Arnold Schwarzenegger
Governor

CHARACTERIZING TEMPERATURE AND MORTALITY IN NINE CALIFORNIA COUNTIES, 1999–2003

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's Public Interest Energy Research (PIER) Program established the **California Climate Change Center** to document climate change research relevant to the states. This Center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

Characterizing Temperature and Mortality in Nine California Counties, 1999-2003 is the interim report for the Climate Change Impacts: Potential Impact of High Temperatures and Air Pollution on Public Health project (contract 500-99-013, work authorization BOA-118) conducted by the California Office of Environmental Health Hazard Assessment.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

Elevated temperature has been associated with increased mortality. Few studies have focused on California, where the climate is generally mild and pollution levels tend to be high. This study examined the association between mean daily apparent temperature and non-accidental mortality for nine California counties from May to September, 1999 to 2003, using case-crossover and time-series analyses. Weather data were obtained from the National Climatic Data Center and death certificate data were abstracted from the California Department of Health Services. Pollutant data, including particulate matter, ozone, carbon monoxide, and nitrogen dioxide, were provided by the California Air Resources Board. Researchers obtained county-specific estimates and combined them using meta-analytic methods. A total of 248,019 deaths were included. Each 10°F increase in same-day mean apparent temperature corresponded to a 2.6 percent increase in mortality (95 percent confidence interval (CI): 1.5, 3.8) in the case-crossover analysis and a 3.7 percent increase in mortality (95percent CI: 2.6, 4.8) from the time-series analysis for all nine counties combined. Air pollutants were not found to be significant confounders or effect modifiers. Excess mortality does not result from extreme temperatures only; this study found an effect in California using mean temperature exposure during non heat-wave periods.

Keywords: Temperature, humidity, mortality, air pollution, epidemiology, California, case-crossover, time-series

Executive Summary

Introduction

Elevated temperature has been documented in previous studies to be associated with increased mortality. However, few studies on this topic have been conducted in California, where the climate is generally mild and air pollution levels, such as particulate matter, ozone, carbon monoxide, and nitrogen dioxide, tend to be high. Estimates from other locales may not be applicable to populations living in California since there is also less temperature variability in California throughout the year compared to other areas, theoretically allowing the population to adapt less readily. Furthermore, many previous studies did not consider air pollutants as potential confounders (a variable that is not considered in a study but can affect the outcome) and/or effect modifiers of the temperature-mortality association, therefore making it difficult to separate the independent effect of either temperature or air pollution.

Purpose

This epidemiologic study sought to estimate the human impact of mortality associated with current California temperature patterns, while accounting for several air pollutants. The methods established in this study could be used in future research to predict the impact of climate change, as well as to develop remediation efforts to lower greenhouse gas emissions.

Project Objectives

This study's objective was to examine the association between daily apparent temperature (which includes both temperature and humidity) and mortality in California, focusing on the warmer months of May to September, 1999 to 2003. Mean daily apparent temperature was used as the main measure of exposure. This metric was used for several reasons: (1) by including only the warm season, potential seasonal confounding was avoided; (2) apparent temperature is a better index of heat stress than temperature alone; and (3) it was important to determine the effects on mortality that would occur during a non-heat-wave period.

The research team specifically accounted for the potential confounding and effect modification by four major air pollutants to which Californians are routinely exposed: particulate matter of less than 2.5 micrometers in aerodynamic diameter ($PM_{2.5}$, or *fine particulates*), ozone, carbon monoxide, and nitrogen dioxide. The California Air Resources Board provided data for air pollutants.

Weather and pollutant data were merged with mortality records for the study period by day and county of death. The California Department of Health Services, Health Data and Statistics Branch provided data on daily mortality for California residents. For this analysis, the research team used data from nine counties: Contra Costa, Fresno, Kern, Los Angeles, Orange, Riverside, Sacramento, San Diego, and Santa Clara. A previous study used the same data in an analysis of fine particulate pollution and mortality. These counties represent heavily populated

metropolitan areas, including approximately 65 percent of the state's population. They include both inland and coastal counties throughout Northern and Southern California. Thus, researchers were able to capture widespread temperature and air pollution exposures with some variation by region. For this analysis, researchers retrieved information on date, cause, and county of death from the death certificate data. Deaths from all causes were considered, excluding accidents, suicides, and homicides, as listed on the International Classification of Deaths codes, Version 10.

Two modern statistical approaches were used to validate the results: case-crossover and time-series. The time-series study design has been commonly used in studies of air pollution and temperature, while the case-crossover has been more recently introduced. Several strengths are inherent in the case-crossover design, such as controlling for known and unknown time-varying confounders. All analyses were accomplished in two steps: (1) obtaining county-specific estimates, and (2) combining county-specific estimates from all nine counties, using a meta-analysis approach that incorporates random effects models.

Conclusions

The research team found an approximately 3 percent increase in mortality from non-accidental causes per 10°F increase in mean daily apparent temperature. Consistent with previous studies, this study found the same-day lag apparent temperature to have the strongest effect with mortality. The case-crossover and time-series analyses produced similar results, regardless of whether they were analyzed by mean, maximum, or minimum apparent temperature, adding to the validity of the findings. Furthermore, ozone, nitrogen dioxide, carbon monoxide, and $PM_{2.5}$ did not appear to be confounders or effect modifiers. After adjusting for each of the pollutants in separate models, the research team still found significant associations between apparent temperature and mortality with similar magnitude, demonstrating an independent effect of apparent temperature on mortality. Since this study used data from 1999 to 2003 (during which time California temperatures were generally mild), the estimate for mortality represents average temperature exposure commonly experienced by Californians, not the worst-case scenario that may occur in years with unusual weather patterns, such as heat waves.

Recommendations

Several future studies could be conducted using an epidemiologic method similar to the one in this study. It is important to conduct studies for California specifically, because adaptability may be different than in other areas. In addition, the temperature exposure tends to be relatively mild, and many homes are not equipped with air conditioning simply because of the moderate climate. Also, patterns of exposure may be different, since more time is spent outdoors. It is possible to identify vulnerable subgroups to prevent heat-related mortality, including an examination of age groups, racial/ethnic groups, education level (marker for socioeconomic status), and gender, as well as to examine specific causes of mortality (such as cardiovascular, respiratory, and other disease-specific outcomes). The research team would also like to analyze temperature and morbidity (specifically hospitalizations and emergency room visits) and address harvesting (those deaths that would have occurred within a few days, regardless of temperature exposure). Finally, it is important to examine health effects during

major heat waves and compare these results to those obtained in the current study, which focused on the entire warmer season.

Benefits to California

This study adds to the growing body of evidence linking short-term ambient temperature exposure with mortality. Much of the evidence for climate change in California has been based on climatological models and ecological consequences; however, it is also important to evaluate the human impact of climate change from epidemiologic studies. Documented studies and case reports show that heat waves can lead to human morbidity and mortality. Less has been known, however, about the effect of ambient background increases in temperature or high ambient temperature on human populations, especially in California. This study found significant associations between mean ambient temperature and mortality in California, which suggests that there will be important public health impacts in California associated with an increase in the average temperature over time. In addition, with increasing severity and duration of heat waves in the future, the association would be expected to be worse, as suggested by the preliminary results of the research team's analysis of the 2006 heat wave. The methods presented in this study could be used to quantify the human impact from reducing greenhouse gas emissions and implementing future technologies and predict the consequences of climate change.

1.0 Introduction

An association between elevated ambient temperature and mortality has been documented in prior studies, particularly in the elderly and other vulnerable subgroups who may not be able to thermoregulate efficiently (Basu and Samet 2002a). When body temperatures rise, blood flow shifts from the vital organs to underneath the skin's surface in an effort to cool down (Bouchama and Knochel 2002). Inadequate thermoregulation may occur when too much blood is diverted, putting increased stress on the heart and lungs. Increased blood viscosity, elevated cholesterol levels associated with higher temperatures, and a higher sweating threshold in the elderly may also trigger heat-related mortality in susceptible individuals (Astrand, Rodahl et al. 2003). Recent studies of heat-related mortality have been conducted using data from the 2003 heat wave in Western Europe, where investigators have indicated an excess of up to 35,000 deaths (Conti, Meli et al. 2005; Garssen, Harmsen et al. 2005; Nogueira, Falcao et al. 2005; Pirard, Vandentorren et al. 2005; Simon, Lopez-Abente et al. 2005; Conti, Masocco et al. 2007; Kovats, Johnson et al. 2006). Many of these deaths occurred prematurely among the elderly living in urban areas. Thus, with climate change and a rapidly growing urban elderly population, mortality from heat waves and other extreme weather events is a significant public health problem that may continue to worsen in the future (Ebi, Mills et al. 2006).

Prior studies across five continents have examined the relationship between temperature and mortality over a wide range of temperatures (Hales, Salmond et al. 2000; Braga, Zanobetti et al. 2002; Curriero, Heiner et al. 2002; Donaldson, Keatinge et al. 2003; Basu, Dominici et al. 2005; Hajat, Armstrong et al. 2005; O'Neill, Hajat et al. 2005; Stafoggia, Forastiere et al. 2006), but few have focused on California (Hayhoe, Cayan et al. 2004; Luers, Cayan et al. 2006). Estimates from other locales may not be applicable to populations living in California since temperature and humidity are generally mild and temperature varies less throughout the year, theoretically allowing the population to adapt readily (McGeehin and Mirabelli 2001). Pollution levels, on the other hand, tend to be higher than in other regions of the United States and the sources, chemistry, size distribution, and patterns of exposure in California are distinct (Blanchard 2003), and thus, may have a different interaction with temperature. Apart from a few recent epidemiologic studies (Hales, Salmond et al. 2000; Basu, Dominici et al. 2005; O'Neill, Hajat et al. 2005; Filleul, Cassadou et al. 2006; Ren and Tong 2006), air pollutants have not been considered as a confounder or as an effect modifier of the temperature-mortality association. While no confounding by pollution was reported in two studies (Hales, Salmond et al. 2000; Rainham and Smoyer-Tomic 2003), particulate matter of less than 10 micrometers in aerodynamic diameter (PM_{10}) was found to be an effect modifier in Australia (Ren and Tong 2006) and a confounder in Monterrey, Mexico, and regions throughout the United States, especially in the summer (Basu, Dominici et al. 2005; O'Neill, Hajat et al. 2005). In another study of nine French cities, the effect of ozone (O_3) and temperature was found to be heterogeneous across cities (Filleul, Cassadou et al. 2006). Because of lack of studies and conflicting results, it is difficult to extrapolate the independent effect of either temperature or air pollution for California.

This study characterized the temperature-mortality relationship for nine counties in California. The research team considered temperature and relative humidity exposure during the warm season in California, rather than the full year (which may contribute to confounding[1]) or limiting the data to only periods of extremely high temperatures or heat waves. The potential confounding and effect modification[2] by several air pollutants was also accounted for, to determine whether there is an independent effect of relatively mild levels of ambient temperature exposure on mortality. Both the case-crossover and time-series analytical techniques were applied to ensure that the findings were robust. The research team hypothesizes that there will be an effect of apparent temperature on mortality in California, even after accounting for air pollutants.

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[1] A *confounder* (Z) is a variable that is related both to the exposure (X) and outcome of interest (Y). If data are available for the confounder, it can be included in the analysis and would increase or decrease the effect estimate.

[2] *Effect modification* refers to the situation in which a measure of effect changes over values of another variable. For example, A factor, *Z*, is said to be an effect modifier of a relationship between a risk factor, *X*, and an outcome measure, *Y*, if the strength of the relationship between the risk factor, *X*, and the outcome, *Y*, varies among the levels of *Z*.

2.0 Methods

2.1. Death Certificate Data

The California Department of Health Services, Health Data and Statistics Branch provided daily mortality data for people who died in California for the study period from May 1, 1999, to September 30, 2003 (1999–2003). Nine counties were selected for the analysis: Contra Costa, Fresno, Kern, Los Angeles, Orange, Riverside, Sacramento, San Diego, and Santa Clara. The same nine counties were used in an earlier investigation of fine particulate pollution and mortality using a subset of the same data through 2002 (Ostro, Broadwin et al. 2006). These counties encompass metropolitan areas, including approximately 65% of the state's population. Although there are expected to be differences between air pollution and temperature exposures throughout each county, the monitored data represent the most heavily populated areas of each county, and far fewer people live in areas further away from the monitors. Both inland and coastal counties throughout Northern and Southern California were included. Thus, the study captured widespread temperature and air pollution exposures with some variation by region. For this analysis, the research team retrieved information on date, cause, and county of death and considered deaths from all causes, excluding accidents, suicides, and homicides (V01-Y98), as listed on the International Classification of Deaths (ICD) codes, Version 10 (1993). Since heat-related mortality has been reported to be an acute event (Basu and Samet 2002a), temperature exposure was based on the county of death for each individual.

2.2. Weather and Pollutant Data

Hourly weather data were obtained from the National Oceanic and Atmospheric Administration National Climatic Data Center (2004) for the study period. Only one monitor was used to represent temperature exposure for each county, except for Orange County, where the monitor was relocated to another nearby location in the same city in 2003. Data were pooled from the two sites by subtracting the means of each monitor from each daily observation and then adding the average of means from the two monitors to each observation. Only monitors that recorded at least 18 hours of daily observations were included for each county. Daily mean apparent temperature in degrees Fahrenheit (°F), also known as the heat index, was calculated to incorporate temperature and relative humidity, using the following formulas:

1. Saturation vapor pressure = $6.112 \times 10^{(7.5 \times \text{temperature } ^\circ\text{C} / (237.7 + \text{temperature } ^\circ\text{C})}$
2. Actual vapor pressure = (relative humidity (%) x saturation vapor pressure) / 100
3. Dew point temperature °C = (-430.22 + 237.7 x ln(actual vapor pressure))/(-ln(actual vapor pressure) + 19.08)
4. Apparent temperature °C = -2.653 + (0.994 x temperature °C) + 0.0153 x (dew point temperature °C)^2
5. Apparent temperature °F = (9/5) x apparent temperature °C + 32

Daily air pollutant data were merged with daily weather data by county and date of death to assess potential confounding and effect modification by five air pollutants. The California Air Resources Board (2004) provided daily data for gaseous pollutants, including carbon monoxide (CO), nitrogen dioxide (NO_2), and O_3, and particulate matter less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$) and PM_{10}. All pollutants were reported as 24-hour averages, except O_3, which was reported both as an eight-hour average and as a one-hour maximum, and NO_2, which was reported as a one-hour maximum. For counties with multiple air pollution monitors, the research team calculated a daily average using all available data. The team also accounted for missing data for some of the monitors using a method described previously without imputing any data (Ostro, Broadwin et al. 2006). The daily average for PM data was developed using the following method: (a) calculating the mean value for each monitor across the study period; (b) subtracting each monitor's mean concentration from the non-missing daily values for the monitor (i.e., centered data); (c) calculating the daily mean of the available centered data across all monitors in a given county; and (d) for each day, adding back the grand mean (the mean of all unadjusted daily values of all the monitors).

2.3. Study Design and Data Analysis

This study used both case-crossover and time-series analyses. In a previous study of temperature and mortality in the United States, investigators demonstrated that these methods produced similar results (Basu, Dominici et al. 2005). Nevertheless, the research team wanted to ensure that the results were also robust for California specifically, and so used both modern statistical approaches.

The case-crossover study is a modification of the matched case-control study, in which each person serves as his or her own control, and temperature on the day of death (case period) is compared to temperature on different days when death did not occur (referent periods). The research team used the time-stratified approach (Levy, Lumley et al. 2001) to select referent periods every third day of the same month and same year as the case period. For example, if a death occurred on the first of the month, all referent periods would occur after the case period; whereas if a death occurred on the last day of the month, all referent periods would occur before the case period. Deaths occurring in the middle of the month would, therefore, have referent periods both before and after the case period (as shown in Figure 1).

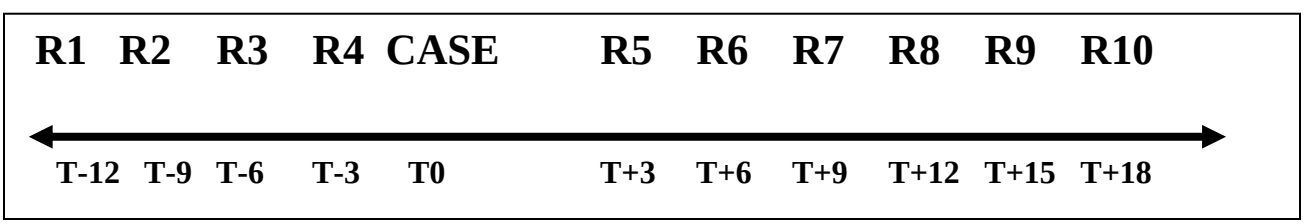

Figure 1. Schematic diagram of the time-stratified case-crossover design. CASE refers to case period and R1-R10 refers to referent periods 1-10. T0 = time that case occurred (death date), with referent periods occurring every third day.

By choosing referent periods within a short period of time from the cases, time-varying factors are accounted for by study design. The estimate for mortality risk would not be biased by this referent period sampling scheme, since referent periods were allowed to be selected at random with respect to the time that the case occurred. In addition to a linear term for apparent temperature, day of the week was added to the model as an indicator variable to account for potential confounding. Each pollutant was added as a linear term to assess confounding and as an interaction term with apparent temperature to evaluate effect modification. To reduce the possibility of residual confounding that may have resulted from simply adding each pollutant to the model, the research team also examined the effects of mean daily apparent temperature only on those days when O_3 was relatively constant (within 2 ppb), using a similar methodology described in a previous analysis (Schwartz 2005). All case-crossover analyses were conducted in SAS (Version 8.2, SAS Institute, Cary, North Carolina, 2001) using the PHREG procedure for conditional logistic regression. A unique identifier was created for each individual so that each case period could be matched with up to ten referent periods for the same individual.

The time-series analysis has been widely applied to the analyses of air pollution and health outcomes (Schwartz, Hasselblad et al. 1988; Peters, Liu et al. 2000; Samet, Zeger et al. 2000; Bell, Dominici et al. 2005; Dominici, Peng et al. 2006; Ostro, Broadwin et al. 2006) and more recently, to temperature (Braga, Zanobetti et al. 2002; Curriero, Heiner et al. 2002; Basu, Dominici et al. 2005). The research team used generalized additive models with a quasi-Poisson link function including a natural spline smoothing function for time trend with four degrees of freedom (df) per year distributed evenly throughout the study period.

As in the case-crossover analysis, day of the week was added as an indicator variable along with apparent temperature. In additional analyses, each air pollutant was included in the model specification and an interactive term (pollution times apparent temperature) was examined. Seasonality was not adjusted for in the analyses, because the analyses was limited to the warmer months. All time-series analyses were conducted using R software (The Comprehensive R Archive Network: http://cran.r-project.org/).

To conduct the data analyses, individual death data were used in the case-crossover study and aggregated daily death data were used for the time-series analysis. The research team calculated percent change in mortality and 95 confidence intervals (95% CIs) per 10°F increase in mean daily apparent temperature. Both analyses were accomplished by first obtaining county-specific mortality estimates and then combining all nine county-specific estimates using a meta-analysis approach incorporating random effects models (DerSimonian and Laird 1986). The counties were combined by taking the weighted average of the inverse of the variance for each county, so that counties with more precise effect estimates had larger weights than counties with less precise estimates. Tests-for-heterogeneity using chi-squared tests determined that fixed effects models were adequate for combining most estimates, but the results were reported from random effect models to account for the few estimates that required it.

2.4. Sensitivity Analyses

The research team conducted several sensitivity analyses. First, several lag times were analyzed to determine whether a single-day effect of same-day temperature exposure (lag-0), or moving averages over the same day and previous three days (lag-03) or the previous three days (lag-13) had the best model fit according to an adjusted R^2. Second, researchers considered a shorter summer season (i.e., June to August) as well as minimum temperature and maximum temperature, both adjusted by mean dew point temperature to account for humidity, in separate models. Third, the research team compared effects between inland counties (Kern, Fresno, Riverside, and Sacramento) and coastal counties (Contra Costa, Los Angeles, Orange, San Diego, and Santa Clara); as well as possible differences between Northern California counties (Contra Costa, Fresno, Kern, Sacramento, and Santa Clara) and Southern California counties (Kern, Los Angeles, Orange, and San Diego). Finally, tests for linearity of the temperature-mortality association were performed, considering apparent temperature models that included day of the week with a squared or a cubic term for apparent temperature and different cut-points for temperature (i.e., 65˚F, 75˚F). An indicator variable for apparent temperatures above the 98th and 99th percentiles of the total distribution were also added to see whether there was a differential effect of mortality observed at the higher end of apparent exposure. To evaluate whether there was a differential effect by month of apparent temperature exposure, the research team conducted an additional analysis with an indicator variable for month and apparent temperature.

3.0 Results

The study population consisted of 248,019 individuals who died in nine California counties in the warmer months of 1999 to 2003. Figure 2 presents the mean apparent temperature and number of deaths for each of the nine counties for the entire study period. The total deaths from all-causes by county ranged from 8,088 to 104,688, and the mean apparent temperature ranged from 65 to 78°F. The blue and green correspond to lower temperatures, more common in coastal areas, while the red and orange correspond to higher temperatures, more common in inland areas.

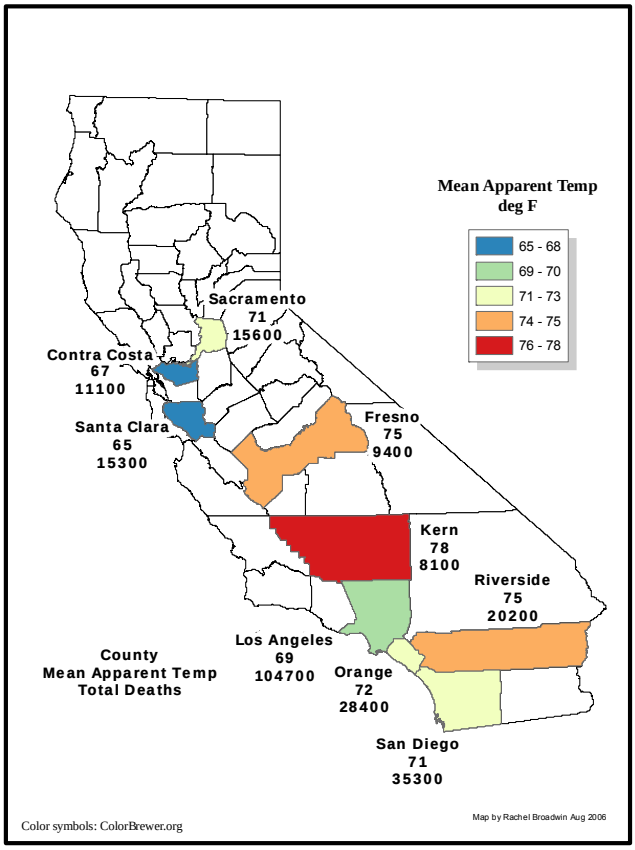

Figure 2. Nine California counties, May–September, 1999–2003

Table 1 depicts the location of each weather monitor (in parentheses) and other descriptive statistics of each county. The monitors represent densely populated areas in each county, with an estimated population in the year 2000 (range among counties: 662,000 to 2,846,000), days with apparent temperature data (range: 522 to 765), minimum temperature range (54.9 to 68.3°F), maximum temperature range (74.8°F to 90.8°F) and mean daily all-cause deaths (range: 10.6 to 136.9).

Table 1. Descriptive statistics by county, May–September, 1999–2003

County	2000 pop (x 1,000)	Min, 25%, 75%, max daily apparent temperature in ºF	Days with apparent temperature data	Mean daily all-cause deaths
Contra Costa (Concord)	949	54.9, 61.7, 72.2, 84.3	765	14.5
Fresno (Fresno)	799	65.6, 70.5, 81.2, 88.5	686	12.2
Kern (Bakersfield)	662	64.1, 73.8, 84.0, 90.8	704	10.6
Los Angeles (Downtown Los Angeles)	9,519	59.3, 65.5, 73.3, 76.1	643	136.9
Orange (Anaheim)	2,846	68.3, 68.2, 76.8, 81.1	522	37.1
Riverside (Riverside)	1,545	64.1, 70.4, 81.6, 85.1	758	26.4
Sacramento (Sacramento)	1,223	59.8, 65.6, 76.1, 86.4	762	20.4
San Diego (Escondido)	2,814	62.1, 66.4, 76.1, 81.7	715	46.1
Santa Clara (San Jose)	1,683	56.9, 61.1, 68.5, 74.8	734	20.1

As summarized in Table 2, the means for the nine counties ranged from: 64.7°F to 78.5°F for apparent temperature, 45.6 to 86.4 parts per billion (ppb) for maximum O_3, 7.6 to 28.4 micrograms per cubic meter ($\mu g/m^3$) for $PM_{2.5}$, 0.5 to 1 parts per million (ppm) for CO, and 20.4 to 50.1 ppb for NO_2 over the study period.

Table 2. Mean (25th %, 75th %) for each pollutant by county, May–September, 1999–2003

County	1-hr O_3 (ppb)	$PM_{2.5}$ ($\mu g/m^3$)	CO (ppm x 10)	NO_2 (ppb)
Contra Costa (CCO)	51.8 (39.0,62.0)	8.6 (5.8,10.1)	5.0 (3.9,5.5)	20.4 (13.5,25.0)
Fresno (FRE)	86.4 (71.8,100.4)	7.6 (3.8,9.8)	4.7 (3.3,5.5)	28.3 (20.2, 34.8)
Kern (KER)	83.0 (71.5,94.4)	11.3 (8.0,13.5)	6.8 (4.6,8.3)	31.9 (25.9,37.9)
Los Angeles (LA)	64.5 (51.7,74.2)	19.8 (14.7,23.3)	10.2 (7.4,12.4)	50.1 (37.9,59.9)
Orange (ORA)	57.2 (47.5,65.0)	17.0 (11.8,21.0)	6.3 (4.4,7.5)	29.1 (20.0,35.0)
Riverside (RIV)	82.7 (70.5,94.0)	28.4 (17.9,36.1)	10.6 (7.8,12.9)	41.9 (32.3,51.3)
Sacramento (SAC)	65.6 (53.2,77.2)	8.8 (5.8,10.1)	5.2 (3.3,6.2)	24.9 (15.5,31.0)
San Diego (SD)	54.8 (47.2,61.9)	13.4 (10.3,15.8)	8.0 (6.0,9.0)	27.0 (20.5,31.4)
Santa Clara (SC)	45.6 (35.5,51.6)	10.8 (7.2,13.8)	7.0 (4.7,8.1)	30.1 (19.3,36.3)

This exploratory analysis found that lag-0 apparent temperature had the best model fit using either study design. Thus, all of the results presented are only shown for lag-0. An average of lag-0 and lag-1 (lag-01) was used for the gaseous pollutants, and lag-0 had the best model fit for $PM_{2.5}$. Meta-analysis results for all counties using either lag-0 or lag-1 pollutant produced virtually the same effect estimates as lag-01, since some counties showed that lag-0 had a better fit, while others showed a better fit for lag-1, so either of these lag times could have been used.

Figure 3 shows the results for each county, followed by the meta-analyses estimates for all nine counties. Per 10°F increase in mean daily apparent temperature, a 2.6% increase in mortality (95% CI: 1.5%, 3.8%) from the case-crossover analysis and a 3.7% increase in mortality (95% CI: 2.6%, 4.8%) from the time-series analysis.

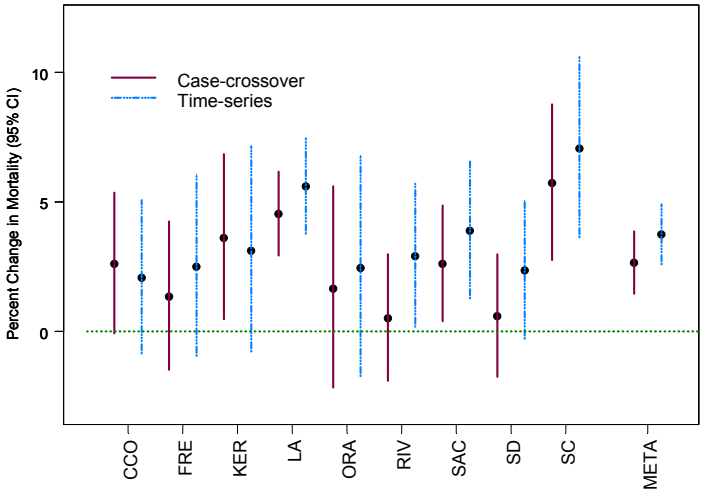

Figure 3. County-specific and meta-analysis results for mean apparent temperature (per 10°F) and non-accidental mortality in nine California counties. County abbreviations are listed in Table 2.

As further demonstrated in Figure 4, the results from the case-crossover and time-series analyses were similar by county. There was also a small range of effect observed for each of the nine counties (odds ratios (OR) and relative risk (RR) ~ 1.0–1.1). Although single-county estimates are shown, the results from the meta-analysis combining multiple areas may be more reliable, because it reduces the likelihood of publication bias or spurious results that may result from analyzing a single county (Anderson, Atkinson et al. 2005). Thus, the following figures present results from these meta-analyses only. All figures were created using S-PLUS Software (Version 7.0, Cambridge, Massachusetts: MathSoft Engineering and Education, 2005).

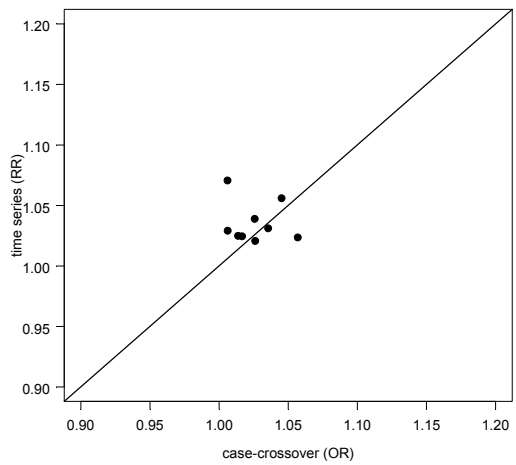

Figure 4. A comparison of the county-specific estimates for the case-crossover and time-series analyses (perfect agreement corresponds to diagonal line)

In separate models, the research team evaluated confounding and effect modification by each air pollutant. As shown in Table 3, adding maximum O_3, NO_2, CO, and $PM_{2.5}$ to the model with apparent temperature and day of the week did not significantly change the result in either the case-crossover or the time-series analyses (each resulted in a 2%–4% increase in mortality). In the case-crossover analysis in which the effect apparent temperature was only considered on days within the same 2 ppb O_3, researchers found a similar mortality increase (2.9%; 95% CI: 1.8%, 4.0%) as in the original analysis. Thus, none of these pollutants appeared to confound the apparent temperature-mortality association.

Moreover, an independent effect of apparent temperature is supported, since these estimates all remained statistically significant after adding any pollutant to the model. Furthermore, these pollutants did not appear to modify the association between apparent temperature and mortality. Of all analyses examining effect modification by pollutants, the research team only found one significant finding (two-sided p-value = 0.05 for Fresno) and one marginally significant finding (two-sided p-value = 0.09 for Riverside) for O_3, but effect modification by O_3 was not significant in a combined analysis of all nine counties (two-sided p-value = 0.55). The results for 8-hour O_3 and PM_{10} were virtually identical to daily 1-hour maximum O_3 and $PM_{2.5}$, respectively, and thus, are not shown.

Table 3. Meta-analysis results for apparent temperature and non-accidental mortality, and adjusted by individual pollutant for nine California counties. Percent increases (95% CI) per 10°F.

Model	Case-crossover	Time-series
Base model: Apparent temperature + day of week	2.6 (1.5, 3.8)	3.7 (2.6, 4.8)
+ 1-hour maximum ozone	2.8 (1.4, 4.2)	4.3 (3.1, 5.6)
+ 8-hour average ozone	2.8 (1.3, 4.2)	4.2 (2.9, 5.5)
Matched by 1-hour ozone	2.9 (1.8, 4.0)	
+ Particulate matter ≤ 2.5 μm	2.9 (1.7, 4.0)	4.4 (3.3, 4.4)
+ Particulate matter ≤10 μm	2.0 (0.4, 3.6)	3.8 (2.4, 5.2)
+ Carbon monoxide	2.2 (1.2, 3.2)	3.5 (2.3, 4.7)
+ Nitrogen dioxide	2.3 (1.3, 3.4)	3.7 (2.4, 5.0)

After exploring various models in sensitivity analyses, the research team confirmed that a linear model was appropriate for apparent temperature and mortality in the warmer months. Specifically, the team did not find an overall improvement to the goodness of fit with a temperature squared term to the model or a cubic term, demonstrating that a linear term for apparent temperature was appropriate. Also, the 98th and 99th indicator variables were not significant for any county, further supporting no change in slope at higher levels of apparent temperature exposure and therefore, a linear association. The estimates produced using mean apparent temperature remained robust to various temperature definitions. For example, examining a shorter summer season produced nearly identical results, and thus, these are not shown. Compared to mean temperature, a slightly higher estimate of increased mortality (~4%) was found for minimum temperature, while a slightly lower estimate of increased mortality (~2%) was found for maximum temperature (Figure 5); however, these differences were not statistically significant. Figure 6 shows the county-specific and meta-analyses results for minimum temperature specifically. In regional analyses, the research team found that the coastal counties (3.4%–95% CI: 2.3–4.5) had a significantly greater risk than the inland counties (2.0%, 95% CI: 0.7, 3.3) and that the estimates for Northern (3.1%–95% CI: 1.8– 4.3) and Southern (2.6%–95% CI: 1.5–3.8) California were slightly, but not significantly, different. These results were from the case-crossover analysis, although the time-series study produced similar findings.

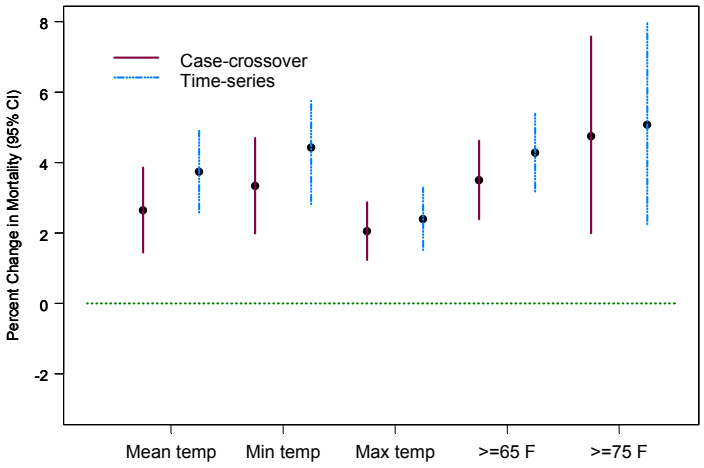

Figure 5. Meta-analysis results for various other temperature definitions (per 10°F) and non-accidental mortality for nine California counties

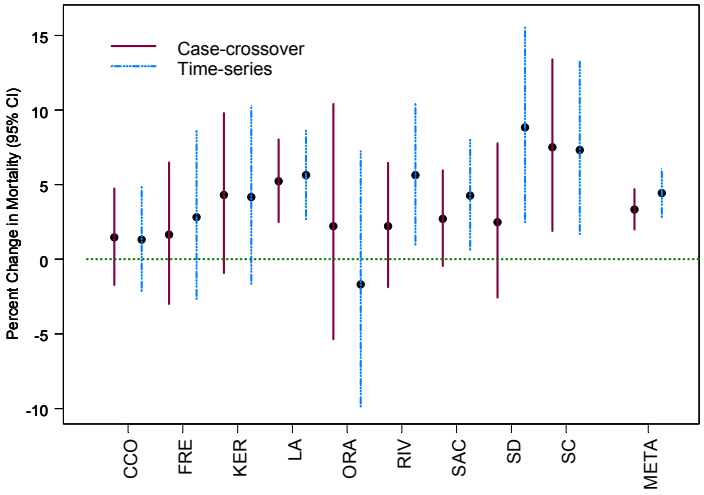

Figure 6. County-specific and meta-analysis results for minimum temperature adjusted by dew point temperature (per 10°F) and non-accidental mortality in nine California counties. County abbreviations are listed in Table 2.

4.0 Conclusions

This study found an approximately 3% increase in mortality from non-accidental causes per 10°F increase mean daily apparent temperature. Consistent with previous studies, the same-day lag of apparent temperature was found to have the strongest effect with mortality (Basu and Samet 2002a). The case-crossover and time-series analyses produced generally similar results regardless of whether mean, maximum, or minimum temperature was analyzed, adding to the validity of the findings. The slightly higher estimates for increased mortality from minimum temperature may be reflective of higher nighttime temperatures from lack of cooling in the warmer months. Furthermore, none of the pollutants appeared to be confounders or effect modifiers, and significant associations were still found between apparent temperature and mortality with similar effect magnitudes, even after adjusting for each pollutant in separate models. Thus, the independent effect of apparent temperature on mortality is supported. Since the study used data in the warmer months of 1999 to 2003 (when temperatures were generally mild in California), the estimate for mortality represents average temperature exposure that is commonly experienced, not the worst-case scenario that may occur in years with unusual weather patterns, such as extreme temperatures and heat waves.

A preliminary investigation of the July 2006 heat wave, where mean daily apparent temperatures ranged from 81°F–100°F in six counties throughout California, depicted the combined effect estimates to be three times higher than those found in this analysis (Roth, Basu et al. in preparation). This study found some evidence of this stronger effect after limiting apparent temperature data to higher cut-offs. While a similar risk was observed for apparent temperatures 65°F and greater (3.5%–95% CI: 2.4–4.6 in the case-crossover analysis), a higher risk was found for apparent temperatures 75°F and greater (4.8%–95% CI: 2.0–7.6 in the case-crossover analysis). Evaluation of thresholds above 75°F for all nine counties were limited by the range of mean apparent temperature in the data. However, a threshold model was not necessary for the main analysis, and as discussed earlier, using a linear model was justified.

It is difficult to directly compare these results with prior epidemiologic studies, because of the various definitions such as lower and higher percentiles, temperature cut-offs, or extreme temperatures used to classify temperature in previous investigations (Hales, Salmond et al. 2000; Hajat, Armstrong et al. 2005; Diaz, Linares et al. 2006; Medina-Ramon, Zanobetti et al. 2006; Stafoggia, Forastiere et al. 2006), rather than reporting estimates effects for mortality per degree increase in mean temperature.

Per each degree Celsius (˚C), other investigators reported a 2.2%, 1.6%, and 1.4% increase (equivalent to about a 4%, 3% and 2.5% increase per ˚F, respectively) in all-cause mortality above 20˚C in New Delhi, Sao Paolo, and London, respectively (Hajat, Armstrong et al. 2005). In Christchurch, a 1% increase (about 2% per ˚F) in all-cause mortality for temperatures above 20.5˚C (68˚F) was reported (Hales, Salmond et al. 2000).

Although the cut-off temperatures in these studies were near the minimum mean temperature in this study, the temperature ranges varied. In an analysis using similar methods, researchers conducted a study of 20 U.S. metropolitan areas, including four counties from California, and

found summer estimates per 10˚F that were also higher than those found in this study (Basu, Dominici et al. 2005). The primary purpose of the previous study, however, was to compare methods; the estimates were only based on one year of data and the results may not be indicative of a longer time period. A recent analysis of nine counties outside of California, where investigators used the same methods as those in this study, a 2% increase in all-cause mortality per 10˚F increase apparent temperature was also found (Zanobetti and Schwartz in preparation), even though the range of mean apparent temperature was higher and range of O_3 was generally lower than in this study, and populations may exhibit different acclimatization patterns. Thus, the relationship between temperature and mortality appears to be linear in these temperature ranges depicting average exposure, and the effect estimate produced from this study seems to provide general mortality risk associated with average apparent temperature exposure.

This study has some limitations generally present in ecologic analyses. By using personal monitoring, as was done in a previous study (Basu and Samet 2002b), researchers could obtain individual exposure data, as well as gather information on key time-activity factors. In this study, one monitor was used to represent apparent temperature exposure in the entire county, which was centrally located to areas where many people reside. As in all ecologic analyses, the potential for misclassification of apparent temperature exposure would be greater for those persons who died further away from a monitor, particularly for larger counties such as Los Angeles, Riverside, Orange, and San Diego counties. This analysis was limited to variables that could be retrieved from death certificate data, and the research team could not assess personal characteristics such as income level or air conditioning use. Air conditioning use may be less of a marker of socioeconomic status in California, however, since many homes in coastal areas do not have air conditioners simply because they have not been needed; coastal temperatures are mild in the summer and generally lower than in inland areas. There may also be some acclimatization for people living in inland areas, where higher temperatures are typically experienced in the summer months, partially explaining the lower estimate compared to the coastal areas, as also reported in another study (Hayhoe, Cayan et al. 2004).

4.1. Recommendations

Several studies could be conducted in the future using an epidemiologic methodology such as the one in this study to expand knowledge of temperature effects in California. It is important to conduct studies for California specifically, because adaptability may be different than in other areas, since the temperature exposure tends to be relatively mild and many homes are not equipped with air conditioning simply because of the moderate climate. Also, exposure patterns may be different, since more time is spent outdoors. Research needs to identify vulnerable subgroups to prevent heat-related mortality, including an examination of age groups, racial/ethnic groups, education level (marker for socioeconomic status), and gender, and also examine specific causes of mortality (e.g., cardiovascular, respiratory, and other disease-specific outcomes). The research team would also like to conduct an analysis of temperature and morbidity (specifically hospitalizations and emergency room visits) and address harvesting, which would determine the amount of life years lost per temperature-related death. Previous analyses of air pollution have addressed this issue to determine the

extent to which mortality may be brought forward by only a few days (Zeger, Dominici et al. 1999; Schwartz 2000).

4.2. Benefits to California

This study adds to the growing body of evidence of the association linking short-term ambient temperature with mortality. Much of the concern for climate change in California has been based on climatological models and ecological consequences. It is also important to evaluate the human impact of climate change from epidemiologic studies. Documented studies and case reports show that heat waves can lead to human morbidity and mortality (Basu and Samet 2002). Less has been known, however, about the effect of ambient background increases in temperature on human populations, especially in California, where lower temperature and humidity are generally observed. Significant associations were found between mean ambient temperature and mortality in California. With increasing severity and duration of heat waves in the future, the projected association would be expected to be worse, as suggested by the preliminary results of the 2006 heat wave. The methods presented in this study could be used to quantify the human impact from reducing greenhouse gas emissions and implementing future technologies, and to predict the consequences of climate change.

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