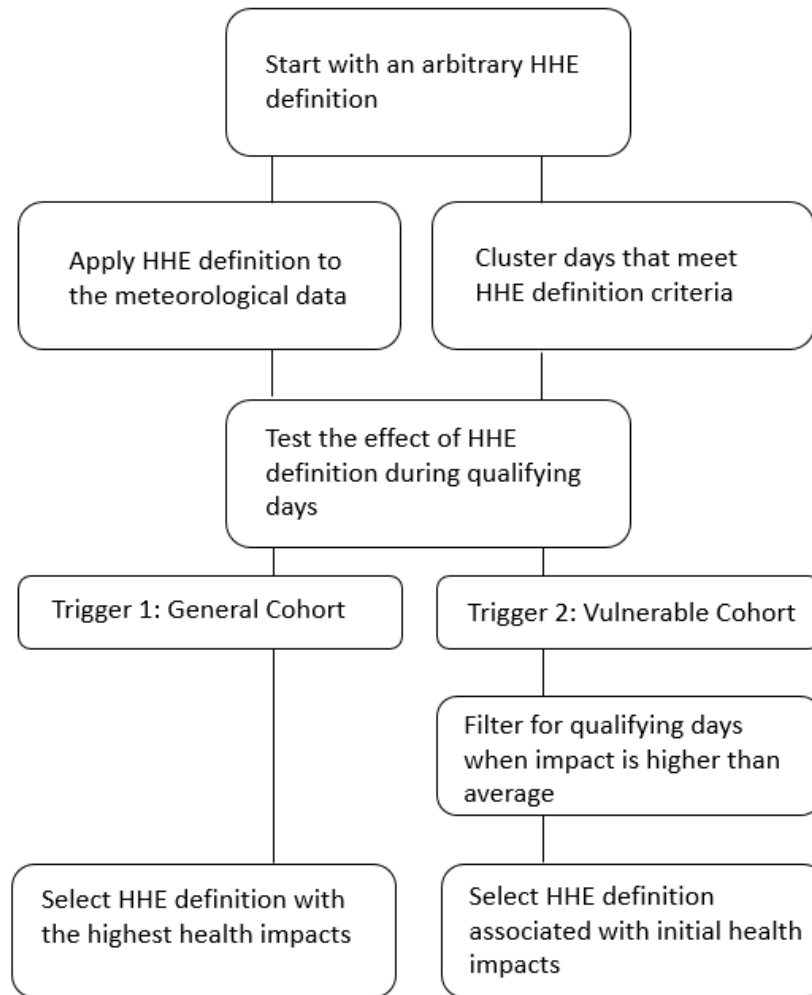


Figure 1: Statistical framework used for testing sensitivity of different Heat-Health Event definitions

Identifying the “best” HHE definition:

In a similar analysis by Vaidyanathan et al. (2017), the identification of the HHE definition that “best” explained the health effect was based on the size of the effect and the assumption that that higher estimated effects correspond with the least attenuation bias. To test this hypothesis, Vaidyanathan et al. (2017) simulated the attenuation bias concept by testing similar definitions and variants and observing the influence of deviation from the other ‘gold standard’ definitions and found that the HHE definition with strongest effect size represents the closest approximation to the highest confidence. The definitions that corresponded with the highest effect size were thus selected for the General cohort to minimize bias and false positives (Figure 2).

However, to test the sensitivity of the Vulnerable cohort, composed of high risk age groups (0-4 and 65+ yr) and race (all non-white), we adjusted the qualifier for “best” HHE definition by selecting the event type that corresponded with average excess morbidity, to accommodate well-documented differences in sensitivity between these age (Schwartz, 2005; Klinenberg,

2003) and racial groups (Basu et al., 2011; Knowlton et al., 2009). Conceptually, we select an event type (i.e., maximum and minimum temperature and duration) closest to the average of all events exceeding normal ED visitation rates (Figure 2). The Vulnerable and General cohort labels in Figure 2 illustrate how definitions are assigned in a hypothetical zone where ED visits and the relative severity of various definition variants are related.

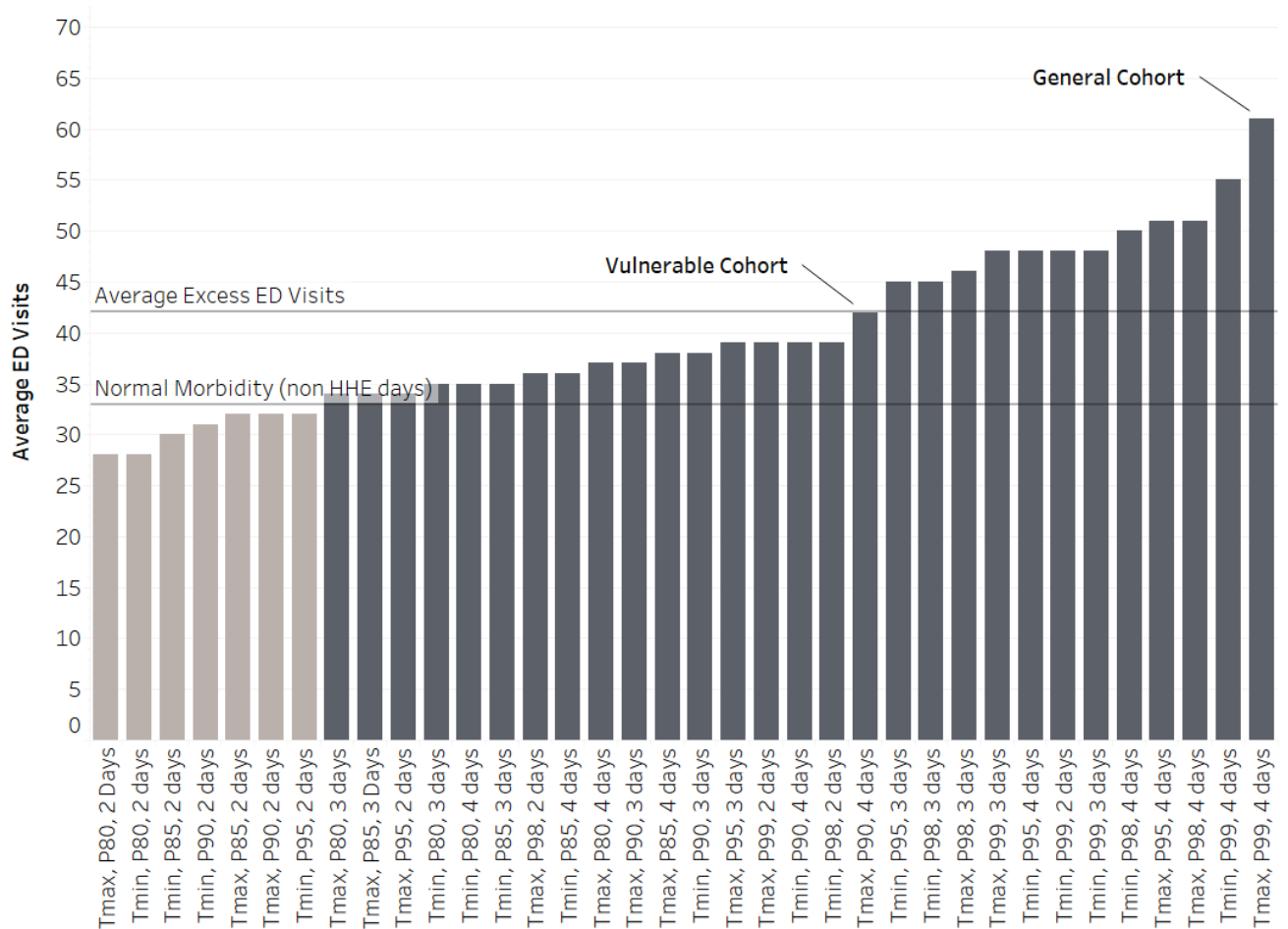


Figure 2: Average number of ED visits, including extended effects, between 2005 and 2013 during qualifying HHE events (shaded). In pane, HHE definition selection criteria for Vulnerable cohort (average) and General cohort (max) for a sample area.

Evaluating the effect of qualifying heat events for all 63 definition variants was resolved through ranking, and the definition/ variants with the largest effect sizes, including effects within 0-4 days lag, were selected. When two or more definitions were associated with the same effect size, we assume there is a moderate degree of agreement between HHE definitions. Collinear definitions, or those that result in similar HHE definitions, were similarly associated with identical effect sizes. To resolve collinear definitions and identical effect sizes, we employed two filters to arrive at a single definition: (1) select the definition with the lower,

more easily attainable percentile threshold (i.e., 95th versus 98th percentile), and where possible, (2) select the definitions with two metrics (i.e., Tmax and Tmin versus Tmin alone).

Definition/ variants were then transformed into HHE signatures consisting of thresholds for the weather variables (maximum temperature, minimum temperature, and duration) for each zone, month, and cohort based on climatology of the area (i.e., 30-year meteorological data). Heat metrics were averaged for all qualifying events; that is, each percentile/ duration variant was associated with one or more heat metric. For example, a definition that consists of Tmax and Tmin at or above the 98th percentile for two consecutive days in the downtown Fresno area is equivalent to 103.34 degrees (°) Fahrenheit (F) Tmax (daytime) and 70.81° F Tmin (nighttime) for two consecutive days. For definitions that included only one qualifying heat metric such as Tmax or Tmin alone, we obtained the counterpart metric from the events that met or exceeded the definition's percentile threshold. For example, when a definition consisted of only one climate metric, we averaged the missing metric over all qualifying days in the test period (2005-2013) accounting for month of occurrence. This exercise allowed the flexibility of testing the sensitivity of HHEs using different climate metrics while retaining a richer, more detailed event signature that included both daytime and nighttime temperature.

To minimize the influence of seasonal acclimation on the definitions, we evaluated definitions and their effects on a monthly basis. A separate period consisting of June, July, and August was developed in addition to the May and September definitions. Middle summer months (June, July, and August) were later grouped because the similarity between signatures (Tmax, Tmin, and event duration) across the three months. The HHE definition with the highest associated effect size was selected to represent this three-month period. Each definition/ variant utilized the monthly meteorological normals and monthly ED visits to account for the potential intra-seasonal variability associated with ED visits.

2006 Heat Wave:

Respondents of the User Needs Assessment (UNA) noted that real-life events such as the 2006 heat wave could serve as powerful reference point in the online, interactive tool. We subsequently developed HHE definitions based on local characteristics of the heat wave that swept across most of the state in 2006. To evaluate relative risk of a single event, we modified the reference and exposure period.

To define an exposure period, we chose a period slightly longer than the peak meteorological conditions, July 15 – August 1, which is also utilized in other evaluations of the 2006 heat wave (Hoshiko et al., 2008). This period is slightly longer than the first and last recorded heat-stroke deaths reported by California coroners, July 16 – 27 (Trent 2007), to account for broader health impacts such as heat-related morbidity that result in higher than average ED visits. Signatures were derived from the average of the four hottest, consecutive days within the period, using a moving average. The normal expected number of deaths for the period was obtained by taking the sum of the ED visits from an equivalent set of days close in time to the heat period, controlling for both month and day of the week. We chose control days with the same month (i.e., July) and day of the week (e.g., Monday, Tuesday, Wednesday, etc.) in 2005 and 2007, and excluded the Independence Day weekend. No reference period was chosen within 2006 to avoid comparison with a period that may have experienced high displacement due to the heat wave. Years 2005 and 2007 were chosen because the relative absence of heat waves in those years and the similarity in population. As a result, we obtained eight control days for each case day. We

then summed the number of ED visits over all qualifying days for each zone and cohort, including the number of ED visits with no lag (i.e., no offset), 1-, 2-, 3-, and 4-day extended effects. Case days were then compared to control days to estimate effect size and relative risk (RR).

3.2 Projecting Future Heat-Health Events

The objective of the future climate analysis element of this project is to identify trends in the frequency and characteristics of future HHEs in each of the 8057 census tracts in California. To accomplish this, we analyzed projections of future conditions using several combinations of signatures for past HHEs based on historical health and weather data to detect events of equal or greater severity. Since the future evolution of the climate is uncertain due to natural variability and uncertainty regarding future emissions and equilibrium climate sensitivity, we did so for an ensemble of projections in order to consider a range of possible future climate conditions.

The ensemble was a subset of the Localized Constructed Analogs (LOCA) downscaled projections developed by the Scripps Institute (Pierce et al., 2014; Pierce et al., 2015) including the twenty-four models that provide daily minimum and maximum relative humidity in addition to daily minimum and maximum temperature. LOCA projections were developed for both RCP 4.5 and RCP 8.5 in order to represent the difference between business as usual emissions (RCP 8.5) and a moderate mitigation scenario (RCP 4.5), resulting in a total of forty-eight projections, two for each model. The spatial resolution of the LOCA projections is 1/16th degree or approximately six kilometers, and daily values of the variables are available from 2006 through 2099.

We analyzed the frequency and average characteristics of HHEs for twenty-year periods centered around 2020 and every ten years following through 2090, (i.e., 2011-2030, 2021-2040 and so on through 2081-2099), for each of the forty-eight projections. Since the centers of successive time periods are ten years apart, there is overlap in the years used with the preceding and subsequent time periods.

For each HWZ, we used the signatures for the Vulnerable cohort, the General cohort, and the July 2006 Heat Wave that had been derived for it. The signatures each take the form of thresholds for maximum daily temperature, minimum daily temperature, and duration. For each time period, we analyzed all forty-eight projections to identify events that satisfied each of the signatures. Specifically, daily minimum and maximum temperatures had to equal or exceed their respective thresholds for a number of consecutive days equal to or greater than the duration threshold. Because the thresholds are all lower bounds, the events detected are of equal or greater severity than the corresponding historical events.

We only considered events that occur from April through October of each year. For the General cohort, we delineated events by those occurring in April/May, June/July/August and September/October. For each event, we captured the average maximum and minimum daily temperature and the average maximum and minimum relative humidity during the event and its actual duration. We calculated the annual frequency by dividing the number of events by the numbers of years in each projection period and the average characteristics by averaging the characteristics of the individual events.

For each cohort, and the July 2006 Heat Wave, we sorted the projections in ascending order based on the number of events. In order to characterize the range of projected outcomes, we then captured the HHE frequencies and average characteristics from the projections nearest the 5th, 33rd, 50th, 67th and 95th percentile.

As illustrated in Figure 3, most census tracts are much smaller than a LOCA grid cell and therefore do not contain a LOCA grid point. For this reason, we chose to analyze HHEs for each heat wave zone (HWZ) based on projected temperatures for the LOCA grid point nearest its center. The results for each census tract are based on the results of its assigned HWZ.

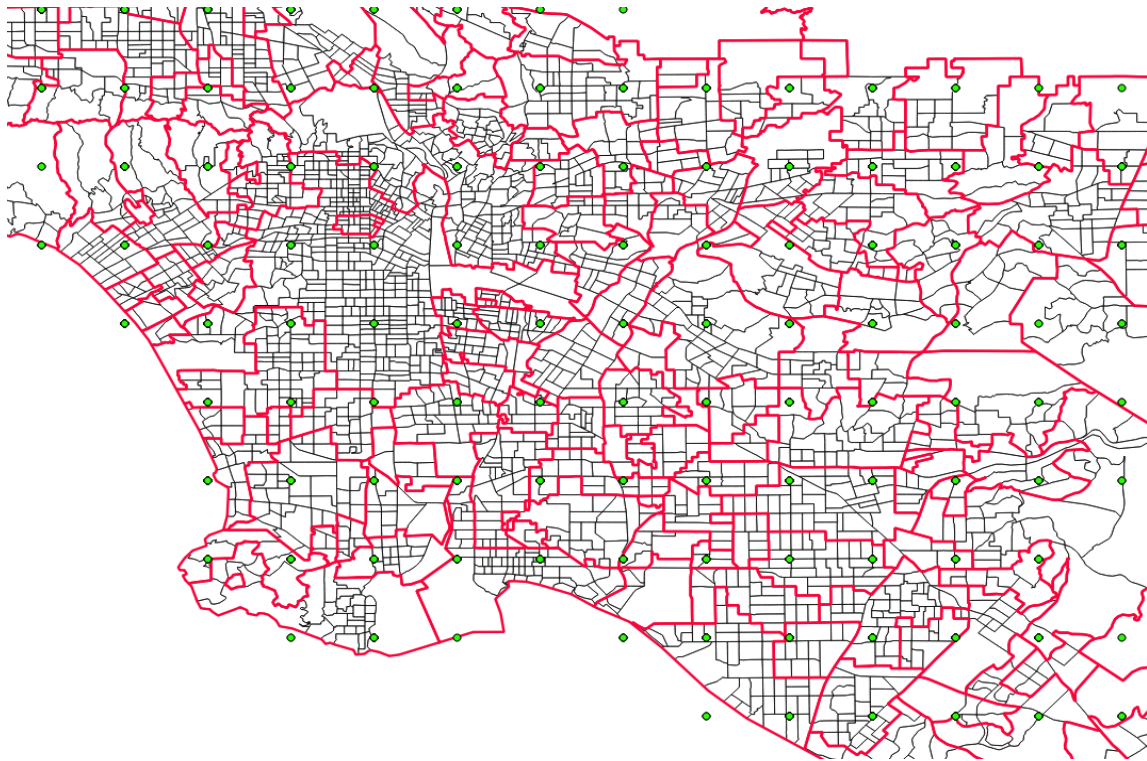


Figure 3: Census tracts, HWZs and LOCA grid points for Los Angeles. Census tract boundaries are black, HWZ boundaries are red and LOCA grid points are green.

3.3 Limitations

Determining Historical Heat-Health Events

During the review of effects arising from historical HHEs, several limitations were encountered that could be attributed to the obscure rules and format of medical data provided by OSHPD. Principally, the spatial boundary used to organize medical information (i.e., zip code tabulation areas) has no logical counterpart in meteorology, and many work-arounds such as the construction of heat wave zones (*Appendix A*) were required to address spatial incongruity. Similarly, medical data suppression rules required each record to include twelve or more individuals. As a result, zip codes were aggregated when they shared a common heat wave zone classification and data from subgroups were sometimes not available. As a result, known

age and race groups were aggregated into a single population subgroup and the construction of monthly HHE definitions for the Vulnerable cohort were not feasible, and therefore HHE definitions were limited to “all season” (MJJAS). Without directly integrating other subgroups, diagnoses codes, and contextual factors into our determination of HHE thresholds, some specific factors are not directly accounted for.

It is worth noting that the use of all ED visits as an outcome variable in this case may not directly quantify the influence of confounding effects, but they are nevertheless captured as part of the total sum. Similarly, some ED visits during HHE days may not be directly related to temperature, but the relative increase in ED visits during HHE days across several years show strong agreement between RR and selected HHE variants (Table 6). As is so often the case in epidemiology, easily accessible surrogate endpoints were selected, in this case, ED visits. ED visits may not capture other heat effects registered through 911 calls or hospitalizations. Also, a person warned about an oncoming heat wave may have a lower threshold for deciding to visit the ED because of anxiety created by the warning, compared to a person who has not been warned. Lastly, HHE signatures generated from ED visitation records between 2005 and 2013 are merely a snapshot in time and do not account for future acclimation, demographic change, or population growth.

Projecting Future Heat-Health Events

Modern global climate models are physics-based representations of the Earth’s atmosphere, land surfaces and oceans whose limitations have been well documented in the literature. In the context of this project, two of the most important are spatial resolution and uncertainty.

The models used for projections in this study are from the Coupled Model Intercomparison Project 5 (CMIP5). The resolution of CMIP5 models is on the order of 1°, or about 100 km, much too coarse to accurately capture the future changes in daily temperatures at the local scale needed for this study. We have addressed this limitation by using the statistically downscaled LOCA projections, as previously discussed. However, statistical downscaling has its own limitations, notably the robustness of the correlations between large scale and fine scale weather patterns it is based on and the inherently unverifiable assumption that those correlations will remain robust over time.

There are three principal sources of uncertainty in climate projections: future emissions, model response to GHG atmospheric concentrations, and natural variability (Hawkins, 2009).

Uncertainty in future emissions is generally addressed by examining projections for two or more emission scenarios, such as the Representative Concentration Pathways we have used in this study. The effects of model response and natural variability is addressed by examining an ensemble of projections, such as the LOCA projections from the 24 models we have used in this study. As discussed in 3.1.2, we ranked the projections based on the frequency of HHEs, providing insight into the range and relative likelihood of various outcomes. In both cases, there is no assurance that the full range of possible future emissions or climate conditions is included in the results.

As discussed in 3.1.1, in some instances the statistical analysis of health data did not generate thresholds for both maximum and minimum daily temperatures. To avoid identifying false positive HHEs in the projections, we used the average value of that variable for the qualifying days in place of the missing threshold. Another possibility would have been to use the minimum value for the qualifying days, but we were concerned that this would have put too

much weight on a single day. A possible consequence of our decision is that there may be false negatives in our analysis of future HHEs. For example, in a small number of cases, the historical frequency of some of the most extreme events witnessed in the historical timeframe was zero under these more restrictive thresholds. Given that these events did happen in the historical record according to their original definition, we set their event count over the baseline to once per thirty years.

Changes in Adaptation Practices and Population Resilience

There is evidence that heat-related mortality has decreased in recent years. For instance, Gasparrini et al. (2015) found that the relative risk for heat-related mortality decreased in many countries from 1993 to 2006. Other studies find a similar trend of decreased negative heat-related health impacts despite increasing temperatures, likely the result of adaptive practices, such as infrastructural changes (e.g. implementation of air conditioners) or awareness and mitigation programs for communities (Bobb et al., 2014; Hondula et al., 2015). It can be assumed that some degree of historical levels of adaptation and acclimation are embedded in the medical data used to inform this study. However, it is not fully understood how the increasing severity, prevalence, and changing characteristics of heat waves will impact this complex, non-stationary relationship. Given the lack of available data that would allow for detailed demographic projections, health outcomes associated with past HHEs are the fairest estimate of future conditions.

4: Results

In this systematic review of HHE thresholds and their corresponding effect size, we found that multiple HHE signatures may serve as a more adequate basis for planning given the heterogeneity of climates and communities across California. This approach can shed light on the varying degrees to which communities are sensitive to heat according to the time of the season, duration, and temperature and humidity levels, all of which are important for characterizing locally-specific heat wave baselines for future projections.

Using these HHE signatures as a baseline for projecting changes in HHEs, we found increases in the severity and duration, and shifts in the timing of HHEs throughout the century and under all emission pathway scenarios. We also found a significant uptick in the number of late season (September, October) HHEs for many regions. In parts of the Central Valley, the duration of the average HHE could increase by up to two weeks, and the area could experience an additional four to six events per summer by mid-century. In the North Sierra region, four to six additional mid-summer HHEs could occur every summer by mid-century.

In addition to more frequent and longer HHEs, public health risk could rise due to increasingly warm nights (limiting the opportunity for physiological recovery and prolonging the period for which negative health outcomes can occur) and the presence of the Urban Heat Island effect, which together poses serious risk to households without air conditioning. Low-income urban areas that we also projected to experience significant increases in the frequency and severity of heat waves could disproportionately suffer. A few of these areas include the San Francisco Bay Area (East Oakland, Vallejo, East Palo Alto), Los Angeles (Compton), and Central Valley (Palmdale and Sanger).

As for signals of a shifting season, we detected significant relative increases during shoulder months, with higher relative increases in the frequency of late season events (September and October), predominately within the South Central Valley and North regions. During mid-summer (June, July, and August), significant increases in the frequency of HHEs are estimated to occur statewide, especially in Southern California. Interestingly, for the Vulnerable cohort, the largest relative increase in frequency of HHEs could occur in the Central Valley region where a large portion of the state's outdoor workers reside.

Perhaps the most consistent trend identified in the HHE projections is the lengthening of HHEs. Regardless of the probability level or the scenario (e.g. RCP 4.5 or 8.5), our findings indicate that HHEs are very likely to last longer throughout California. By mid-century, the duration of HHEs could increase by up to a week for many areas. By the end of century, HHEs in parts of the Central Valley and North could last up to two weeks.

Each characteristic of future HHEs is explored in more detail below.

4.1 Characteristics of Heat-Health Events

4.1.1 Historical Heat-Health Events

In California, there is no one heat wave that can be considered typical. Across all 487 heat wave zones (*Appendix A*), HHE definitions vary widely (Table 4). Definitions based on minimum temperature percentiles make up most definitions, and the majority consist of events equal to or greater than the historical 95th percentile. We found distinct differences in the type of HHE definitions between the Vulnerable and General cohort. Nearly half of the zones were assigned a definition below the 90th percentile regardless of metric. Very few "extreme" HHE definitions (i.e., 98th and 99th percentile, mean+2 standard definitions) were assigned to zones when considering the Vulnerable cohort, implying a lower trigger is needed to alert vulnerable individuals. Table 5 summarizes the percent of HHE definitions by metric/percentile/duration for the Vulnerable cohort.

Table 4: Percent of HHE definitions by metric/percentile/duration variant across all the 487 California heat wave zones considering General cohort (white, ages 6-64).

Percent of HHE Definitions Relative Threshold (General Cohort)								
Daily heat metric	Duration (days)	P80	P85	P90	P95	P98	P99	Mean + 2 std dev
Tmax	≥2		0.6	0.6	0.4	1.2	1.6	1.6
	≥3	0.6		0.6	1.4	2.9	1.4	1.2
	≥4	0.6	0.2	1.2	1.2	1.6	3.1	0.6
Tmin	≥2	0.6	0.8	0.4	2.3	2.9	5.1	2.9
	≥3	0.6	1.2	0.6	1.2	3.5	2.5	1.8
	≥4	1.8	1	1.6	4.3	3.3	2.7	6
Tmax and Tmin	≥2		0.2	0.2	0.4	2.1	4.7	
	≥3	0.6	0.2	0.6	2.1	2.9	2.7	
	≥4	1	1.8	1.2	4.5	3.3	1.2	

Table 5: Percent of HHE definitions by metric/percentile/duration variant across all the 487 California heat wave zones considering Vulnerable cohort (over the age of 65, under age of 5, and all non-white individuals). Blanks indicate that definition was not assigned.

Percent of HHE Definitions Relative Threshold (Vulnerable Cohort)								
Daily heat metric	Duration (days)	P80	P85	P90	P95	P98	P99	Mean + 2 std dev
Tmax	≥2	6.2	4.3	2.2	3.1	1.8	2.8	1.5
	≥3	2.2	3.1	2.8	0.3	1.2		0.3
	≥4	0.6	0.3	1.8	0.3			0.3
Tmin	≥2	4.9	3.4	2.5	2.2	2.2	1.5	3.1
	≥3	2.8	1.5	1.2	2.2	0.6	0.9	1.2
	≥4	2.8	1.5	0.9	0.9	0.3	0.3	0.9
Tmax and Tmin	≥2	5.5	2.8	2.8	2.2	1.2	0.9	
	≥3	3.1	1.5	1.2	1.8	0.3		
	≥4	1.5	1.2	0.6	0.3			

When considering medically-informed thresholds (i.e., HHEs) as a baseline, we found that emergency department (ED) visits from 2005 to 2013 during HHEs (63 unique definitions based on metric/percentile/duration variants) were 7% greater than ED visits during days with designated Excessive Heat Warnings issued by the National Weather Service.⁷ Similarly, the average number of daily ED visits during HHE days were greater than non-HHE days (Figure 5). We also found that the appropriate signature for vulnerable subgroups may be up to 6-8° F lower than the General cohort in some areas (Figure 7).

For the Vulnerable cohort, we also estimate dangerous HHEs occurred 184% (almost twice) more often and were associated with 18% more heat-related emergency department visits when compared to the same NWS signature. When evaluating excess ED visits during HHE and non-HHE days, HHE days accounted for an additional 17.3% ED visits throughout the summer between 2005 and 2013. Across California, some regions exhibited higher degree of sensitivity (RR) even at lower temperature percentiles (Table 6).

⁷ A commonly used definition for Excessive Heat Warnings by NWS includes two consecutive day when daytime and nighttime temperature high exceed the local, 95th percentile. Many California NWS offices will initiate alert procedures when the daytime heat index exceeds 105°-110° F for at least two consecutive days, but thresholds may vary slightly depending on the local climate and the expert judgment of station meteorologists.

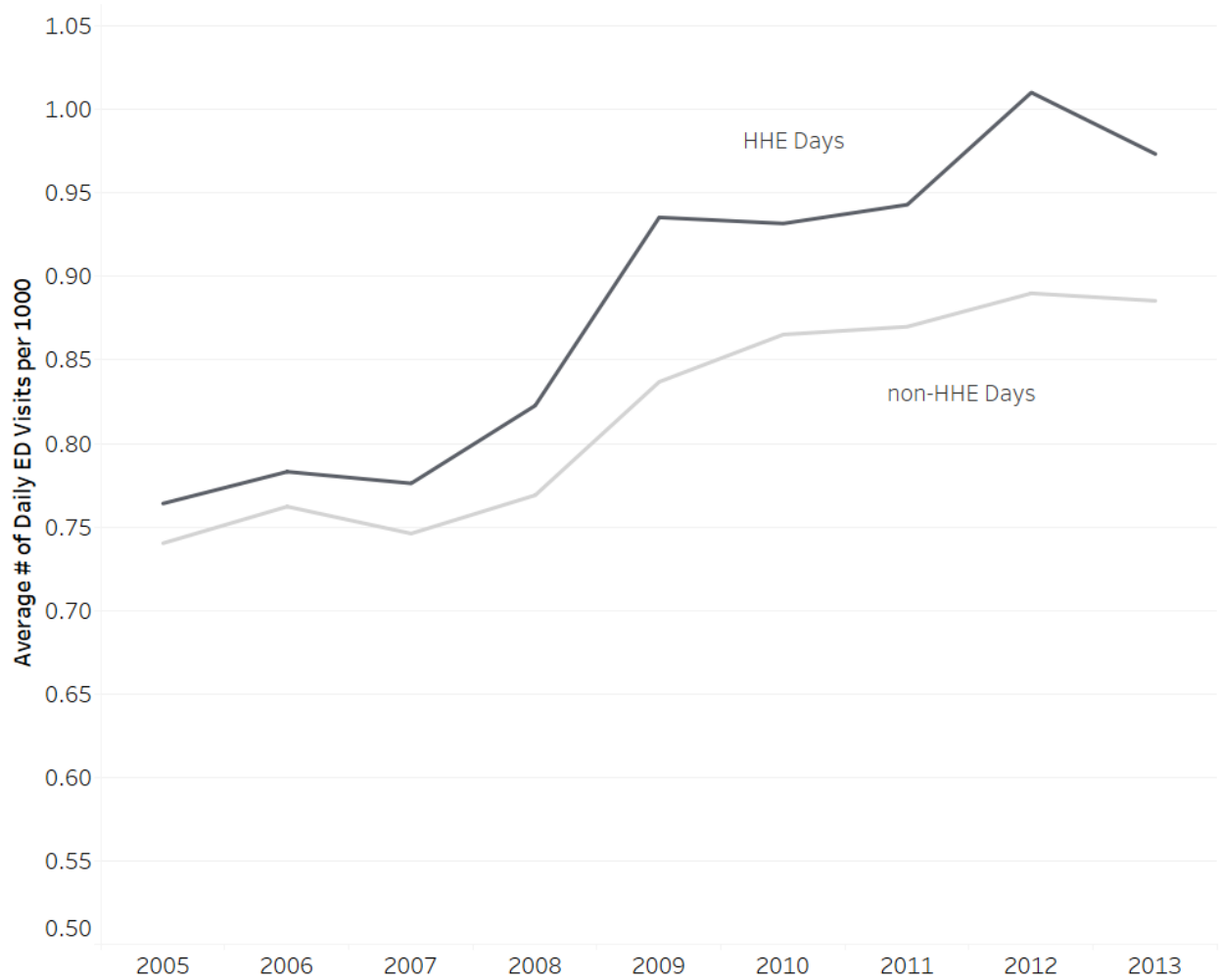


Figure 5: Average number of statewide daily ED visits per 1000 residents across HHE days and non-HHE days for the study period. Some daily records not included due to suppression level rules.



Figure 6: Climate Impact Regions (CIR) as defined by the California Natural Resources Agency

Table 6: Average percentile maximum temperature during historical HHEs (1984-2013) and associated Relative Risk (2005-2013) during midsummer (JJA) for all Climate Impact Zones and General cohort. Note, minimum temperature included in HHE criteria, but excluded from table.

Climate Impact Region	Relative Risk (95% CI)	Percentile (Tmax)
Bay Area	1.19 (1.17 1.21)	91.71
Central Coast	1.24 (1.20, 1.29)	96.84
Desert	1.19 (1.17, 1.21)	94.11
North	1.17 (1.09, 1.25)	97.05
North Central Valley	1.20 (1.18 1.22)	95.27
North Coast	1.16 (1.11, 1.22)	92.47
North Sierra	1.17 (1.12, 1.23)	96.7
South Coast	1.19 (1.18, 1.21)	95.07
South East Sierra	1.12 (1.04, 1.21)	98
Southern Central Valley	1.20 (1.18, 1.23)	91.8

Figure 7 summarizes the maximum and minimum temperature thresholds at which an HHE, as defined in our analysis, occurred between 2005 and 2013. Across the state, HHE temperature thresholds increase from May to midsummer and decrease slightly in September. The duration of HHEs (not visualized), varied less significantly, and statewide, the average HHE lasted 3 to 4 days.



Figure 7: Heat-Health Event Temperature thresholds (maximum and minimum temperature) by month and Climate Impact Region.

Figure 8 illustrates the temperature threshold differences between the General and Vulnerable cohort for the entire summer season. The relative difference between cohorts is slightly more pronounced for the South Coast, Bay Area, and North Coast. The average difference in both maximum and minimum temperature between the General and Vulnerable cohort is approximately +4° F and as high as +8.6° F in the city of Antioch, presumably due to the higher rates of heat related factors that influence response rates.



Figure 8: Heat-Health Event Temperature thresholds (maximum and minimum temperature) by cohort and Climate Impact Region for the entire summer season (MJJAS).

We found the relative risks for all-cause ED visits during the 2006 heat wave were higher in the North Coast and Central Coast (Table 7). Though less pronounced, Knowlton et al., (2009) similarly found higher relative risk in the Central Coast, despite lower temperatures.

Table 7: Relative risk and average maximum and minimum temperature and humidity during the 2006 heat wave for all Climate Impact Regions.

Climate Impact Region	Relative Risk (95% CI)	Average Event Tmax (degF)	Average Event Tmin (degF)	Average Event RH max (%)	Average Event RH min (%)
Bay Area	1.07 (1.05, 1.09)	98.22	68.64	69.37	32.65
Central Coast	1.08 (1.05, 1.13)	95.24	66.04	72.25	32.96
Desert	1.05 (1.03, 1.07)	107.95	76.64	64.79	23.94
North	1.07 (1.01, 1.14)	103.84	70.91	54.62	19.23
North Central Valley	1.07 (1.05, 1.09)	109.54	75.69	67.56	28.4
North Coast	1.09 (1.03, 1.14)	94.94	66.72	66.65	30.45
North Sierra	1.07 (1.02, 1.13)	104.2	71.93	55.12	19.96
South Coast	1.06 (1.05, 1.08)	97.5	72.6	81.59	39.84
South East Sierra	1.05 (0.93, 1.18)	91.73	63.53	56.87	21.62
Southern Central Valley	1.07 (1.04, 1.09)	108.69	78.11	62.18	25.01

4.1.2 Projected Heat-Health Events

Generally, we found increases in severity, duration, and in most cases, changes to when HHEs occur within a season.⁸ The wider Central Valley will experience the greatest relative increases in the frequency and duration of HHEs in all scenarios and probabilities, in contrast to historical HHE frequency of occurrence, particularly in the mid-summer months. Similarly, for the Vulnerable cohort, the largest relative increase in frequency of HHEs could occur in the Central Valley region across all percentiles.

Frequency

In several regions, changes in the number of HHEs are most pronounced during JJA (Figure 9). In the Sierras and nearby foothills within El Dorado and Placer counties, early summer HHEs could occur once every four years⁹ by mid-century in a business-as-usual scenario. Across the

⁸ The projected changes in HHE signatures are specific to area and timing within the summer season. To qualify as an HHE, all future events had to equal or exceed their respective thresholds for consecutive days equal to or greater than the duration threshold and a minimum and maximum temperature. Because the thresholds are all lower bounds, the events detected are of equal or greater severity than the corresponding historical events, which means any relative increases in the signature of HHEs in the projection periods represents an increase in the tail-end of the distribution for all variables (temperature, humidity, duration), as well as frequency of occurrence.

⁹ Two consecutive days exceeding maximum temperature of 95° F and nighttime temperature of 63° F.

state, all regions should expect increases in the frequency of HHEs by the end of the century, with the possible exception of the North Coast under only low-end projections (i.e., the 5th and 33rd percentile projections).

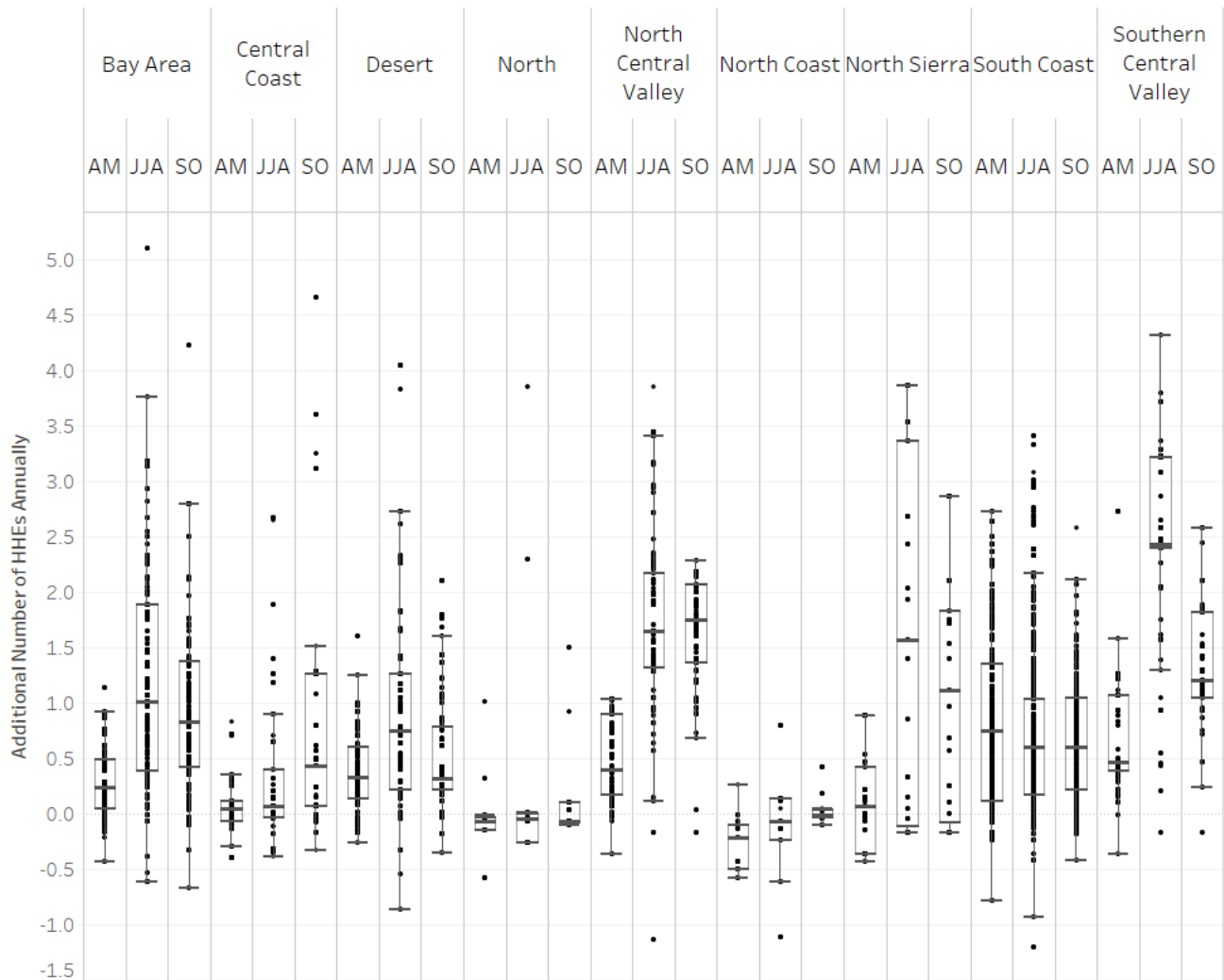


Figure 9: Difference in annual number of HHE by mid-century under a business-as-usual scenario, 50th percentile.

Duration

Perhaps the most consistent trend identified in the HHE projections is the lengthening of HHEs. Regardless of the probability level (i.e., 5th or 95th percentile) or the scenario (i.e., RCP 4.5 or 8.5), our findings indicate that HHEs are very likely to last longer throughout California. By mid-century, the duration of HHEs could increase by up to two weeks in some areas (Figure 10). By the end of century, HHEs in parts the Central Valley and North could last up to two

weeks. The greatest relative changes in the duration of HHEs within a season occur predominantly later in the season (Table 8). By mid and end century, the duration of mid-summer (JJA) and late season (SO) events may increase significantly in all regions with more modest increases in the North Coast. Several cities in the northern reaches of the Bay Area could experience early season HHEs that are three to four days longer than historically. South Central Valley and North regions dominate the trend in duration, but by the end of century, HHEs in parts of the South and Central Coast could last more than a week, on average, in even the low-end projections (i.e., 5th percentile).

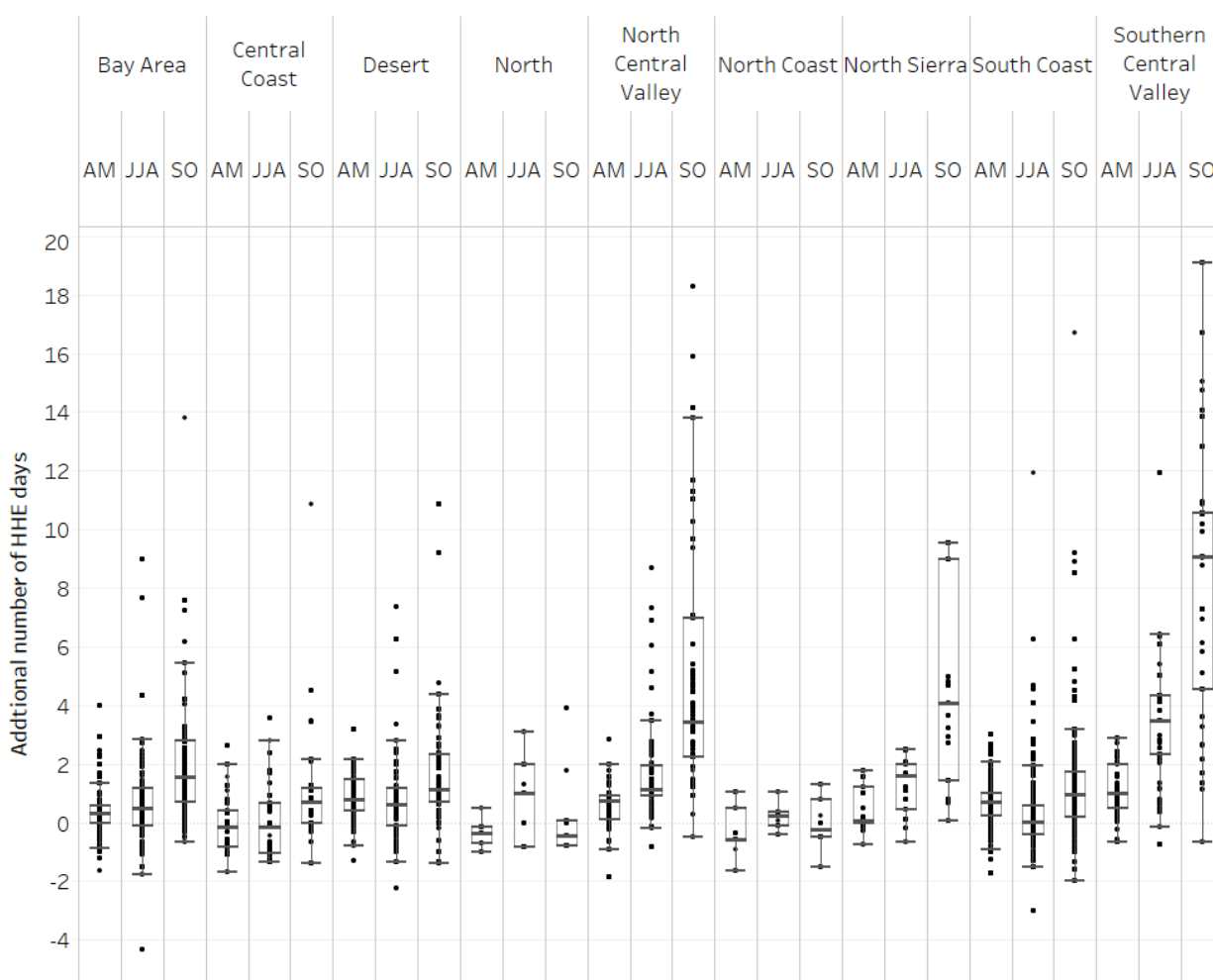


Figure 10: Additional length (days) of HHEs during JJA by mid-century, 50th percentile, General cohort.

Severity

Maximum and minimum temperatures will increase statewide during HHEs, but the highest relative changes in nighttime temperature are most apparent along the coasts. In the late season, higher changes in temperature are apparent across all regions (Table 8). Large swaths of the North Coast in Santa Rosa and Mendocino counties could experience HHEs that are, on average, 10° F hotter mid-summer (JJA) by mid-century, under a business-as-usual scenario. Under the same scenario, areas in Los Angeles and San Diego could experience HHEs up to 12°

F hotter than the historical record (1984-2013). In Compton, a city with an RR of 1.07 during mid-summer HHEs, nighttime and daytime temperatures could each increase by 10° F.¹⁰ Between mid- and end of century, Tmax and Tmin increase in nearly all regions throughout the season (Table 8).

¹⁰ In Compton, an HHE consist of any day when Tmax reaches or exceeds 91.2° F and Tmin reaches or exceeds 70.4° F. By mid-century, in a business-as-usual scenario, the average Tmax and Tmin of all qualifying HHEs is 100.7° F and 80.2° F, respectively.

Table 8: Relative increase (%) of average maximum and minimum HHE temperatures, mid- and end-of-century, RCP 8.5, 50th percentile

Climate Impact Region	Time Period	HHE Tmax (F)	Projected HHE Tmax, Relative Change (%)		HHE Tmin (F)	Projected HHE Tmin, Relative Change (%)	
		Historical	2050	2090	Historical	2050	2090
Bay Area	AM	88.4	-0.8%	-1.9%	58.3	2.0%	4.4%
	JJA	91.2	1.9%	1.4%	62.8	2.9%	4.5%
	SO	88.8	3.5%	2.4%	60.0	5.8%	8.9%
Central Coast	AM	85.2	2.8%	2.2%	55.9	2.2%	2.2%
	JJA	91.5	2.6%	2.5%	61.4	4.1%	4.7%
	SO	89.7	4.5%	2.9%	60.2	6.3%	7.2%
Desert	AM	98.7	1.9%	1.9%	64.2	1.8%	2.6%
	JJA	104.3	3.7%	3.7%	74.5	1.1%	2.7%
	SO	100.5	5.5%	6.2%	72.9	1.7%	2.7%
North	AM	92.7	-1.2%	2.5%	58.5	1.2%	-2.1%
	JJA	100.1	2.0%	4.7%	68.0	0.8%	3.6%
	SO	96.2	2.4%	3.7%	60.7	2.7%	3.7%
North Central Valley	AM	96.3	1.1%	1.0%	61.0	4.1%	4.8%
	JJA	104.2	1.8%	1.6%	68.6	3.2%	4.3%
	SO	91.3	7.1%	6.6%	63.7	2.6%	3.4%
North Coast	AM	86.7	-3.8%	-3.2%	55.0	1.5%	0.1%
	JJA	89.9	2.4%	1.6%	60.9	-2.5%	0.1%
	SO	89.7	4.3%	4.4%	59.0	2.1%	3.4%
North Sierra	AM	90.3	-0.3%	0.7%	57.3	4.4%	5.1%
	JJA	101.0	1.4%	1.6%	66.0	5.0%	6.5%
	SO	89.7	5.4%	4.9%	62.0	4.0%	5.4%
South Coast	AM	90.1	-0.3%	-0.7%	62.6	3.0%	3.8%
	JJA	93.8	3.4%	2.7%	71.4	2.0%	3.0%
	SO	93.7	4.0%	3.7%	69.9	3.4%	4.5%
Southern Central Valley	AM	98.3	1.3%	1.2%	64.8	2.7%	3.7%
	JJA	104.8	1.1%	2.3%	73.2	0.0%	0.0%
	SO	95.4	5.3%	5.5%	69.3	0.6%	1.2%

Re-Occurrence of 2006 Heat Wave

Extreme heat events, such as the 2006 heat wave, are also expected to occur more frequently. By the end of century, events lasting five or more days of equivalent or greater temperatures as observed during the 2006 heat wave (see *Chapter 3.1.1 Defining Historical Heat-Health Events, 2006 Heat Wave*), could occur more than once per year in some regions (Figure 11). When comparing projections to locally observed temperatures during July 2006, we found that an

event equivalent to the 2006 heat wave has a 50% chance of occurring 2-3 times per year in parts of Monterey County and San Luis Obispo County. Both counties were particularly affected by the 2006 heat wave (Knowlton et al., 2009). In parts of the Northern Sierras (El Dorado and Placer counties), 2006 heat wave conditions (daytime temperatures > 110° F) could occur once every year and remain for up to a week by the end of the century under a business-as-usual scenario.

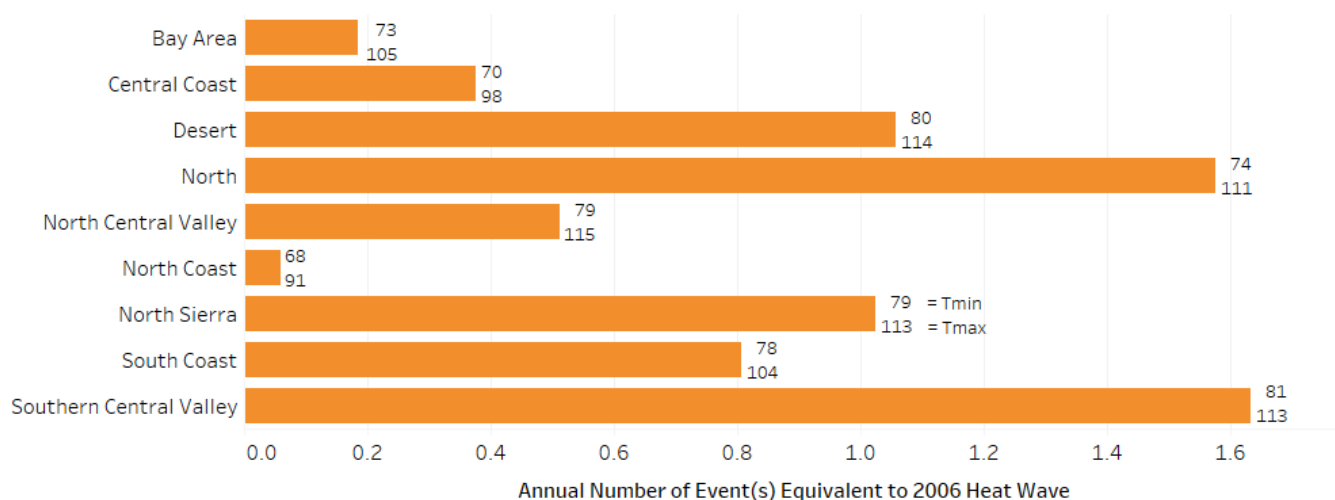


Figure 11: Frequency of event(s) equivalent (Tmax, Tmin, duration) to the 2006 heat wave and lasting at least five consecutive days, by end of century, under RCP 8.5, 50th percentile.

5: Discussion

5.1 Heat-Health Events in Practice

While a heat wave is a meteorological event, for the purposes of long-term planning for public health, its severity should not be assessed independently of human impacts. From a climate change perspective, the lack of a unified index can cause confusion when discussing the complexities involved in evaluating and projecting the frequency and intensity of heat extremes in a changing climate. In epidemiological studies of heat morbidity, extreme heat is often ambiguously defined by some statistical threshold, which is then applied uniformly. Using a definition that only identifies extremely hot days, or similarly, using a uniform statistical threshold to define extreme heat, may introduce false negatives and underestimate risks faced by unacclimated and vulnerable populations and individuals. Similarly, the added effect of heat waves lasting several days can have a pronounced health effect (Hajat, 2006), and the association of morbidity and temperature through single day linear regression or time-series analysis may underestimate the residual impacts of prolonged heat, such as heat waves.

We thus have attempted to examine the effect of increases in ambient temperature over a period of days, identifying temperature and duration thresholds at which associated health impacts are apparent for two coarsely defined cohorts (*Chapter 3.1 Heat-Health Events*). In this systematic

review of HHE thresholds and their corresponding effect size, we found less stringent thresholds may serve as a more adequate basis for planning under increasingly warm temperatures, affecting heat sensitive individuals and groups in increasingly dense, urban environments as well as agrarian-dominated areas. To the best of our knowledge, the medically-informed HHE thresholds explained in the *Chapter 3.1 Heat-Health Events* section are the first applied version of the statistical framework first outlined by Vaidyanathan et al. (2017).

It is our understanding that variability in temperature thresholds from one region to the next and across the summer season is the result of differences in climatology, seasonal acclimation, built environment, and even social vulnerability. Given rising average temperatures and increasingly frequent and prolonged heat waves, developing climate- and population-specific thresholds may offer a more adequate basis for climate change adaption planning.

HHE thresholds may be especially useful for seasonal- and population-specific heat wave planning. We found that statewide, maximum and minimum temperature thresholds are, on average, 4° F lower for vulnerable populations and 8° F lower in some areas. Within a season, HHE thresholds can also vary widely. Coastal areas such the North and South Coast and the Bay Area are, historically, susceptible to heat-related health impacts from heat events occurring in May when daytime highs only reach 80° F for three consecutive days.

While adequate thresholds alone do not prevent heat-related illnesses and death, locally relevant heat-health thresholds and contextual information can help support officials in sustainability, housing, transportation, urban planning and public health. Current heat thresholds are not always relevant for communities living in cooler climates that are not physiologically or technologically acclimatized to extreme heat and where seasonal or local temperature anomalies often fall below thresholds, yet still generate significant heat-health impacts. It is our hope that the use of medically-informed baselines to project future HHEs may provide a more adequate basis for evaluating future health risks with the use of climate projections.

5.2 A Changing Climate

When considering the intensity of future HHEs, coastal HHEs (Central Coast, North Coast, and the Bay Area) are expected to become progressively hotter relative to historical HHEs. Under a similar set of parameters, Gershunov and Guirguis (2012) found that the California coastline could see the highest relative increases in daytime temperature while Gershunov et al. (2009) also found the humidity-dominated heat waves were more likely to occur along the coasts. These coastal populations have shown to be more sensitive to heat events in part due to their low of acclimation to both high heat and humidity (Knowlton et al., 2009).

Though most of acute heat-related impacts tend to occur during the first heat wave day, the overall health implications are often more pronounced when heat waves last for several days (Hajat, 2006; Kalkstein and Smoyer 1993). While research would suggest that health effects of heat waves decreases as the summer progresses, the effect modification of changing patterns of heat wave duration and intensity during late summer and early fall is not well understood. Earlier HHEs during the shoulder months of April and May could have a pronounced health affect for individuals not yet acclimated to higher summer temperatures and could also affect the timing of snowmelt in mountainous regions. Increasing numbers of late season HHEs could extend or worsen fire conditions, especially in parts of the northern Sierra where late season

HHEs could double in frequency in a business-as-usual scenario. Evident from the 2017 fires in southern California, fires can extend into the winter when preceded by hot and dry conditions. In the city of Temecula, just east of Oceanside, late season HHEs could increase by a factor of seven, increasing from 1-2 events every thirty years historically (1984-2013) to once every other year by mid-century in a business-as-usual scenario.

Increasingly warm nights pose an additional risk, limiting the opportunity for physiological recovery and prolonging the period for which negative health outcomes can occur. For predominately urban areas, the risk of high nighttime temperatures is compounded by the presence of UHI, which poses elevated risk to households without air conditioning. While studying the influence of UHI and HHEs was outside the scope of this study, our projections signal a relationship between nighttime temperature and predominately impervious census tracts. In the cities of Compton and Buena Park, the average nighttime temperatures for mid-summer HHEs could increase by 10° F by mid-century.¹¹ In both cities, impervious surfaces cover over half of the land area.

"We need to focus on long-term interventions and not being overly dependent on air conditioning as our only option. In many rural counties, we are all working individually to get off the grid because there are too many eggs in one basket." (Health Officer)

Changes in relative humidity could also pose a significant public health risk.

Several California regions, including the Central Valley and the North Coast, are more prone to heat illness during extreme humidity (Gershunov and Guirguis, 2012). Humidity and pockets of stagnant warm air are uncharacteristic in most of the state's climate, but more humid, nighttime-dominated heat waves have been observed over the last 60 years and are predicted to intensify over the coming century (Pierce et al., 2012). Statewide, the Bay Area, Central Coast, and South Coast regions are expected to experience the steepest increases in maximum relative humidity during HHEs. Relative to other areas, coastal regions are expected to experience higher relative changes in temperatures, and to a degree that may necessitate wider adoption of air conditioning as an adaptation strategy. However, we found that there are few instances when minimum relative humidity, which generally coincides with maximum temperature, exceeds 60% during events that meet or exceed HHE thresholds. HHE definitions are characterized by higher daytime temperatures; therefore, our results do not indicate that relative humidity is a main driving factor of future HHE severity. Nevertheless, humidity should be explored in the tool at the city or even sub-city level as humidity is a very local affair.

Over time, communities may adjust to warmer and more frequent periods of excessive heat, but their ability to cope may vary considerably. Some populations may in fact adapt to higher temperatures through new technologies, behaviors, or physiological acclimation, effectively reducing their heat-related mortality (Hondula et al., 2015). Some of the most effective precautions necessitate significant changes in behavior and disruptions to daily routines that

¹¹ In Buena Park, an HHE during mid-summer (JJA) consists of three consecutive days exceeding maximum temperature of 97.7° F, minimum temperature of 70.76° F, (1984-2013). The average minimum temperature of all events exceeding this threshold by mid-century under a business-usual scenario is approximately 80.3°F, a +10° F increase.

many high-risk populations, especially vulnerable groups such as outdoor workers, do not always have the luxury to adopt.

5.3 Long-term Planning Opportunities

Long-term preventative strategies focus on how to decrease heat impacts through improvements in the built environment and strengthening social capital at the neighborhood level. Over the long term, efforts to build heat resilience through changes in the built environment will include: improved building standards that result in cooling of internal and external environments; land use cooling strategies; and urban heat island mitigation through use of cool pavements, cool and green roofs, increased tree canopy cover, greater green space and green infrastructure, and urban stream restoration (CAT, 2013).

The established relationship between the impacts of land use/cover on surface temperatures is an important environmental factor which could influence the overall temperature of an urban center, and subsequently the health of urban residents, especially those living in high-density environments. Studies show that one important factor affecting urban heat island patterns in cities is the amount of vegetation in relation to the impervious surfaces in a given area (Lo and Quattrochi 2003; Yuan and Bauer, 2007, Liang and Weng, 2008), making tree canopy and green space expansion efforts (Christopher et al., 2012; Loughner et al., 2012) one of the most promising opportunities for mitigating the amplification of oppressive temperatures in dense urban environments.

Living conditions, including the quality of housing and access to green space, are also critical factors in minimizing health impacts associated with heat waves. The potential thermal comfort of housing has direct linkages to excess risk during heat waves (Evans, et al., 2003; Howden-Chapman, 2004; Lawrence, 2004) while urban, well-vegetated parks can help improve air quality (Nowak, 2005) and provide a refuge of cooling during heat episodes (Spronken-Smith et al., 1999).

Technologies for alternative roofing systems are also being implemented as a heat reduction strategy. Roofs that can lower surface temperatures, thereby decreasing subsequent sensible heat flux to the atmosphere, come in two forms: cool roofs, designed to increase the albedo (proportion of reflected radiance or light) by use of reflective materials (typically white paints, elastomeric, polyurethane or acrylic coatings), and green or living roofs, which are partially or completely covered with vegetation. The installation of green roofs has resulted in significant reductions in air surface temperature in urbanized regions of China ($-0.20^{\circ} \pm 0.18^{\circ} \text{F}$) and the U.S. ($-0.25^{\circ} \pm 0.22^{\circ} \text{F}$) (Zhang et al., 2016). In Southern California, Vahami et al. (2016) simulated the cooling effect of cool roofs across metropolitan Southern California and found that cool roofs could reduce daytime air temperature by 1.62°F during the month of July and that the local cooling effects of industrial/ commercial cool roofs were even higher. However, these figures are concentrated to small regions and further analysis is needed to investigate the context and scale to which cool roofs and green roofs affect solar albedo and latent heat (Santamouris, 2014). Nevertheless, these studies demonstrate the potential of cool roofs to meaningfully decrease outdoor and indoor temperatures, reduce energy demand, and offset CO_2 emissions.

Other sources of resilience may arise from within communities. A strong social network, one with a high degree of community engagement and connectivity, is an important characteristic

of any resilient community (Gunderson and Holling, 2002). Strong social capital can also have a positive influence on healthy behaviors and perceptions that help enhance resilience to weather-related emergencies. Such communities also benefit from an element of togetherness, not as common in neighborhoods suffering from significant differences in age and income (Szreter et al., 2004) or linguistically isolated communities (Nawyn et al., 2012). Yet the effectiveness of social capital is sensitive to context, and in some instances, perceptions of risk may be distorted when misinformation is spread within social and neighborhood networks (Wolf et al., 2010). In some cases, awareness strategies such as “buddy systems” and targeted outreach by neighbors have been shown to be effective substitutes to organized outreach campaigns (Seguin, 2008), but there is little evidence in the heat literature to suggest which components of social capital are universally needed to reduce heat vulnerability, and opportunities for building up social capital are community-specific.

While social capital remains a difficult factor to accurately measure and evaluate across California, there are opportunities for investigations of fine-scale variation in social and environmental neighborhood contexts to temperature-mortality relationships in neighborhoods suffering from poor connectivity to neighbors and social programs. For example, programs such as Meals on Wheels, home weatherization, and various aging and adult services are important mechanisms for identifying particularly vulnerable individuals, communicating heat risks, and planning or prevention opportunities. Such programs offer important starting points for building social capital and connectivity, and ultimately, determining where social programs can have a lasting impact.

6: Conclusion

In an effort to address information and technology gaps identified in our User Needs Assessment,¹² we sought to (1) apply a framework to establish local HHE thresholds, which can also serve as a baseline for climate projections and adaptation planning, (2) map heat-specific social and environmental variables alongside a composite measure of heat vulnerability, and (3) develop an user-friendly tool¹³ that enables users to assess current and future levels of heat vulnerability and explore how heat waves are changing in their local area.

Utilizing a simple statistical framework, we generated 63 unique, health-informed heat thresholds tailored to California’s diverse tapestry of climates and demographics. Our results confirm that heat event definitions that are most closely associated with heat-related morbidity vary across the state, as well as across different populations and times of year, and that more flexible definitions may better represent heat-related health risks in many cases. Using these thresholds as a baseline to identify trends in the frequency and characteristics of future HHEs in each of the 8057 census tracts in California, we found increases in the severity, duration, and shifts in the timing of HHEs throughout the century and under all percentiles and greenhouse gas emission trajectories.

¹² 427mt.com/2017/01/17/california-heat-health-project/

¹³ cal-heat.org

The comparison of relative changes in heat to existing levels of social vulnerability shows that many urban, low-income, and poorly acclimated regions of the state are particularly exposed to health effects from extreme heat. Holding variables such as population growth and demographic changes constant, users can co-locate areas of high relative change and social vulnerability using individual factors or the Heat-Health Action Index. After identifying high risk census tracts, users can also identify which long-term interventions are most suitable given changing conditions in HHEs and existing vulnerabilities. Future research efforts could include population projections and more precise locations for vulnerable subgroups such as homeless and outdoor laborers, which in turn can help better direct climate preparedness and long-term planning efforts.

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APPENDIX A: Heat Wave Zones

To map heat-health event (HHE) definitions to a useful scale, we developed what is referred to as a Heat Wave Zone (HWZ) (Figure 2). Given the low sample size and medical data suppression rules set by OSHPD,¹⁴ it is often not possible to evaluate population sensitivity using medical data at a useful planning scale such as ZIP Code Tabulation Areas (ZCTAs) or census tracts. At even larger scales, such as counties or climate zones, populations and landscapes are often too diverse and dissimilar to be aggregated. Thus, we developed 487 unique HWZs, which consist of several ZCTAs that share common extreme heat characteristics.

HWZs were generated based on the likenesses of severity (temperature), humidity level, and timing of heat waves that have occurred between 1981 and 2010. Extreme heat characteristics were classified using a simple criterion: two consecutive days where the daytime and nighttime maximum temperatures exceeded the historical (1981-2010) 98th percentile. Note that this heat wave definition was not used to define HHEs, but is merely used as a means to spatially aggregate health data otherwise unusable due to data suppression rules.

Temperature and relative humidity data were obtained from PRISM and examined using a 4-km resolution and refitted to ZCTA, which were then grouped based on likeness of extreme characteristics (severity, humidity, and seasonal timing). Each metric was used to classify a heat wave zone, and clustered based on a three-digit tag.

First digit = average max temperature during defined heat wave

- 1 first two quantiles
- 2 last two quantiles

Second digit = weighted average of the month in which heat waves occur

- 1 May through early June
- 2 June through late July and/ or even distribution throughout season
- 3 late July through September

Third digit = average relative humidity during defined heat waves

- 1 first two quantiles
- 2 last two quantiles

¹⁴ Suppression level rules are established by The Office of Statewide Health Planning and Development (OSHPD), which requires each unique record to meet or exceed 12 visits.

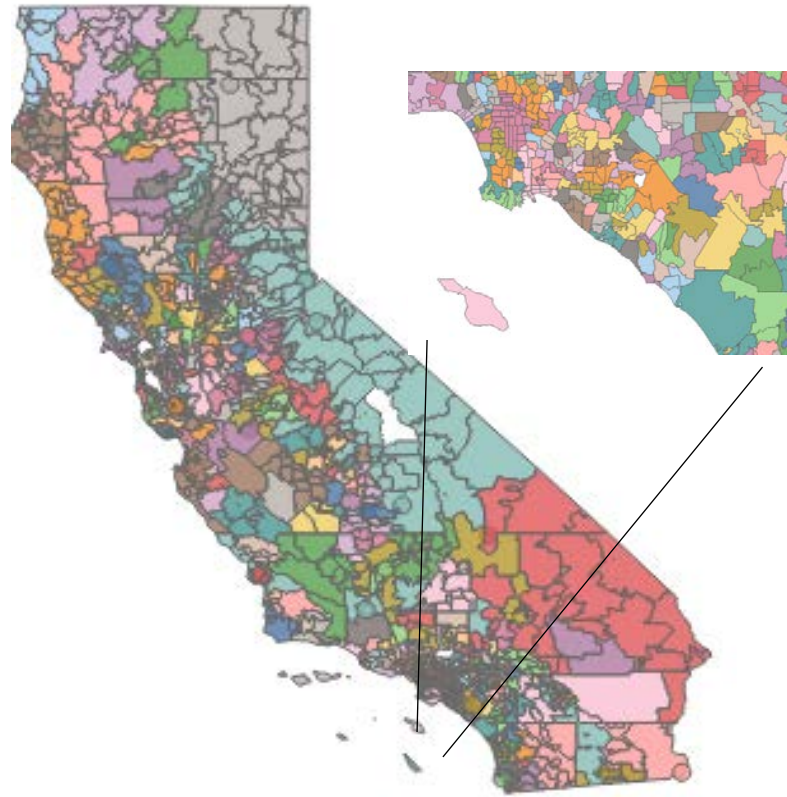


Figure A1: Heat Wave Zones (color) and boundaries represent zip code tabulation areas (ZCTAs). Blank areas represent are of no population. Pop-up shows greater Los Angeles area.

For example, a HWZ with the classification 113 is intended to represent an area that may experience warmer, early, and relatively more humid heat waves as compared to other zones across the state. Quantiles were defined around the median, each quantile contains an equal number ZCTAs, and quantiles for first and third digit are relative to all ZCTAs in California.

Most ZCTAs that shared a heat wave classification also shared a border, and thus, were grouped together to meet suppression level rules. Most often, this suppression rule was met when a ZCTA was equal to or greater than 15,000 inhabitants (Census, 2013-2015). Many ZCTAs were too small in terms of total inhabitants to receive a unique heat wave zone designation and were thereby grouped with nearby, similarly classified ZCTAs within the same county. When grouping ZCTAs which share extreme heat characteristics, consideration was also given to the larger administrative boundaries so that zones did not bisect county boundaries.

However, for an urban ZCTA with tens of thousands of inhabitants, zones were disaggregated based on the distribution of population density across the city, despite sharing a common heat wave classification. For example, ZCTAs within the city of Fresno experience similar heat wave characteristics according to these measures, but two heat waves zones were generated to account for the two large population clusters in northeast and southwest Fresno. In metro areas, the benefit of splitting a single heat wave zone into multiple zones is that each zone, while similar based on extreme heat characteristics, may differ in its racial and age makeup, which may influence response rates.

The mapping of census tracts to HWZ was done using the spatial relationship between census tracts and ZCTAs provided by the United States Census Bureau.¹⁵ In order to assign a census tract to a ZCTA for our purposes (defining HHEs), census tracts were assigned to the ZCTA in which the maximum proportion of their population lives. In other words, a census tract that intersects with multiple ZCTAs was mapped according to which of these ZCTA/ census tract intersections held a plurality of the census tract's population. Once a census tract was assigned to a ZCTA, the mapping between ZCTA and HWZ was used to make this assignment, as HWZs are built upon ZCTAs.

¹⁵ <https://www.census.gov/geo/maps-data/data/relationship.html>

APPENDIX B: Estimating Relative Humidity from PRISM

To generate a daily minimum and maximum measure of relative humidity, vapor pressure deficit minimum and maximum were first calculated as the difference between the actual (measured) vapor pressure of water and the saturation vapor pressure at the current temperature (Eq. 1).

$$(Eq. 1) \quad vpd = es(T) - ea,$$

where vpd is vapor pressure deficit, es is the saturation vapor pressure as a function of Temperature (T), and ea is the actual vapor pressure. Minimum vapor pressure will correspond to the highest values of Relative Humidity. In order to calculate es at a given temperature, the Clausius Clapeyron relationship is used, specifically the following approximation:

$$(Eq. 2) \quad es = 6.1078 * \exp((17.269 * T) / (237.3 + T)),$$

where T is in degrees Celsius. For vpd_{min} , T_{min} was used to calculate es and T_{max} was used for vpd_{max} . Actual vapor pressure (ea) is calculated after determining $es(T_{min})$ and $es(T_{max})$ from Eq. 2, using Eq. 1. In order to aggregate over grid cells within a boundary, we convert ea from vapor pressure to a measure of absolute humidity, or vapor density, derived from the ideal gas equation:

$$(Eq. 3) \quad rho = (0.622 * ea) / RT,$$

where rho is the vapor density in g/m³, R is the universal gas constant, and T is absolute temperature (Kelvin) corresponding to the ea used to calculate rho . Rho is averaged over the grid cells corresponding to the spatial boundaries defined by Heat Wave Zones (HWZ). Subsequently, average temperature (HWZ average T_{min} and T_{max}) over the zone is used to calculate the HWZ's average saturation vapor density using equation 2 and substituting $es(T)$ for ea in equation 3. RH is then calculated at the zone level:

$$(Eq. 4) \quad RH = (rho / rhoS) * 100,$$

where rho is the vapor density, $rhoS$ is the saturation vapor density.

APPENDIX C: Social Vulnerability and Extreme Heat

Our survey included a question focused on understanding if and how respondents use online, interactive tools that are already available to them when identifying vulnerable populations and/or individuals during a heat event. Thirty percent of all respondents reported that they do not currently use any tools to identify vulnerable populations during a heat event with some noting that they were not aware of the example online tools¹⁶ and that they would be interested in learning more about them. Twenty-seven percent of respondents reported using some type of tool to identify vulnerable populations while 29 percent reported that they rely on “internal mapping” (data gathered at the local level and maintained by local agencies) instead of tools. Many respondents and interviewees noted that they appreciated that this internal mapping is tailored to the specific needs of their individual jurisdiction and that they could trust this data is updated regularly. This was especially important to smaller counties who have found that some online tools do not incorporate data specific enough to be relevant for their jurisdiction.

We also asked survey respondents if they do not currently have access to information that would be helpful to better plan for extreme heat events. Forty-one percent of all respondents noted that it would be helpful to have more local information on vulnerable populations. In the open-ended responses, many noted that they do not have adequate information on the locations of outdoor workers or homeless individuals within their jurisdiction. They also noted the difficulty in keeping this type of data up-to-date as well as the fact that they are not confident that they could ensure that all individuals within their jurisdiction who are (or could become) vulnerable to extreme heat impacts could be identified and/or located during a heat event. One respondent noted that having access to this type of information in a tool format (combined with data on heat-related illnesses) following a heat event would enable local Health Departments to combine data to create a local overview of heat-health impacts.

There are opportunities for investigations of fine-scale variation in social and environmental neighborhood contexts to temperature-mortality relationships in cities with distinctly different climates, demographics, and acclimatization. Results can help target resources and identify interventions specific to these contexts. For example, through the CDC-sponsored CalBRACE project (Building Resilience against Climate Effects), the California Public Health Department partnered with ten local health departments to generate Health Profiles with census tract-level data. We have incorporated several indicators from the Health Profiles to help illustrate where health and climate inequities might persist. Building on the concepts, empirical analysis, and social theories presented in the last decade of heat vulnerability literature, indices such as the CalBRACE project are important starting points for determining how vulnerability varies across space and where targeted social interventions are most needed today.

There are also concerns as to whether the most vulnerable groups are being adequately identified and reached through current intervention strategies (Bassil et al., 2010). Some strategies have been found to be particularly effective when targeting the most vulnerable groups (e.g., direct community outreach, automated phone notifications, green urban design) (NCCEH, 2008). Some counties are coordinating with sustainability programs and others to

¹⁶ See full list of tools and other responses in *The California Heat & health: A Decision Support Tool*, published December 12th, 2017 (<http://427mt.com>)

implement actions to reduce the effects of the urban heat island (UHI). Many of these actions also help to reduce GHG emissions (e.g., weatherization, changing building codes to require cool roofs, increasing tree canopy) and illustrate the value of aligning climate and health goals.

Our interviewees noted that agencies often do not have adequate information on the locations of outdoor workers or homeless individuals, which are prevalent subgroups in the Central Valley and Los Angeles area, respectively. While the social vulnerability map does not enable the specific identification of such groups at a local level, these maps may help identify which census tracts deserve more attention.

To address some of these needs and because heat impacts disproportionately affect vulnerable populations, we present a statewide, heat-related social vulnerability index in the tool called the Heat-Health Opportunity Index (HHOI), as well as all of the individual social vulnerability indicators detailed below. This index, developed through a Principal Component Analysis (PCA) evaluating social, demographic, and environmental indicators at the census-tract level, helps identify neighborhoods or areas that are likely to be more susceptible to future HHEs. This index is then overlaid with the projections of HHEs in the online tool, to allow public health professionals and planners to identify areas where interventions are most needed and will be most impactful.

C1 Measuring Social Vulnerability to Extreme Heat

There are numerous factors that influence heat vulnerability (see *Chapter 2.1.1 Vulnerable Groups and Regions in California*). To illustrate the heat-related population, health, and environmental factors across California, we integrated a number of indicators of heat and health vulnerability. We worked with staff from CDPH to integrate climate and health vulnerability indicators identified by the CDC-sponsored CalBRACE project (Building Resilience against Climate Effects) (2016); downloaded health outcome variables collected by California Office of Statewide Health Planning and Development (OSHPD) (2013-2015) which were included in the CalEnviroScreen 3.0 tool (2017); and downloaded urban heat island information from the California Environmental Protection Agency (CalEPA). All CalBRACE indicators were developed using the same methods as the Healthy Communities Data and Indicators Project (HCI) and updated to reflect the latest year of available census data, when possible. Methods for measuring health outcomes and UHI can be found on the CalEnviroScreen 3.0 and (<https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-30>) CalEPA UHI Index (<https://calepa.ca.gov/climate/urban-heat-island-index-for-california/>) websites, respectively.

Table C1: Descriptions and metadata of indicators associated with heat vulnerability. Factors marked with an asterisk (*) were not included in the principal component analysis.

Name	Definition	Relation to Heat	Year(s)	Source
Social Factors				
Hispanic*	Percent of residents that identify as Hispanic	The combination of greater exposure to climate change impacts, increased sensitivity, and reduced adaptive capacity compound the overall susceptibility of race/ethnic minorities to the health impacts of climate change. Nationally, African Americans were 52% more likely, Asians 32% more likely, and Hispanics 21% more likely than Whites to live in areas where impervious surfaces covered more than half the land surface, and more than half the population lacked tree canopy.	2015	American Community Survey, US Census Bureau
Non-White*	Percent of Non-White residents			
Asian*	Percent of residents that identify as Asian			
NHOPI*	Percent of residents that identify as Native Hawaiian or Other Pacific Islanders			
African American*	Percent of residents that identify as African American			
Children*	Percent of population aged 5 years or younger	Due to physiological and developmental factors, children are disproportionately impacted from the effects of heat waves, air pollution, infectious illnesses, and trauma resulting from climate change. Children, infants, and pregnant women are also vulnerable to increased heat exposure because they may not be able to efficiently thermoregulate.	2015	American Community Survey, US Census Bureau

Poverty	Percent of population whose income in the past year was below poverty level	Poverty limits the acquisition of basic material necessities and can impact the ability to live a healthy life by restricting people's access to housing, food, education, jobs, and transportation. Poverty is associated with societal exclusion and higher incidence and prevalence of mental illness and low-income earners are more likely to be uninsured and to have limited access to quality health care, are more likely to suffer from chronic diseases like diabetes and heart disease, acute and chronic stress, and to die prematurely.	2015	American Community Survey, US Census Bureau
Transit Access*	Percent of population not residing within 0.5 mile of bus/ferry/ferry stop with <15 minutes waiting time during peak commute hours	A strong and sustainable transportation system supports safe, reliable, and affordable transportation opportunities for walking, bicycling, and public transit, and helps reduce health inequities by providing more opportunities for access to healthy food, jobs, healthcare, education, and other essential services. Further, the transition from automobile-focused transport to public and active transport offers environmental health benefits, including reductions in air pollution, greenhouse gases and noise pollution, and leads to greater overall safety in transportation.	2012	San Diego Association of Governments, Southern California Association of Governments, the Metropolitan Transportation Commission, Sacramento Council of Governments, U.S. Census Bureau, California Department of Finance

Elderly	Percent of population aged 65 years or older	Pre-existing health conditions (including cardiovascular diseases, respiratory illnesses, and diabetes), the side effects of some medications, and social isolation can increase susceptibility to more severe consequences of climate change for the elderly. Acute renal failure, electrolyte imbalance, and nephritis were the most common heat related morbidities among elderly in the 2006 California heat wave.	2015	American Community Survey, US Census Bureau
Linguistic Isolation	A "limited English speaking household" is one in which no member 14 years old and over (1) speaks only English or (2) speaks a non-English language and speaks English "very well." In other words, all members 14 years old and over have at least some difficulty with English	Linguistic isolation may hinder protective behaviors during extreme weather and disasters by limiting access to or understanding of health warnings. Additionally, natural disasters and extreme weather can lead to disruptions to management of chronic conditions for people who are socially or linguistically isolated. Linguistic isolation is prevalent among new immigrants from non-English speaking countries and older first-generation immigrants who revert to their first languages later in life due to aging.	2015	American Community Survey, US Census Bureau

Education	Percent over the age of 25 without a HS diploma or GED	Through three inter-related pathways, education influences health: health knowledge and behaviors, employment and income, and social and psychological factors. Completion of formal education (e.g., high school) is a key pathway to employment and access to healthier and higher paying jobs that can provide food, housing, transportation, health insurance, and other necessities for a healthy life. Education is linked with social and psychological factors, including sense of control, social standing, and social support.	2015	American Community Survey, US Census Bureau
Outdoor Workers	Percent of people employed and aged > 16 years working outdoor	Outdoor occupations most at risk of heat stroke include construction, refining, surface mining, hazardous waste site activities, agriculture, forestry, and fishing. A review of miners, construction workers, farm laborers, first responders, and military personnel emphasized that heat-related illness may be the most common cause of nonfatal environmental emergency department admission in the United States and between 1992-2006, 68 farm workers died from heat stroke, representing a heat stroke rate nearly 20 times greater than all civilian workers in the country.	2010	American Community Survey, US Census Bureau
Vehicle Access	Percent of occupied households with no vehicle ownership	Vehicle ownership is a measure of mobility and access to transportation. Transportation is a critical resource for survival, because it improves access to evacuation and shelter from environmental exposures, such as wildfire, air pollution, heat waves, and flooding, allowing people to move to cooler or other safe areas.	2010	American Community Survey, US Census Bureau
Health Factors				

Ambulatory Disability	Percent of population having serious difficulty walking or climbing stairs	Persons with physical disabilities face disadvantages with limited resources and mobility during the phases of evacuation, response, and recovery. Improved preparation is required to ensure preventable health impacts on those with physical disabilities due to climate change. A retrospective study among elderly population in Italy found that the following were significant risk factors for heat-related death: living in a nursing home or requiring assistance, cognitively impaired, taking a large number of drugs, and having a higher degree of disability (Foroni et al, 2007).	2015	American Community Survey, US Census Bureau
Cognitive Disability	Percent of population having physical, mental, or emotional problem, difficulty remembering, concentrating, or making decisions	Climate change may affect people with mental health disabilities directly through exposure to trauma or by affecting their physical health. Persons with severe mental illness, such as schizophrenia, are at higher risk because their medications may interfere with self-regulation of body temperature. Increasing heat exposure can also worsen the clinical condition of people with pre-existing chronic diseases and mental health problems.	2015	American Community Survey, US Census Bureau
Asthma	Asthma emergency department visits per 10,000 people	Asthma symptoms can worsen during periods of extreme heat, which subsequently degrade air quality conditions, especially ozone levels.	2013	California Office of Statewide Health Planning and Development
Cardiovascular	Heart attacks per 1,000	Nearly 46 percent of all victims from the 2006 California heat wave suffered from a pre-existing cardiovascular disease (Trent 2007). Short-term exposure to outdoor air pollution following a heart attack has also shown to increase the risk of death.	2013	California Office of Statewide Health Planning and Development

Low Birth Weight	Percent of low weight births	Babies who weigh less than about five and a half pounds (2500 grams) at birth are considered. A growing body of literature has documented positive associations between increased apparent temperatures and adverse birth outcomes (Strand 2011; Beltran 2014; Chodick 2009).	2012	California Office of Statewide Health Planning and Development
Environmental Factors				
Impervious Surfaces	Percent of area covered by impervious surfaces such as concrete or buildings (population weighted)	Impervious surfaces retain heat and limit absorption of water into the ground, which can lead to the urban heat island effect, a phenomenon in which urban areas are warmer than the surrounding non-urban areas. Communities of color are disproportionately represented in densely populated areas with more impervious surfaces, which increases their risk of exposure to heat stress. Studies in cities, including Montreal, Barcelona, Hong Kong, and Taiwan, and in the United States found associations between heat-related health effects and impervious surfaces.	2011	Multi-Resolution Land Characteristics Consortium, National Land Cover Database (NLCD)
Change in Development	Percent increase in developed area between 2001 and 2050 under a worst-case scenario	Urbanization and the conversion of non-developed area to developed, impervious surfaces increase the total area where the urban heat island effect can occur, and subsequently, heat stress exposure.	2017	The Land Use and Carbon Scenario Simulator (LUCAS)

Ozone Exceedance	Three-year ozone concentration exceedance above state standard	Higher temperatures increase ground-level ozone and other secondary air pollutants created from chemical reactions with pollutants directly emitted from power plants, motor vehicles, and other sources, creating smog and air pollution. With projected increasing temperatures, demand for electric power generation will increase and may contribute further to poor air quality. Laboratory studies in which human subjects were exposed to measured concentrations of ozone for brief periods demonstrate that ozone can reduce lung function, increase respiratory symptoms, increase airway hyper-reactivity, and increase airway inflammation.	2011	Air Monitoring Network, California Air Resources Board
PM Concentration	Annual mean ambient concentration of PM2.5	Particulate matter (PM) is one of two indicators of air pollution, ozone being the other, that is linked to short- and long-term adverse health effects. PM2.5 is small enough to enter deep into the lungs and is associated with a host of illnesses, including lung cancer, heart disease, respiratory disease, and acute respiratory infections. The health impacts of air pollution are likely to be exacerbated by climate change, because degradation of air quality will compound the health hazards posed by warmer temperatures.	2011	Air Monitoring Network, California Air Resources Board
Tree Canopy	Percent of area not covered by tree canopy	Urban greening, such as parks and trees, may have a local cooling effect through shade and evapotranspiration: a systematic review of evidence linking urban greening and the air temperature of urban areas has shown that green sites are generally cooler than non-green sites. Evidence links tree canopy coverage to positive health outcomes from reduced exposure to ultraviolet radiation, reduced urban heat island effects, and mitigation of air pollution.	2011	Multi-Resolution Land Characteristics Consortium, National Land Cover Database

The Urban Heat Island*	Temperature difference from nearby rural areas	Urban heat island effects are a result of buildings and pavement absorbing heat during the day and then radiating that heat at night, which limits nighttime cooling and amplifies daytime high temperatures. UHI can have substantial implications for public health, since, in addition to high generating excess heat, air quality deteriorates in these areas as cooling energy demand increases, emissions of pollutants increase, and ozone formation accelerates.	2015	California Environmental Protection Agency
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Several studies have attempted to measure cumulative vulnerability through a single indicator derived from several socioeconomic, demographic, and physical measures (Vescovi et al., 2005, Reid et al., 2009; Cutter et al., 2010). Several respondents from both our user needs assessment and beta user interviews pointed out the need for a heat-specific index. Our aim for developing this single composite indicator was to help synthesize the multitude of heat-related vulnerability indicators statewide and at the census tract, enabling a clearer picture of overall vulnerability for communication purposes. Condensing individual variables into a single composite variable also enables quick, albeit not comprehensive, understanding of vulnerability while reducing correlation within a larger dataset and maintaining the uniqueness of the original variables.

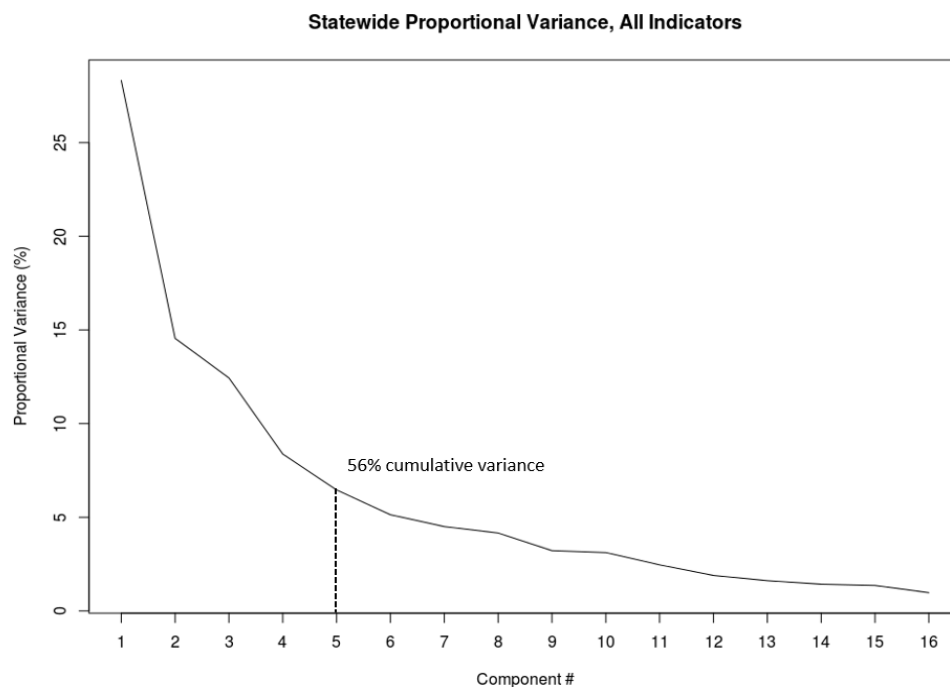


Figure C1: Scree plot of variance explained by each additional PCA component

We subsequently run a PCA and varimax rotation to reduce the dimensionality arising from correlation (Figure C2) between some of the remaining sixteen variables. Original measure values are standardized to a 0-1 scale through a min-max method for comparability purposes. A varimax rotation is then used to improve the interpretation of the original variables. We retain five factors based on the percentage of variance explained (56%) and used a standard loadings cutoff of 0.3 based on similar analysis by Reid et al., (2008) (Table C2). The cumulative level of variance explained by the five retained factors level is relatively low for PCA. The reason we select this cutoff of 56%, which is generally a subjective decision in factor analysis (Cangelosi et al., 2007), is to ensure each factor retains at least three variables, which is often considered the absolute fewest number of variables for any one factor (Spector, 1992; Lawley 1940).

Indicators are then calculated for each of the five factors and applied as loadings to census tracts, and finally converted into 0-100 range using a min-max method (Cutter et al., 2010), with low scores indicating lower risk and 100 representing the most vulnerable census tract. In the final tool, the composite indicator appears as the default map while individual variables can be explored further upon user selection.

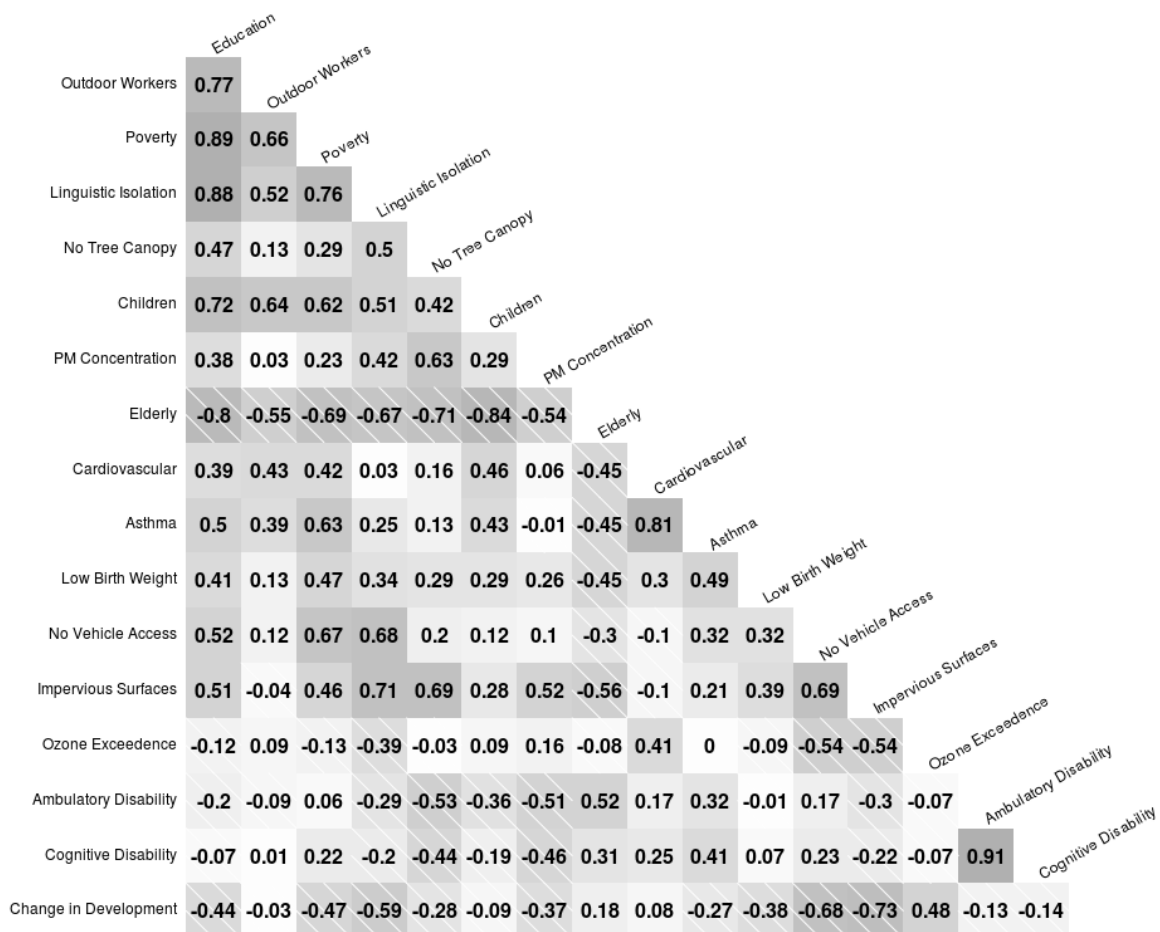


Figure C2: Spearman rank correlation for eighteen indicators across all census tracts (n= 8,046)

C2 Results of Principle Component Analysis

Several factors influence the heat-morbidity relationship, few of which can be expressed as broadly as social vulnerability. We assessed social vulnerability to heat considering income, race, education, occupation, health, social isolation, and environmental attributes such as tree canopy and air quality. Built environment and sociotechnical systems also play a significant role in heat vulnerability (Pincetl, Chester, and Eisenman, 2016), but due to lack of consistent, high resolution data, these indicators were excluded from our analysis. We considered indicators both independently and together since many of the factors are highly correlated (Figure C2). When considered together, we applied the vari-max rotated loadings (Table C2) to generate scores for each census tract (Figure C3) as a method to develop a single generic indicator.

Table C2: Factor loadings for the remaining 16 variables for all census tracts. Only loadings above 0.3 or below -0.3 considered.

	Factor 1- Socio-economic	Factor 2-Poor Health	Factor 3- Disability	Factor 4- Environment	Factor 5-Other
No Tree Canopy				0.70	
No Vehicle Access	0.39		0.35		0.57
Impervious Surfaces				0.43	0.77
Children	0.47	0.51			
Elderly	-0.34	-0.49	0.53		
No High School Diploma	0.84				
Outdoor Workers	0.79				
Poverty	0.71	0.31			
Ambulatory Disability			0.90		
Cognitive Disability			0.77		
Linguistic Isolation	0.75				0.38
Ozone Exceedence				0.50	-0.64
PM2.5 Concentration				0.81	
Cardiovascular Disease		0.77			
Asthma		0.80	0.31		
Change in Development					-0.65

Normalized indicators were scaled to a range of 0 to 100, with 0 representing the lowest (or best score) for a specific indicator and 100 corresponding to the highest (or worst score). The scores in the HHAI, summed across all five factors (Figure 12), ranged from 0 (several locations including Grenada Hills, Los Angeles County) to 100 (Stockton, San Joaquin County) with a

median of 35.6 (San Jose, Santa Clara County), a mean of 37.3, and a standard deviation of 15.5. Of the State's ten most populous census tracts, Victorville (San Bernardino) and Goshen (Tulare County) are among the most socially vulnerable when using the variables included in this analysis.



Figure C3: Heat-Health Action Index score by census tract (n=8,046), weighted according to the five retained varimax-rotated indicators: socioeconomic, poor health, environment, disability, and other. In more detail, Map A illustrates the Bay Area and Map B shows greater Los Angeles area.

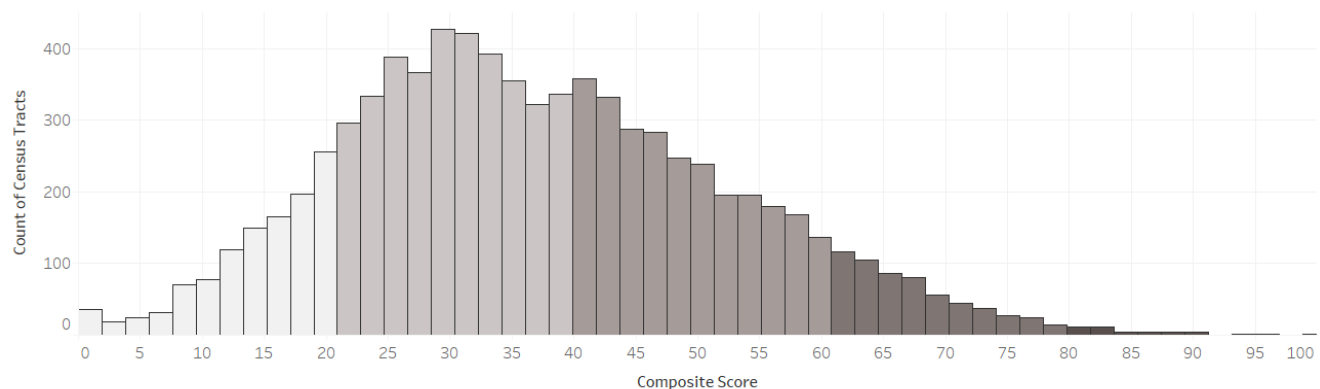


Figure C4: Distribution of composite Heat-Health Action Index scores by census tract (n=8,046)

We also compared our results of future HHEs to current Heat-Health Action Index scores and filtered for the census tracts that fell within the top 3rd for three indicators (1) social vulnerability, as estimated through the HHAI score; (2) relative change in Tmax and Tmin and (3); relative change in frequency of HHEs by mid-century in a business-as-usual scenario. The results indicate a strong association to low-income, non-white areas in the San Francisco Bay Area (East Oakland, Vallejo, East Palo Alto), Los Angeles (Compton), and Central Valley (Palmdale and Sanger).

We also found that many social vulnerability factors are predictors of heat-related health impacts in some regions, but results are location-specific, and we encourage users to explore their area by intersecting the relevant climate and social variables. While the use of social vulnerability in this study does not allow for a single summary estimate of future heat vulnerability, the comparison of relative changes in heat to existing levels of social vulnerability can help shed light on the anticipated heat-related risks under a hypothetical scenario, holding variables such as population growth and demographic changes constant. This blended evaluation strategy may help planners and policymaker co-locate areas of high relative change and heat vulnerability.

C3 Limitations in the Development of the Heat-Health Action Index

It is important to note that not all indicators, including the Heat-Health Action Index scores, are predictive of actual heat-related risks. Also, trends in ageing, gentrification, and impervious surfaces are rapidly occurring throughout California, and these estimates are largely reflective of conditions between 2011 and 2015. Efforts will be made to update the tool as new data becomes available.

Transit access and the UHI indicator were not included in the PCA due to relatively low geographic coverage with values for larger cities only. Racial groups were also excluded from the PCA to ensure users would not violate Proposition 209, which stipulates grants cannot be awarded on the basis of race.

PCA also has its limitations. Many nonlinear relationships may not be well represented, and correlations between variables are largely preserved orthogonally. Also, when interpreting results from the initial PCA, the qualitative descriptors are somewhat subjective based on our interpretation of the clustering of measures.