# *Future heat vulnerability in California, Part II: projecting future heat-related mortality*

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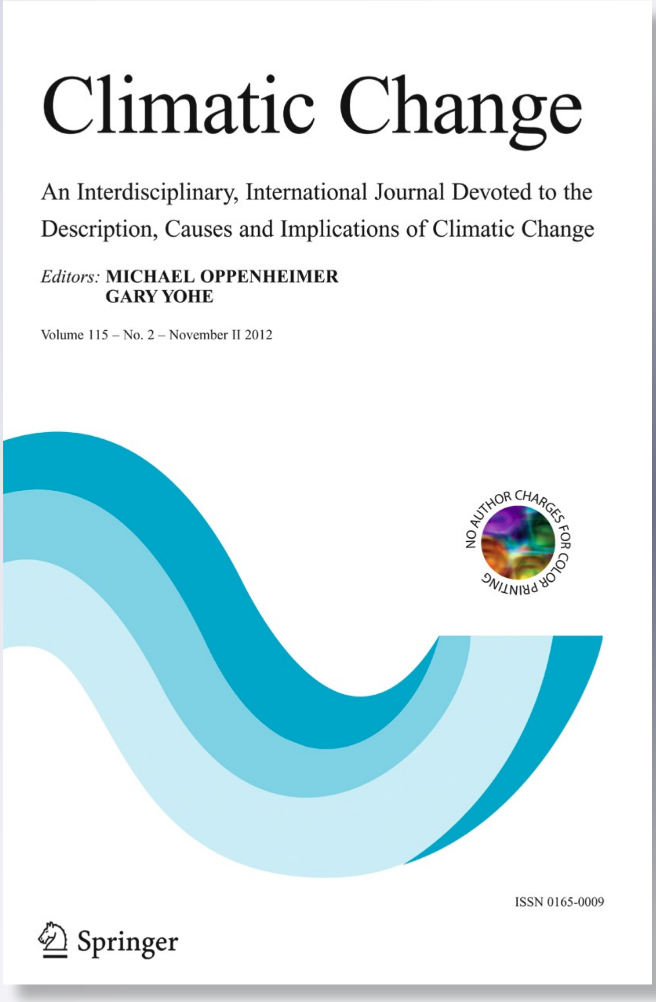

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# Future heat vulnerability in California, Part II: projecting future heat-related mortality

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**Abstract** Through the 21st century, a significant increase in heat events is likely across California (USA). Beyond any climate change, the state will become more vulnerable through demographic changes resulting in a rapidly aging population. To assess these impacts, future heat-related mortality estimates are derived for nine metropolitan areas in the state for the remainder of the century. Heat-related mortality is first assessed by initially determining historical weather-type mortality relationships for each metropolitan area. These are then projected into the future based on predicted weather types created in Part I. Estimates account for several levels of uncertainty: for each metropolitan area, mortality values are produced for five different climate model-scenarios, three different population projections (along with a constant-population model), and with and without partial acclimatization. Major urban centers could have a greater than tenfold increase in short-term increases in heat-related mortality in the over 65 age group by the 2090s.

## 1 Introduction

Heat is generally recognized as the deadliest atmospheric hazard in the developed world (e.g., CDC 2004). The human impacts of heat exposure have been widely studied and summarized in the literature (e.g., Kovats and Hajat 2008; Basu 2009). Significant research has also evaluated which subsets of the population are most vulnerable to the heat (e.g., Bouchama et al. 2007), identifying physical factors (e.g., age, inability to leave home, cardiovascular problems) social factors (e.g., socioeconomic status, level of social interaction), and behaviors (e.g., use of fans or air conditioning) as risk factors that influence vulnerability. Though some research has suggested an overall decrease in heat vulnerability in recent decades in developed nations (e.g., Davis et al. 2002; Carson et al. 2006), especially as air-conditioning has become more commonplace (e.g., O'Neill 2003), there is still a clear vulnerability to heat (Sheridan et al.

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2009). Air conditioning is still unaffordable to many people, potentially augmenting the socioeconomic disparity in vulnerability (e.g., McGregor et al. 2006), and the usage of air conditioning may enhance the urban heat island, increasing the overall heat burden. Some research suggests that the decline in heat-related mortality is found in moderate heat events but not the most extreme events (Muthers et al. 2010). Further, dramatic mortality episodes have occurred in recent years, including the Midwestern US in 1995 (Semenza et al. 1999), western Europe in 2003 (Valleron and Boumendil 2004), and Russia in 2010 (Barriopedro et al. 2011).

Research specific to the state of California (USA), however, has been more limited. A heat-health relationship broadly in line with other middle-latitude locations has been identified (e.g. Basu et al. 2008; Anderson and Bell 2009; Sheridan et al. 2009). The recent heat event of July 2006 across the state was relatively uncommon in affecting nearly the entire state, as well as having record maximum and minimum temperatures simultaneously (Gershunov et al. 2009). Two recent papers have analyzed the impacts of the 2006 event. Ostro et al. (2009) evaluated the total increase in mortality during this event, and suggested that the 'official' heat toll of 147 deaths is an underestimate by a factor of 1.5–3. Moreover, their research suggested that the temperature-mortality relationship was more acute in the 2006 event than overall, suggesting that there is an added 'heat wave effect', that is, that the relationship between heat and mortality is non-linear, so that the population responds more significantly to a longer sequence of oppressive weather (Anderson and Bell 2010). Knowlton et al. (2009) examined hospitalizations and emergency room visits during the 2006 event, and discovered significant increases statewide; interestingly, the largest relative increases were found in the Central Coast region, which had lower absolute temperatures than most other regions, suggesting that acclimatization to local climate is significant.

There have been a number of studies that have examined the projected frequency and intensity of future heat events (see Part I for relevant review). In the future, non-climatic factors such as demographic change will also significantly affect collective human vulnerability to future heat events (Luber and McGeehin 2008). Simply, the population of much of the developed world, including California, is collectively aging at an unprecedented rate. Though the US population as a whole is projected by the Census Bureau (Census 2010) to increase by around 41 % from 2010 to 2050, the population of those 65 and older is expected to more than double from 40 million to over 88 million (and comprise 20 % of the US population); those over 85 are expected to triple to more than 19 million. As the elderly are most susceptible to the heat, these changes strongly point to a future population that is collectively much more heat vulnerable than at present.

Aside from model projections themselves, there are two further sources of uncertainty with regard to future heat-related mortality estimates: mortality displacement (or harvesting) and acclimatization (or adaptation). Mortality displacement refers to the fact that short-term mortality increases during a heat event have been observed to be offset somewhat by short-term mortality decreases following the event (e.g., Hajat et al. 2005). Thus, a percentage of apparent heat-related deaths are deaths that would have occurred soon afterwards anyway. This effect has been estimated from near zero (meaning that no displacement occurs) to near total (meaning that all the mortality increase is compensated by an equal decrease), depending upon location or heat event magnitude and strength (e.g., Hajat et al. 2005; Kyselý and Kim 2009).

Adaptation is another uncertainty. Just as heat-mortality relationships in the present day are place-specific due to the local population acclimatization, it is expected that the population in a future, warmer world could at least partially acclimatize to a changed climate (Kinney et al. 2008). Acclimatization can occur through physiological adaptation; as heat-related deaths are more common in areas in which excessive heat is rare (Kinney et al. 2008), and threshold temperatures—the point above which mortality is observed to rise—vary with a location's climate (e.g., Curriero et al. 2002). Thus, a population with a slowly warming background climate may at least partially acclimatize. Further, people may adapt through behavioral mechanisms, such as relying more significantly on air conditioning (e.g., O'Neill 2003), by changes to an urban structure to reduce the heat burden, or simply by changing the structure of their activities. While these are all different mechanisms with different time frames of implementation, one difficulty in examining their efficacy is that it is difficult even to utilize the historical record of the heat-health relationship to distinguish among these effects, and thus even more difficult to quantify moving forward (Gosling et al. 2009a; Kinney et al. 2008).

Relatively few works have tried to estimate heat-related mortality in the future, although the number of studies has increased significantly over the last decade. Many have attempted general assessments to evaluate the offset between heat-related mortality increases and cold-related mortality decreases, with conflicting results (e.g., Donaldson et al. 2001; Nicholls 2009; Doyon et al. 2008) suggesting the offset may be place-specific or that the methodology used plays a critical role. Gosling et al. (2009b) also tested model performance in their estimates of heat-related mortality for six cities in the US and Europe. The results varied widely, and suggested strongly that model bias, if unaccounted for, can lead to a significant miscalculation in mortality estimates.

Among the research that has specifically focused on quantifying mortality from heat impacts, Knowlton et al. (2007) showed a significant increase in heat-related mortality across the greater New York metropolitan area, ranging from 47 % to 95 % through the 2050s depending on scenario used. Analog-city acclimatization (discussed further below) reduced heat mortality in the future by 25 %. Their work also analyzed the area on the county level, and showed much greater increases in the urban areas than the rural periphery. Dessai (2003) in a similar time frame showed heat-related mortality in Lisbon increasing from 5.4 to 6 deaths/100,000 in the historical record to 7.3 to 35.6, with the large range in uncertainty due to model choice. Hayhoe et al. (2004) showed an increase in annual heat-related mortality in Los Angeles from 165/year to 394 to 1429/year by 2070–2099; this increase in mortality was reduced by 20 % if acclimatization was included. Hayhoe et al. (2010) projected annual heat-related mortality rates were expected to increase by a factor of 3.5 to 9 over present day levels by the 2090s in Chicago. One study, which utilized the 2003 European heat wave as an analog for climate change in major U.S. cities, showed that such conditions would increase heat-related mortality by up to five times typical summer mortality rates (Kalkstein et al. 2008). Few studies have accounted for population changes, though Voorhees et al. (2011) utilize a modeling study that covers the continental US, and incorporates population increases, and project that by 2048–2052 heat-related non-accidental mortality could range from 21,000–27,000 per year.

In Part I, future weather-type frequency was projected for six weather stations across the state of California. Here in Part II, future heat-related mortality is projected for nine regions across the state for the remainder of the 21st century (Fig. 1). These regions in the 2000 census included 26,791,319 Californians, nearly 80 % of the state total population (Table 1). This research is explicitly designed to build upon existing literature by emphasizing the many facets of uncertainty involved in projecting the future—emissions scenario, GCM, demographic changes, and potential acclimatization—that make predicting future vulnerability especially difficult.

## 2 Materials and methods

### 2.1 Population and mortality data

Historical population data for the state of California have been obtained from the Census (2010) on a county level for the years 1970, 1980, 1990, and 2000. Data are stratified by age groups, sex, and race.

**Fig. 1** The nine regions used in this study. The numbers refer to the SSC stations utilized for projected weather conditions, and are listed in Table 1

Population projections developed by Sanstad et al. (2009a, b) are used in this research. Population values are available on a county level for five-year intervals from 2000 to 2100, and were stratified by age (in bins of 5 years), race, and sex. Three sets of these population projections were used in this research, termed the *low-growth*, *medium-growth*, and *high-growth projections*, based on different projections of fertility rates, mortality rates, interstate migration and international migration. The projections vary widely in later years, with the California state population ranging from 47.8 million people in 2100 in the low-growth projection to 147.7 million in the high-growth projection.

**Table 1** The nine regions utilized in this research, and the corresponding SSC station (number in parentheses refers to label in Fig. 1)

| Region | SSC station | Counties | Population (2000) |
|---|---|---|---|
| Fresno | Fresno (3) | Fresno, Madera | 922,516 |
| Los Angeles | El Toro (5) | Los Angeles | 9,519,338 |
| Oakland | Mountain View (2) | Alameda, Contra Costa | 2,392,557 |
| Orange County | El Toro (5) | Orange | 2,846,289 |
| Riverside | Riverside (4) | Riverside, San Bernardino | 3,254,821 |
| Sacramento | Sacramento (1) | El Dorado, Placer, Sacramento | 1,628,197 |
| San Diego | San Diego (6) | San Diego | 2,813,833 |
| San Francisco | Mountain View (2) | Marin, San Francisco, San Mateo | 1,731,183 |
| San Jose | Mountain View (2) | Santa Clara | 1,682,585 |

For use in this research, population values for both the historical and future periods were calculated for each of the nine regions in Table 1 for three age groups: under 65, 65 to 74, and over 74. As population baselines were needed on an annual basis, annual values were derived by linear interpolation between the years provided.

Historical mortality data covering the period 1975 to 2004 were acquired from the National Center for Health Statistics. Mortality data for each death in California are available with information on county, date, age, sex, race, and cause of death. For each of the nine regions, mortality totals by day in the historical period were summed for each of the three age groups.

## 2.2 Methods

### *2.2.1 Mortality data standardization and determination of heat-mortality relationships*

The daily mortality totals for each of the nine regions for each of the three age categories were first standardized to account for demographic changes over the 1975–2004 baseline period. Rates were calculated in terms of deaths per 100,000 for each of the categories. From these rates, anomalous mortality rates were calculated, through procedures (e.g., Sheridan and Kalkstein 2004) that account for both the season cycle (through an 11-day running mean mortality rate over the period of analysis) and long-term trends (through a 3-year running mean mortality rate). Alternate season-cycle averaging periods were tested in previous research (Sheridan and Kalkstein 2010) with negligible difference in results. From this standardization, mean anomalous mortality rates from baseline ('expected') mortality are available for each day, each region, and each age group.

To develop the historical relationship between human mortality and weather, potential independent variables were developed to estimate anomalous mortality (dependent variable). These independent variables fall into three categories: weather-type related, seasonality related, and temperature related.

In Part I, we described the Spatial Synoptic Classification (SSC; Sheridan 2002) that forms the basis for our future projections. The SSC is a classification system that categorizes a given day at an individual location into one of several previously defined weather types, based on surface temperature, dew point, atmospheric pressure, wind speed and direction, and cloud cover. Of all the weather types, previous research has shown that the two tropical types, Dry Tropical (DT) and Moist Tropical (MT), are associated with the most significant increase in mortality (Sheridan and Kalkstein 2004). As these synoptic weather types have delineated heat vulnerability previously, they formed the basis of regression equations that were derived for each region/age group. Hereafter, the DT and MT weather types are collectively referred to as "oppressive" weather types; these are considered synonymous to excessive heat exposure, though thermal conditions vary on these days spatially and temporally. The SSC station used for each region, chosen based on the nearest available station to the population centroid, is listed in Table 1. As possible independent variables in the regression equations, four variables were derived from the SSC weather-type information, including:

- A *Day in Sequence* (DIS) variable, which counts the number of consecutive days in which DT or MT occurs. Research has shown an added 'heat wave effect' in human vulnerability to hot weather (e.g., Anderson and Bell 2009; Ostro et al. 2009; Kalkstein et al. 2010).
- Along the same line, a *binary lag DIS* variable was set to 1 if the prior day was DT or MT.
- Two individual binary variables for DT and MT, set to 1 if the weather type occurred on the given day.

As there is significant seasonal variability in the heat-health relationship (e.g. Sheridan and Kalkstein 2010), due to acclimatization and/or changes in the size of the pool of susceptible people, two variables were created to account for the season cycle: a *Julian day* (JD) variable, and a season cycle (SC) variable, defined as the sine of the season cycle as reflected in the SSC—a value of 1 (−1) for the warmest (coldest) weather-type day of the year at a given station.

As there is within-weather type variability in atmospheric conditions, two continuous variables—the historical 850mb temperatures (from NCEP-NCAR reanalysis) at two grid points (36°N, 123°W and 36°N, 118°W)—were included as potential variables. In Part I, gridded data at 5° resolution on a domain of 26°N to 46°N latitude and 108°W to 128°W were used to assess synoptic patterns. Temperature at 850mb can serve as a good indicator of surface thermal conditions, and in using these data there is no need to downscale GCM data to points associated with the SSC stations. These two grid points in particular were selected as they are centrally located over the region, and initial regression analyses showed these to be best correlated with mortality.

Once all potential independent variables were calculated, multiple linear regression equations were determined based on a stepwise entry method. Non-linear effects were considered but were not statistically significant. A separate regression equation was produced for each age category for each region. The final output model's coefficients were utilized for the regression equation to predict future mortality.

Throughout this research, a 9-month warm season (March to November) is the basis for analysis. The reasons behind this decision are discussed in further detail in Part I. Briefly, previous research (e.g., Sheridan and Kalkstein 2010) suggests a relatively broad season during which heat-related mortality can occur; California's unique climate includes incidence of excessive heat events outside of 'meteorological summer', such as Santa Ana winds (Raphael 2003); and given climate change is analyzed, there is likely to be a shifting seasonality of synoptic patterns into the future (e.g., Lee 2011).

### *2.2.2 Projecting future heat-related mortality*

The calculation of projected atmospheric weather-type classifications is discussed in Part I. In this research, three of the six IPCC (2007) scenarios (from the Special Reports on Emissions Scenarios; SRES) are used: A1FI ("higher emissions"), A2 ("mid-high emissions"), and B1 ("lower emissions"). A total of five model-scenarios are individually assessed: three scenarios from the Community Climate System Model 3 (CCSM3; Collins et al. 2006), the A1FI, A2, and B1; and two scenarios from the Coupled Global Climate Model, or the CGCM3 (Environment Canada 2009a, b), the A2 and B1. CCSM3 projections spanned all years of the 21st century, whereas only 2045–2064 and 2081–2100 were available for CGCM3. For baseline projections of future heat-related mortality, the regression equations derived above were utilized with projected SSC weather type data for each of the five model-scenarios to derive rates of heat-related mortality. These rates were then converted to projected mortality by multiplying by the population projections. Heat-related mortality was then summed for each year for each of the nine regions for each of the five GCM-scenarios.

#### *2.2.3 Estimating heat-related mortality that accounts for acclimatization*

There is considerable uncertainty about the variability of the heat-health relationship if climate variability changes (Kinney et al. 2008), as well as the uncertainties in the modeling of adaptive mechanisms such as air conditioning, which is likely to eventually reach saturation while perhaps relying on a tenuous electricity grid (O'Neill 2003). There are further inherent uncertainties such as the fact that trends in the heat-health relationship are not linear (e.g., Sheridan et al. 2009; Davis et al. 2002).

Several different approaches have been taken previously to model adaptation. An *analog city* method assumes that if a city's climate changes in the future to that of a warmer city, then its heat-mortality relationship in the future will be similar to the warmer city's (e.g. Knowlton et al. 2007). An *analog summer* method assumes that a population within a given city responds less strongly to weather conditions in hot summers than in relatively cool summers, and thus future mortality estimates can be based on the historical relationship only during the hottest summers, as those would be most similar to future summers (similar to Kalkstein et al. 2008). Last, there are fixed-value methods, in which the heat-mortality relationship is adjusted by a fixed value, e.g. 2 °C, representing a certain amount of acclimatization (e.g., Gosling et al. 2009b). To date these methods, while producing broadly similar results, cannot readily be verified as being appropriate. None of these methods is appropriate for the present study, given California's unique climate, and the use of a methodology that does not directly utilize surface temperatures.

With the added 'heat wave effect' and short-term mortality displacement, in this research, we considered acclimatization and short-term displacement by adjusting the day-in-sequence. Specifically, we defined acclimatization as neglecting all heat-related mortality that occurs in the first 3 days of a given string of oppressive weather type days. We believe that this method captures a measure of the potential for adaptation to short-term heat events, where physiological and behavioral adaptations may be more significant, yet still evaluates the impact of longer-term heat events, where physiological and behavioral adaptation may be less valuable, and thus, the mortality response is more significant.

## 3 Results

### 3.1 Historical weather type – mortality relationships

Relationships between the oppressive weather types and mortality for the nine regions indicate that there are clear-cut associations (Table 2). The results for the under-65 age group were weak and inconsistent, with several cities showing no statistical association at all. As a result, the study only evaluates the 65–74 and over 74 age groups. For the 65–74 age groups, generally the strongest response is only observed when the DT weather type

**Table 2** Regression terms defining the relationship between mortality in each MSA and the SSC weather type at the corresponding SSC station. DT and MT refer to dummy variables related to the incidence of a Dry Tropical or Moist Tropical weather type, respectively; 36N123W and 26N118W are 850mb temperature values for the grid point at that specific latitude and longitude; SSC curve refers to the annual cyclical curve used in weather type calculation (1 = warmest day of the year, -1 = coldest day); DIS is day in sequence of a DT or MT weather type, and JD is Julian Day of year. Only statistically significant variables were included in each regression equation; where a column is blank no statistically significant results were observed. ** represents models significant at α=.01; * represents models significant at α=.05

| Region | Constant | DT | MT | 36N, 123W | 26N, 118W | SSC Curve | DIS | JD |
|---|---|---|---|---|---|---|---|---|
| | 65–74 Age Group | | | | | | | |
| Fresno* | 0.038 | | | | | | | |
| Los Angeles** | −1.456 | 0.186 | | 0.005 | | | | |
| Oakland* | 0.088 | | | | | | | |
| Orange County** | −0.012 | 0.387 | | | | | | |
| Riverside* | 0.051 | | | | | | | |
| Sacramento* | 0.131 | | | | | | | |
| San Diego** | 0.024 | 0.179 | | | | | | |
| San Francisco** | 0.010 | 0.293 | | | | | | |
| San Jose* | 0.047 | | | | | | | |
| | Over 74 Age Group | | | | | | | |
| Fresno** | −0.071 | 0.570 | | | | | | |
| Los Angeles* | −12.480 | 0.841 | 0.740 | 0.044 | | −0.290 | | |
| Oakland** | −12.871 | 1.203 | 1.302 | 0.045 | | −0.374 | −0.148 | |
| Orange** | −0.065 | 0.583 | 1.114 | | | | | |
| Riverside** | −0.186 | 0.556 | 0.927 | | | | | |
| Sacramento** | 0.299 | 0.750 | | | | | | −0.002 |
| San Diego** | 0.069 | | 0.971 | | | | 0.123 | |
| San Francisco** | 0.362 | 1.266 | | | | | | −0.002 |
| San Jose** | −10.417 | 0.942 | | 0.143 | −0.103 | | | −0.004 |

occurred along several coastal cities; otherwise, mortality increases are relatively slight. A more complex and significant relationship is observed in the over 74 age group.

### 3.2 Future heat-related mortality estimates (without acclimatization)

Figure 2 presents a range of mortality estimates (assuming no acclimatization) for the five-different model-scenarios, using both the medium-growth population projection as well as a constant-population projection (in which population and demographics remain at their 2000 levels), to help separate between climate- and demographic-related changes in heat-related mortality. Across the regions as a whole, under the constant-population projection, heat-related mortality is projected to increase by a factor of 2 (B1) to 4 (A1FI), to between 1075 and 2056 deaths per year by the 2090s. As with the weather-type results in Part I, a significant divergence appears between B1 and the other scenarios from the 2050s onward. Over the latter part of the 21st century, annual heat-related mortality does not change in the constant-population scenario for B1, while it accelerates for A1FI and A2. Using the medium-growth population projection, heat-related mortality increases far more substantially, 9- to more than 17-fold depending upon scenario, to an estimate of 4684 to 8757 deaths per year.

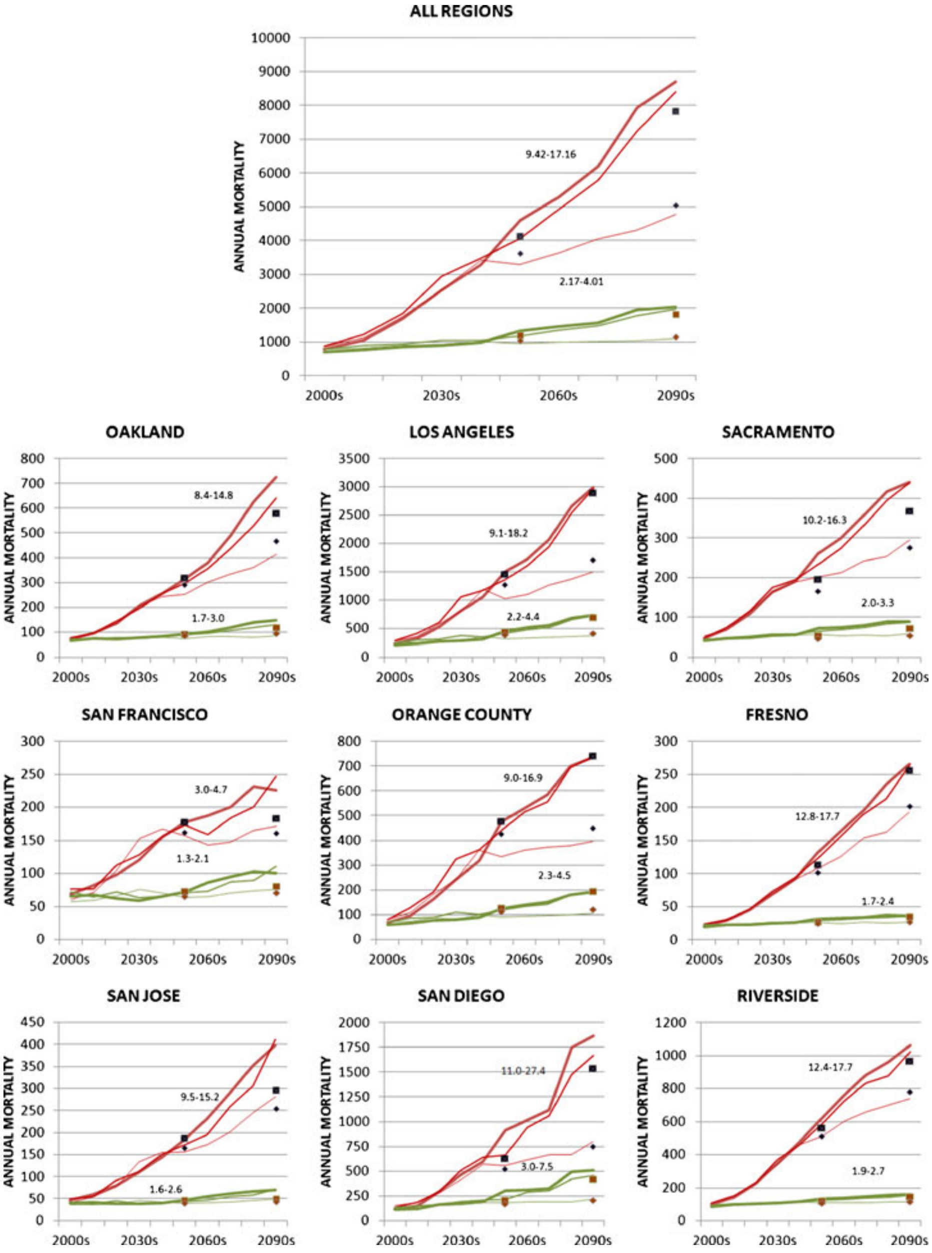

**Fig. 2** Projected mean annual future heat-related mortality (with no acclimatization) under the medium population projection (red lines – CCSM; black symbols - CGCM) and with steady 2000 population (green lines - CCSM; brown symbols - CGCM) for ages 65 and over by region (2000–2099). Numerical labels are relative rate of mortality across scenarios for 2090s (1.0 = historic). Thickest line is CCSM A1FI scenario; mid-weight line is CCSM A2 scenario; thin line is CCSM B1 scenario. CGCM A2 scenario is shown with filled box; CGCM B1 scenario is shown with filled diamond. Note the change of scale in the vertical axis among the charts

Increases in heat-related mortality are observed across all nine regions, regardless of population projection and model scenario. However, substantial differences can be observed in the magnitude of these changes. In examining the constant-population projections, spatial variability emerges, with greater rates of increase, along with greater variability among model-scenarios, along the southern coast; Los Angeles, Orange County, and San Diego all are associated with a more than doubling of heat-related mortality regardless of model scenario; in the case of San Diego, the CCSM A1FI is associated with a more than 7-fold increase in heat-related mortality, including a large step increase from the 2070s to 2080s. Cities across the interior- Fresno, Riverside, and Sacramento—have projected increases that vary less across scenario, and also are more linear, with a generally steady increase over the century. The Bay Area regions—San Francisco, Oakland, and San Jose—show lesser increases than the other regions; in San Francisco for the CGCM3 B1 scenario, with population constant, the heat-related mortality is only 34 % higher in the 2090s than in the historical period of record. In comparing the CGCM3 and CCSM3, in most cases the projections with the CCSM3 are similar or higher than the CGCM3, especially with regard to the A2 scenario.

Accounting for population growth, the differences become more substantial. Most regions have projected mortality increases that are well in excess of historical values by a factor of 10 or more. Not surprisingly, Los Angeles will potentially have the greatest number of heat-related deaths based on model projections. Using the medium-growth population projection, Los Angeles' mean annual heat-related mortality is approximately 1500 in the 2050s under the A1FI scenario, and approaches 3000 by the 2090s. Even accounting for increased emissions controls, mortality is projected to exceed 1000 for the B1 scenario in the 2050s, and reaches 1500 by the 2090s. San Diego is projected to see the largest magnitude jump, up to a 27-fold increase by the 2090s in the CCSM3 A1FI scenario, from 68 to 1865 deaths per year. Across the inland cities, increases are nearly as large, although here a driving factor is the higher rate of population increase that is projected. San Francisco is alone in not being projected to have as substantial an increase as all other regions; in addition to the relatively minimal increase in climate-related changes, its population is projected to change least of all the regions.

There are other population projections that have been used in this analysis as well (Table 3). The low-growth population projection presents mortality estimates that are much higher than the constant-population scenario, by a factor of around 3; even with minimal population growth, the low-growth model still contains significant aging not inherent in the constant-population scenario. The high-growth projection is about 50 % higher than the medium-growth projection. While these projections affect overall magnitude of mortality, they do not disproportionately affect any part of the state, indicative of the inherent assumptions in the population models.

### 3.3 Future heat-related mortality estimates (with acclimatization)

In a warmer world, it is likely that humans will partially adapt, rendering the unacclimatized estimates above as the upper limit in terms of heat-related mortality estimates. In the 2090s, across the regions as a whole, acclimatization may reduce heat-related mortality by 37 to 56 % from their unacclimatized values, to annual totals of 2045 to 5559 per year (Table 4). These acclimatized values, however, are still from 4 to 11 times the historical mortality values. In general, the higher-emissions scenario (A1FI) demonstrates the lowest decrease in acclimatized heat-related mortality, while the most conservative emissions scenario (B1) shows the largest. This is possibly because there are many more oppressive weather-type

**Table 3** Range in annual mean heat-related mortality in the 2090s (low and high estimates of the five model-scenarios analyzed) in each region for three population growth scenarios as well as constant year 2000 population. No acclimatization is assumed

| Region | Historic | Constant population | Low growth | Medium growth | High growth |
|---|---|---|---|---|---|
| Fresno | 15 | 27–36 | 127–176 | 192–266 | 278–385 |
| Los Angeles | 165 | 368–732 | 893–1778 | 1501–2997 | 2250–4499 |
| Oakland | 49 | 85–149 | 213–375 | 413–726 | 619–1089 |
| Orange County | 44 | 105–197 | 273–512 | 95–742 | 724–1362 |
| Riverside | 60 | 113–162 | 602–862 | 741–1063 | 1331–1914 |
| Sacramento | 27 | 55–88 | 198–317 | 275–440 | 440–727 |
| San Diego | 68 | 207–511 | 502–1247 | 750–1865 | 1266–3163 |
| San Francisco | 53 | 71–10 | 89–136 | 161–247 | 275–424 |
| San Jose | 27 | 44–71 | 109–175 | 256–11 | 383–615 |
| All regions | 508 | 1075–2056 | 3006–5578 | 4684–8757 | 7566–14178 |

days in the A1FI, and the number of consecutive-day runs of these days is likely to remain relatively high (see Part I).

While all regions studied show the same general characteristics, some regional differentiation is apparent. The Bay Area regions demonstrate the greatest decrease in mortality attributed to acclimatization, with reductions as high as 81 % at Oakland under the CCSM2 B1 scenario. As a result, in these B1 scenarios, acclimatized mortality projections for the 2090s at Oakland and San Francisco are similar to today's unacclimatized heat-related mortality levels. The inland cities of Riverside, Sacramento, and Fresno—where heat events are presently and are projected to continue to be the longest lasting—show the smallest decreases from unacclimatized mortality, generally between 20 and 40 % aside from the B1 scenario at Sacramento, which is substantially higher. Los Angeles and Orange County are somewhere intermediate, while coastal San Diego is an outlier, with smaller decreases similar to the inland cities.

**Table 4** Range in annual mean heat-related mortality in the 2090s (low and high estimates of the five model-scenarios analyzed) in each region for the medium population growth projection assuming acclimatization. The percent reduction refers to the difference between acclimatized and unacclimatized values (shown in Table 3). Rate of mortality across scenarios is based on comparison with historic values (1.0 = historic); these values can be compared with unacclimatized values in Fig. 2

| Region | Annual heat-related mortality (with acclimatization) | Percent reduction due to acclimatization | Rate of mortality compared to historical values (with acclimatization) |
|---|---|---|---|
| Fresno | 108–212 | 20 %–46 % | 7.2–14.1 |
| Los Angeles | 605–1763 | 41 %–65 % | 3.7–10.7 |
| Oakland | 89–202 | 72 %–81 % | 1.8–4.1 |
| Orange County | 154–427 | 41 %–66 % | 3.5–9.7 |
| Riverside | 458–838 | 21 %–41 % | 7.6–14.0 |
| Sacramento | 102–309 | 30 %–63 % | 3.8–11.4 |
| San Diego | 401–1500 | 20 %–46 % | 5.9–22.1 |
| San Francisco | 49–109 | 56 %–70 % | 0.9–2.1 |
| San Jose | 79–199 | 52 %–69 % | 2.9–7.4 |
| All Regions | 2045–5559 | 37 %–56 % | 4.0–10.9 |

## 4 Discussion

The array of numbers presented in this research underscores the many uncertainties when developing future heat-related mortality estimates. Among them are the assumptions inherent in utilizing the output of GCMs, and their ability to reproduce critical features of the climate; the applicability of emissions scenarios; the inherent uncertainty in demographic change; and how the heat-mortality relationship may change in the future. Nevertheless, the development of these estimates can provide some range of how heat-related mortality may change in future decades.

In assessing the sources of variability, while some differences appeared between the CGCM3 and CCSM3, these were generally minimal, with resultant differences in projected mortality within 20 % in all cases in the 2090s, except for the A2 scenario at San Francisco and San Jose. In this work, the similarity among the results suggests that these models have similar capability in reproducing the upper-level patterns that were associated with oppressive surface weather types, as shown in Part I. Since there are many more GCMs available, future work may assess whether these results are robust across a wider spectrum of GCMs, as other studies (Peng et al. 2010; Gosling et al. 2011) have noted model-related uncertainty to be the primary source of uncertainty.

Differences across the emissions scenarios are substantial, and proportionate with the intensity of greenhouse gas emissions. The range between the scenarios diverges considerably after 2050, and varies from region to region. Across the inland regions, the range of mortality projections by the 2090s across the model-scenarios is relatively small, from 38 % in Fresno to 43 % in Riverside and 60 % in Sacramento. Higher levels of variability are observed in the Bay Area (with a range of 57 % at San Francisco, 60 % at San Jose, and 76 % at Oakland). The greatest variability appears in the southern coastal regions, with the range among the scenarios at 88 % in Orange County, 100 % in Los Angeles, and 149 % in San Diego. For San Diego, this translates to a scenario uncertainty of over 1000 deaths per year between the B1 and A1FI scenarios (using acclimatization and the medium-growth projection).

The mortality increases themselves for the various emissions scenarios are generally regionally coherent. Increases are steady and linear across the inland regions, with constant-population heat-related mortality projected to increase by a factor of 1.7–3.3, and unacclimatized medium-growth projections between 10.2 and 17.7 times the historical values. The southern coastal regions are projected to have a somewhat greater increase, with more model-scenario variability (2.2–7.5 with constant-population; 9.0–27.4 with unacclimatized medium-growth). The Bay Area locations generally have the lowest increases in heat-related mortality projected (1.3–3.0 with constant-population; 3.0–15.2 with unacclimatized medium-growth). The constant-population results are generally similar to other studies that have assessed short-term increases in mortality (e.g. Gosling et al. 2009b), and somewhat larger than others (e.g. Knowlton et al. 2007). Comparisons across studies are made more difficult by the range of uncertainties covered (GCM, scenario, acclimatization) as well as what is being predicted (heat-related mortality or all-cause mortality).

Broad differences are observed among the population projections. While an assessment of the plausibility of the different projections is beyond the scope of this paper, the near 3-fold difference between the low-growth and high-growth models clearly indicates how critical the selection of a population projection is to the ultimate results. Moreover, the stark contrast in mortality projections between any of the future population projections and the reference constant-population projection—for all nine regions, the absolute increase in projected mortality due to population changes substantially exceeds the increase due to climate change—strongly suggests that the incorporation of demographic changes into any future impact studies is critical.

The final source of variation is the role of acclimatization on heat-related mortality. The procedure utilized in this research, which assumes that in an acclimatized world, there will be less sensitivity at the beginning of consecutive day runs of oppressive days, shows significant reductions when compared to the unacclimatized results. The decreases associated with acclimatization projected in this research are generally similar to or somewhat larger than acclimatized mortality adjustments reported in other literature (Gosling et al. 2009b; Knowlton et al. 2007). The greatest mortality reductions are projected to occur in the Bay Area locales, and the smallest are projected to occur within the hot inland cities. This reflects that there will likely be a greater number of long heat events in the hottest cities. This noted, there is a large level of uncertainty with these acclimatized results, as with most such studies, as there is no agreed standard for assessing acclimatization (Gosling et al. 2009a). In this paper, the new acclimatization procedure inherently treats all early days of a heat event as the same, something which would likely not be the case in reality. Hence, this will impact the results. Future expansion of our methodology could incorporate intensity along with duration, where certain very hot DT or MT days may be considered part of a day in sequence, while less intense DT or MT days may not.

Beyond the methodology, there is considerable uncertainty with regard to adaptive capacity itself. Given California's unique climate, an increase in heat events over coastal California within its relatively mild climate may mean that physiological adaptation in coastal areas will be less efficient than inland where hotter conditions are projected to become more typical. However, these same coastal locations are ones for which it is likely that significant increases in behavioral mechanisms (e.g., air conditioning prevalence) will take place, in comparison to inland locations where such mechanisms are already near saturation.

Last, the issue of mortality displacement must be considered in light of the results presented herein. The unacclimatized values presented in this research must be considered to be acute increases in mortality due to oppressive weather conditions. Some of this mortality is certainly short-term mortality displacement; a 'true' toll of increased mortality may be less, potentially far less, than the values stated. As mentioned in the introduction, there is substantial variability in terms of observed mortality displacement in existing research, and it is not established how this may change in the future, making this an important question for future research. Nevertheless, the acclimatization method used in this research does likely capture some of this displacement, however, as more significant heat events may have less mortality displacement along with a higher death toll (e.g. Kyselý and Kim 2009).

## 5 Summary and conclusions

To help assess the impacts of climate change on human health, the goal of this project has been to provide a range of 21st century heat-related mortality projections for nine major urban centers in the state of California. This project explicitly attempted to account for many inherent uncertainties in projecting future heat vulnerability, including emissions scenario, GCM, adaptation, and demographic change. Historical relationships between weather and mortality were derived to assess potential impacts of heat on human mortality using data from 1975 to 2004 for the nine regions. Mortality rates accounted for weather type, weather type persistence, and seasonality, and were developed separately for three separate age groups. These relationships were then utilized along with the future weather type projections to estimate the changes in heat-related mortality for each urban area.

Supporting previous research, the results here indicate that DT and/or MT weather types play a statistically significant role in increasing heat-related mortality in nearly every major urban center—especially for those over the age of 74. Thus, the broadened future seasonality and the increase in the frequency of these weather types along with the increased frequency of consecutive-day heat events, are likely to have a substantial effect on mortality. Short-term increases in mortality due to heat historically have averaged around 500 deaths per year across the nine regions, although some of this is offset by mortality displacement. Using the medium population projection, with the exception of San Francisco, all major urban centers could have a greater than tenfold increase in heat-related mortality in those over the age of 65 by the 2090s. Collectively, heat-related mortality in the medium population projection would rise by more than a factor of 9, to an annual total of 4684 to 8757 deaths per year depending upon GCM scenario. However, much of this increase is due in large part to a rising and aging population. In keeping a steady (age 65+) population from 2000 through 2099, the increase in mortality due specifically to a warming climate is projected to be 1.9 times (San Francisco) to 7.5 times (San Diego) greater than current levels by the 2090s under the A1FI scenario. It is critical that future climate-change assessments of heat-related mortality explicitly account for demographic changes as the largest relative increases will be in the most vulnerable age groups.

An estimate of the well-documented effect of acclimatization on heat-related mortality was evaluated. With the medium-growth population projection for those aged 65 and over, statewide mortality increases were lessened by 20 % to 80 % from unacclimatized values, with a statewide range of 2045 to 5559 deaths per year. Though acclimatization is projected to help mitigate some heat-related mortality, it is important to note that despite the lessened impact, these numbers still represent overall increases in deaths due to a warming climate and aging population.

Fundamentally, it has been recognized that heat-related mortality is largely preventable (O'Neill et al. 2009). Accordingly, many locations, mostly across the developed world, have initiated heat watch-warning systems over the past 15 years (e.g., Sheridan and Kalkstein 2004), which assess whether forecast weather conditions over the coming days resemble those in the past that have led to increased mortality, and through these systems short-term mitigation plans are implemented. These systems have been shown to save lives, and should be even more valuable in a warmer world (Greene et al. 2012). Beyond these short-term programs, long-term planning must begin to be undertaken in California, as well as much of the developed world, to account for the substantial increase in the population most vulnerable to excessive heat.

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## References

Anderson BG, Bell ML (2009) Weather-related mortality, how heat, cold, and heat waves affect mortality in the United States. Epidemiol 20:205–213

Anderson BG, Bell ML (2010) Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. Env Health Persp 119:210–218

Barriopedro D, Fisher E, Luterbacher J, Trigo RM, García-Herrera R (2011) The hot summer of 2010: redrawing the temperature record map of Europe. Science. doi:10.1126/science.1201224

Basu R (2009) High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. Environ Heal 8:1–13

Basu R, Feng WY, Ostro BD (2008) Characterizing temperature and mortality in nine California Counties. Epidemiol 19:138–145

Bouchama A, Dehbi M, Mohamed G, Matthies F, Shoukri M, Menne B (2007) Prognostic factors in heat wave-related deaths, a meta-analysis. Arch Internal Med 167:E1–E7

Carson C, Hajat S, Armstrong B, Wilkinson P (2006) Declining vulnerability to temperature-related Mortality in London over the 20th century. Amer J Epidemiol 164:77–84

Census (2010) Census Bureau Homepage. Website: http://www.census.gov/ Accessed Jul 2010

Centers for Disease Control (CDC) (2004) Extreme heat: a prevention guide to promote your personal health and safety. http://www.bt.cdc.gov/disasters/extremeheat/heat_guide.asp. Accessed Jul 2010

Collins WD, Bitz CM, Blackmon ML, Bonan GB, Bretherton CS, Carton JA, Chang P, Doney SC, Hack JA, Henderson TB, Kiehl JT, Large WG, McKenna DS, Santer BD, Smith RD (2006) The community climate system model: CCSM3. White paper, NCAR, Boulder

Curriero FC, Heiner KS, Samet JM, Zeger SL, Strug L, Patz JA (2002) Temperature and mortality in 11 cities of the eastern United States. Amer J Epidemiol 155:80–87

Davis RE, Knappenberger PC, Novicoff WM, Michaels PJ (2002) Decadal changes in heat-related human mortality in the Eastern US. Clim Res 22:175–184

Dessai S (2003) Heat stress and mortality in Lisbon part II. An assessment of the potential impacts of climate change. Int J Biometeorol 48:37–44

Donaldson GC, Kovats RS, Keatinge WR, McMicheal AJ (2001) Heat- and cold related mortality and morbidity and climate change. In: Maynard RL (ed) Health effects of climate change in the UK. Department of Health, London, pp 70–80

Doyon B, Belanger D, Gosselin P (2008) The potential impact of climate change on annual and seasonal mortality for three cities in Quebec, Canada. Int J Health Geographics 7:1–12

Environment Canada (2009a) The Third Generation Coupled Global Climate Model (CGCM3), http://www.cccma.bc.ec.gc.ca/models/cgcm3.shtml. Accessed Jan 2010

Environment Canada (2009b) The Third Generation Atmospheric General Circulation Model (AGCM3), http://www.cccma.bc.ec.gc.ca/models/gcm3.shtml. Accessed Jan 2010

Gershunov A, Cayan DR, Iacobellis SF (2009) The Great 2006 heat wave over California and Nevada: signal of an increasing trend. J Clim 22:6181–6203

Gosling SN, Lowe JA, McGregor GR, Pelling M, Malamud BD (2009a) Associations between elevated atmospheric temperature and human mortality: a critical review of the literature. Clim Change 92:299–341

Gosling SN, Lowe JA, McGregor GR (2009b) Climate change and heat-related mortality in six cities Part 2: climate model evaluation, sensitivity analysis, and estimation of future impacts. Int J Biometeorol 53:31–51

Gosling SN, Lowe JA, McGregor GR (2011) The benefits of quantifying climate model uncertainty in climate change impacts assessment: an example with heat-related mortality change estimates. Climatic Change. doi:10.1007/s10584-011-0211-9

Greene JS, Kalkstein LS, Mills D, Samenow J (2012) Performance of U.S. Cities in reducing excess mortality from extreme heat events: 1975–2004. *Weather, Climate, and Society.* In Press

Hajat SA, Ben G, Gouveia N, Wilkinson P (2005) Mortality displacement of heat-related deaths: a comparison of Delhi, Sao Paulo, and London. Epidemiol 16:613–620

Hayhoe K, Cayan D, Field CB, Frumhoff PC, Maurer EP, Miller NL, Moser SC, Schneider SH, Cahill KN, Cleland EE, Dale L, Drapek R, Hanemann RM, Kalkstein LS, Lenihan J, Lunch CK, Neilson RP, Sheridan SC, Verville JH (2004) Emissions pathways, climate change, and impacts on California. Proc Nat Acad Sci 101:12422–12427

Hayhoe K, Sheridan SC, Kalkstein LS, Greene JS (2010) Climate change, heat waves, and mortality projections for Chicago. J Great Lakes Res 36:65–73

Intergovernmental Panel on Climate Change (IPCC) (2007) Summary for policymakers. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 7–22

Kalkstein LS, Greene JS, Mills D, Perrin A, Samenow J, Cohen J-C (2008) Analog European heat waves for U.S. Cities to analyze impacts on heat-related mortality. Bull Amer Meteorol Soc 89:75–86

Kalkstein LS, Greene JS, Mills D, Samenow J (2010) An evaluation of the progress in reducing heat-related human mortality in major U.S. cities. Natural Hazards 56:113–129

Kinney P, O'Neill MS, Bell ML, Schwartz J (2008) Approaches for estimating effects of climate change on heat-related deaths: challenges and opportunities. Env Sci Policy 11:87–96

Knowlton K, Lynn B, Goldberg RA, Rosenzweig C, Hogrefe C, Rosenthal JK, Kinney PL (2007) Projecting heat-related mortality impacts under a changing climate in the New York City region. Amer J Publ Health 97:2028–2034

Knowlton K, Rotkin-Ellman M, King G, Margolis HG, Smith D, Solomon G, Trent R, English P (2009) The 2006 California heat wave: impacts on hospitalizations and emergency department visits. Env Health Persp 117:61–67

Kovats RS, Hajat S (2008) Heat stress and public health: a critical review. Ann Rev Publ Health 29:41–55

Kyselý J, Kim J (2009) Mortality during heat waves in South Korea, 1991 to 2005: How exceptional was the 1994 heat wave? Clim Res 38:105–116

Lee C (2011) Utilizing syniptic climatological methods to assess the impacts of climate change on future tornado-favorable environments. Nat Hazards. In press.

Luber G, McGeehin M (2008) Climate change and extreme heat waves. Amer J Prevent Med 35:429–435

McGregor GR, Pelling M, Wolf T, Gosling SN (2006) The social impacts of heat waves. Report to environment agency. Environment Agency, Bristol, p 41

Muthers S, Matzarakis A, Koch E (2010) Climate change and mortality in Vienna—A human biometeorological analysis based on regional climate modeling. Int J Environ Res Public Health 7:2965–2977

Nicholls N (2009) Estimating changes in mortality due to climate change. Clim Change 97:313–320

O'Neill MS (2003) Air conditioning and heat-related health effects. Appl Env Sci Publ Health 1:9–12

O'Neill MS, Carter R, Kish JK, Gronlund CJ, White-Newsome JL, Manarolla X, Zanobetti A, Schwartz JD (2009) Preventing heat-related morbidity and mortality: new approaches in changing climate. Maturitas 64:98–103

Ostro BD, Roth LA, Green RS, Basu R (2009) Estimating the mortality effect of the July 2006 California heat wave. Env Res 109:614–619

Peng RD, Bobb JF, Tebaldi C, McDaniel L, Bell ML, Dominici F (2010) Toward a quantitative estimate of future heat wave mortality under global climate change. Environ Health Perspect 119

Raphael MN (2003) The Santa Ana winds of California. Earth Interact 7:1–13

Sanstad AH, Johnson H, Goldstein NC, Franco G (2009) Long-run socioeconomic and demographic scenarios for California. California Energy Commission Report, CEC-500-2009-013-F, pp 49

Sanstad AH, Johnson H, Goldstein N, Franco G (2009), Long-Run Socioeconomic and Demographic Scenarios for California. PIER Research Report, CEC-500-2009-013-F, California Energy Commission, PIER Program, Sacramento, CA, pp 49

Semenza JC, McCullough J, Flanders D, McGeehin M, Lumpkin J (1999) Excess hospital admissions during the 1995 heat wave in Chicago. Am J Prev Med 16:269–277

Sheridan SC (2002) The redevelopment of a weather type classification scheme for North America. Int J Climatol 22:51–68

Sheridan SC, Kalkstein LS (2004) Progress in heat watch-warning system technology. Bull Amer Meteorol Soc 85:1931–1941

Sheridan SC, Kalkstein AJ (2010) Seasonal variability in heat-related mortality across the United States. Natural Hazards 50:291–305

Sheridan SC, Kalkstein AJ, Kalkstein LS (2009) Trends in heat-related mortality in the United States, 1975–2004. Natural Hazards 50:145–160. doi:10.1007/s11069-008-9327-2

Valleron AJ, Boumendil A (2004) Epidemiology and heat waves: analysis of the 2003 episode in France. Comptes Rendus Biologies 327:1125–1141

Voorhees AS, Fann N, Fulcher C, Dolwich P, Hubbell B, Bierwagen B, Morefield P (2011) Climate change-related temperature impacts on warm season heat mortality: a proof-of-concept methodology using BenMAP. Environ Sci Technol 45:1450–1457