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Challenges associated with projecting urbanization-induced heat-related mortality

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HIGHLIGHTS

- Extreme heat is a public health hazard in metropolitan Maricopa County, Arizona.
- Urbanization is a key driver of future regional temperature changes.
- Projections of heat–health impacts for 2050 vary across urbanization scenarios.
- The sign and magnitude of projections are also sensitive to exposure variable choice.
- Consideration of urbanization effects is critical for heat–health policymaking.

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ABSTRACT

Maricopa County, Arizona, anchor to the fastest growing megapolitan area in the United States, is located in a hot desert climate where extreme temperatures are associated with elevated risk of mortality. Continued urbanization in the region will impact atmospheric temperatures and, as a result, potentially affect human health. We aimed to quantify the number of excess deaths attributable to heat in Maricopa County based on three future urbanization and adaptation scenarios and multiple exposure variables. Two scenarios (low and high growth projections) represent the maximum possible uncertainty range associated with urbanization in central Arizona, and a third represents the adaptation of high-albedo cool roof technology. Using a Poisson regression model, we related temperature to mortality using data spanning 1983–2007. Regional climate model simulations based on 2050-projected urbanization scenarios for Maricopa County generated distributions of temperature change, and from these predicted changes future excess heat-related mortality was estimated. Subject to urbanization scenario and exposure variable utilized, projections of heat-related mortality ranged from a decrease of 46 deaths per year (−95%) to an increase of 339 deaths per year (+359%). Projections based on minimum temperature showed the greatest increase for all expansion and adaptation scenarios and were substantially higher than those for daily mean temperature. Projections based on maximum temperature were largely associated with declining mortality. Low-growth and adaptation scenarios led to the smallest increase in predicted heat-related mortality based on mean temperature projections. Use of only one exposure variable to project future heat-related deaths may therefore be misrepresentative in terms of direction of change and magnitude of effects. Because urbanization-induced impacts can vary across the diurnal cycle, projections of heat-related health outcomes that do not consider place-based, time-varying urban heat island effects are neglecting essential elements for policy relevant decision-making.

1. Introduction

Extreme heat is the leading weather-related cause of death in the United States (Luber et al., 2006), and urbanization, population aging, and global-scale climate change will likely conspire in future years to increase population vulnerability to heat. Despite a growing body of research advancing our understanding of spatial, temporal, environmental, social, and behavioral dimensions of heat-related health risks (e.g., Anderson and Bell, 2009; Harlan et al., 2013; Hondula et al., 2012), the institution of warning systems and other intervention measures (e.g., Hondula et al., 2013; Sheridan and Kalkstein, 2010), and the fact that relatively simple measures can prevent heat-related illnesses and

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deaths (e.g., Luber and McGeehin, 2008; O'Neill et al., 2009), heat persists as a public health burden. There has been an increase in research efforts to apply climate change projections to health outcomes, with the greatest emphasis on predicting future heat-related mortality. From a global perspective, increasingly frequent and severe hot days are expected to lead to an increase in corresponding negative health outcomes (McMichael et al., 2006). There is now interest in quantifying the related health burdens to inform planning and policy (Ebi et al., 2006; Gosling et al., 2009; Sheridan et al., 2012). The level of an investment a particular municipality would make in mitigation and adaptation programs aimed at reducing thermally stressful situations in the future would likely be influenced by the magnitude of the expected changes in undesirable heat-attributable health outcomes.

Populated cities in hot climates offer an interesting case for analysis of resident sensitivity to heat under current and future climatic conditions. The population of Maricopa County, Arizona, home of the Phoenix metropolitan area, the hottest major urban area in the United States, is not immune to the dangerous effects of heat (Chuang et al., 2013; Harlan et al., 2013). Unlike many other large metropolitan areas in the United States where episodic heat is associated with elevated risk of illness and death (Anderson and Bell, 2009, 2011; Barnett et al., 2010; Sheridan and Kalkstein, 2004), dangerously high temperatures persist in Maricopa County for much of the warm season. Whereas cities in the southeastern United States exhibit decreased (or no) sensitivity to heat compared with mid-Atlantic and northeastern cities (Curriero et al., 2002; Davis et al., 2003), the temperature extremes present for such an extended period of time result in high heat sensitivity among residents of Maricopa County.

A wide range of studies has documented a significant heat effect in Maricopa County and its associated cities (e.g., Phoenix, Tempe, Glendale, Scottsdale, Mesa, Chandler, Gilbert, and Peoria) (e.g., Harlan et al., 2013; Yip et al., 2008). Most recently, the Maricopa County Department of Public Health reported 106 heat-related deaths in the county in 2011 and at least 102 deaths in 2012 (with 13 cases pending review) (MCDPH, 2013). Heat-related mortality in the region occurs among young and elderly populations alike: a majority of indoor deaths during the period 2000–2005 occurred among the elderly while a majority of outdoor deaths occurred among those less than five years old (Yip et al., 2008). Analysis of a different time period (2002–2009) showed that men in agricultural and construction/extraction occupations were at particularly high risk (Petitti et al., 2013). National-scale studies have reached mixed conclusions regarding the sensitivity of the region's population to extreme heat compared to other cities, ranging from little to no effect of heat (Kalkstein and Greene, 1997; Sheridan and Kalkstein, 2010) to statistically significant effects equal or greater than those in other major U.S. cities (Anderson and Bell, 2009, 2011; Saha et al., 2014).

Here, we compare projections of heat-related deaths for Maricopa County using regional urbanization scenarios associated with high growth, low growth, and adaptation-oriented growth (Georgescu et al., 2013). In Maricopa County, urbanization and urban heat island intensity have been linked to higher heat vulnerability (Chow et al., 2012; Golden et al., 2008; Harlan et al., 2006; Jenerette et al., 2011; Ruddell et al., 2009). There has been minimal research specifically examining the extent to which urbanization (versus greenhouse gas-forced climate change) may contribute to future increases or decreases in heat-related mortality, which is important to consider because urbanization rates can be managed at the local and regional levels. Urban development modifies regional climate primarily through reduced evening and nighttime longwave energy loss to the overlying atmosphere, relative to rural areas, based on the geometry and higher heat capacity of the built environment (Georgescu et al., 2011). We also explore the extent to which choice in exposure variable (e.g., maximum, mean, or minimum temperature) impacts the projection, which has been largely unaddressed to date (Huang et al., 2011). Exposure variable is especially important to consider in semiarid environments where urbanization-induced changes can lead to substantial differences in projected minimum and maximum temperatures.

2. Methods

2.1. Data sources

Maricopa County is located in central Arizona in the northern portion of the Sonoran Desert (see Fig. 1). The urbanized area is contained largely in a valley surrounded by mountains ranging from 300 m to 2000 m above the valley floor. Summer afternoon temperatures regularly exceed 40 °C, and occasionally approach 50 °C. The metropolitan area continues to be one of the fastest growing in the United States, growing from just over 3,000,000 residents in 2000 to over 4,000,000 in 2010, despite a downturn in the economy during that time period. The County is the anchor of the ever-growing Arizona Sun Corridor that extends from Tucson and Nogales to the south and Prescott to the north and west.

All-cause daily mortality data for residents of Maricopa County were obtained from the Office of Vital Records at the Arizona Department of Health Services for the time period 1983–2007. Over the 25-year period of record there were 472,327 deaths in the study region. The increasing daily mortality counts over the period of record are primarily reflective of the rapid population growth in Maricopa County (see Supplemental Material Fig. S1). Seasonal variability is also evident in the data with mortality peaking in January and at a minimum in August. We elected to use all-cause mortality as the variable of interest for this study because exposure to high ambient temperatures can exacerbate a range of health problems and lead to premature death (Sheridan and Kalkstein, 2004; Kovats and Hajat, 2008). The use of all-cause mortality also facilitates comparison with other studies projecting future heat-related health impacts (e.g., Greene et al., 2011; Petkova et al., 2013; Sheridan et al., 2012). The use of human subject data in this research is exempt from the IRB per Title 45 Part 46 Exemption Category 4. These data were preserved by public agencies for research purposes and personal identifiers were removed, eliminating the requirement for consent.

Daily minimum and maximum temperature data for the geographic centroid of Maricopa County were obtained from Daymet (Thornton et al., 2012). The Daymet model provides daily values for a suite of meteorological parameters over a 1 km by 1 km continuous surface spanning the United States and portions of Canada and Mexico based on meteorological observations and a digital elevation model (Thornton et al., 1997). We used Daymet data to facilitate the future extension of this work to other locations where ground-based monitors may not be available. Daily mean temperatures were calculated as the average of daily minimum and maximum temperatures.

Urbanization-induced climate change scenarios were based on Maricopa Association of Governments (MAG)-projected high- and low-development Sun Corridor expansion scenarios for 2050 (Georgescu et al., 2012, 2013). The expansion scenarios considered included a maximum (both geographical urban extent and density) and minimum (both geographical urban extent and density) expansion, hereafter referred to as SunCorrHi and SunCorrLo, respectively. These scenarios account for the largest degree of uncertainty associated with differing Sun Corridor urbanization paths, whose actual development trajectory remains unknown. Finally, widespread adoption of cool (i.e., highly reflective) roofs was utilized as an adaptation approach corresponding to the SunCorrHi expansion scenario (hereafter SunCorrAdapt). These scenarios were incorporated into and used as surface boundary conditions for the Weather Research and Forecasting (WRF) Model (Skamarock and Klemp, 2008; Georgescu et al., 2013). WRF simulation output was extracted for 0500 and 1700 local standard time (LST), consistent with observed average daily minimum and maximum temperatures (Georgescu et al., 2011). The average of the 0500 and 1700 LST data

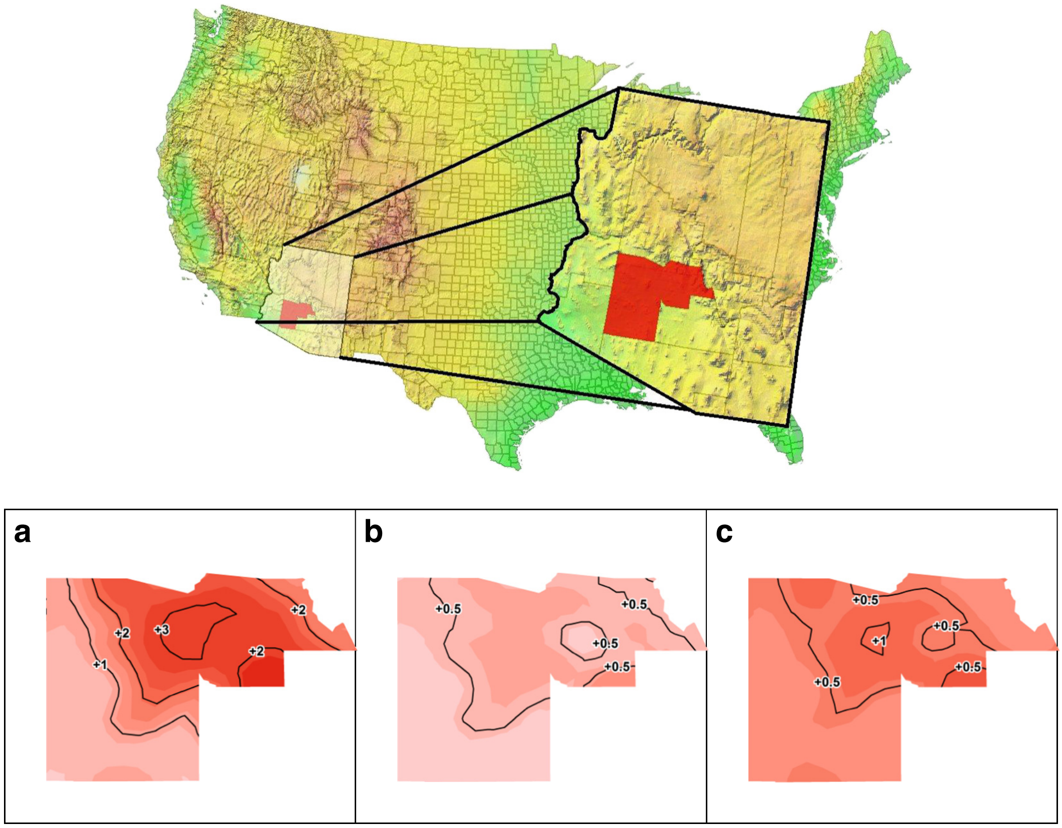

Fig. 1. A map highlighting the study region, Maricopa County, Arizona, United States. The insets show projected changes in summer mean daily temperatures (°C) in Maricopa County under (a) a high-growth scenario (SunCorrHi), (b) a low-growth scenario (SunCorrLow), and (c) an adaptation scenario (SunCorrAdapt) for year 2050.

was a proxy for daily mean temperature (typically calculated as the average of the daily minimum and daily maximum temperatures).

2.2. Statistical modeling: historical impacts of heat

To determine the specific relationship between temperature and mortality in Maricopa County, we employed a time series Poisson regression model that accounts for long-term time trends in the mortality records. The model is expressed as:

$$E(M) = s(\text{trend}, k = n \times y) + s(\text{temperature}, k = m) \quad (1)$$

where E(M) is the expected value of daily mortality and s represents a natural penalized smoothing spline with k knots. For the trend term we used five knots (n) for each of the 25 years (y) and for the temperature term we used a total of five knots (m). Sensitivity analyses tested the impact of varying n and m. The trend term is included in the model to minimize confounding of the temperature–mortality relationship that might result from long-term changes in the mortality rate (associated with population growth and/or demographic changes) as well as seasonal variability in mortality believed to be related to influenza and other factors that are not directly related to temperature (e.g., Davis et al., 2003). The dependent variable used throughout the study is the daily count of all-cause mortality. We tested a number of different independent variables to examine potential differences between the current and future climate (defined in this manuscript as impacts due to urbanization alone, separate from greenhouse gas forcing) with respect to daily temperatures and periods of sustained high temperatures ("heat waves") relative to normal summer conditions in Maricopa County. Specifically, nine different independent variables were considered: daily maximum temperature, daily mean temperature, and daily minimum temperature, as well as the three-day and five-day trailing moving averages of each. A separate temperature–mortality relationship was developed for each of these independent variables. Statistical modeling was performed using the *mgcv* package in the R computing environment (version 2.13.2) (R Development Core Team, 2012; Wood, 2006).

Subsequently, we quantified the number of excess deaths attributable to heat during the ten-year period 2003–2012 period (henceforth, present day). We restricted the analysis to the months of June, July, and August for consistency with climate model output. To calculate excess mortality, we first identified ten different seasonal baseline mortality patterns by generating predictions from the model represented by Eq. (1) for the ten most recent years of mortality data while holding temperature constant at the summer mean over the same time period. Baseline mortality (M_B) is a theoretical value representing what the expected mortality count would be on every single day assuming that the temperature on each day was equal to the summer mean—it solely captures seasonal variability unrelated to temperature. Next, we used ten years of summer temperature observations (2003–2012) and applied the temperature–mortality relationships calculated previously to the M_B time series, shifting each day's expected mortality up or down based on the modeled temperature–mortality curve. For example, if the model associates a 40 °C daily maximum temperature with a relative risk of mortality of 1.10, a day on which the daily maximum temperature was 40 °C had its M_B multiplied by 1.10 to generate the predicted mortality count with the temperature effect included (M_T). Heat-attributable mortality (M_H) was calculated as the sum of the positive differences between M_T and M_B. An illustration of this process is shown in the Supplemental Material.

2.3. Projecting future impacts

For each urbanization scenario and exposure variable (27 different combinations) we generated an empirical distribution of temperature for each of the four model runs as well as the mean of the four model runs. We then found the difference between each scenario/exposure variable distribution and the control run distribution at each 1/10th of one percentile of the respective distributions. Collectively, these differences capture the *change* in temperature expected in the region in 2050. Gosling et al. (2009) demonstrated the importance of accounting for changes in temperature variability as well as changes in the mean when projecting future heat-related mortality and our percentile-based method fully captures the projected temperature changes across the entire temperature distribution.

We applied the percentile-specific temperature changes to the 2003–2012 temperature observations derived from Daymet to generate a synthetic daily temperature time series for the future. Each observation in the historical record was assigned to a specific percentile, and the corresponding change from the distributional analysis was applied to that observation to generate the synthetic data. For example, the 90th percentile summer daily minimum temperature in the historical observations was 30.3 °C, and the distributional analysis for the SunCorrHi scenario indicated that the 90th percentile daily minimum temperature would increase by 6.9 °C by 2050; all historical observations of 30.3 °C were replaced with values of 37.2 °C in the synthetic time series. This calculation is illustrated in the Supplementary Material (Fig. S4).

To estimate future excess mortality, we repeated the calculation described above for estimating excess mortality for the present-day period (2003–2012) but replaced the historical temperature observations with the new synthetic temperature time series. Ultimately, excess heat-related mortality for different future urbanization scenarios was compared to that found for present-day conditions.

3. Results

The historical relationship between temperature and mortality was found to be statistically significant ($p < 0.001$) for daily mean, minimum, and maximum temperatures, as well as the three- and five-day moving averages thereof. The strongest relationships were found for single-day maximum and mean temperature. All relationships demonstrated the familiar "U-shaped curve" for the temperature–mortality relationship also found for other cities in the U.S. (e.g., Curriero et al., 2002; Li et al., 2013). Fig. 2 shows examples for daily maximum and minimum temperatures (all models are shown in Supplemental Material Fig. S5). For maximum temperature, there is a positive association between temperature and mortality for temperatures above 20 °C, but

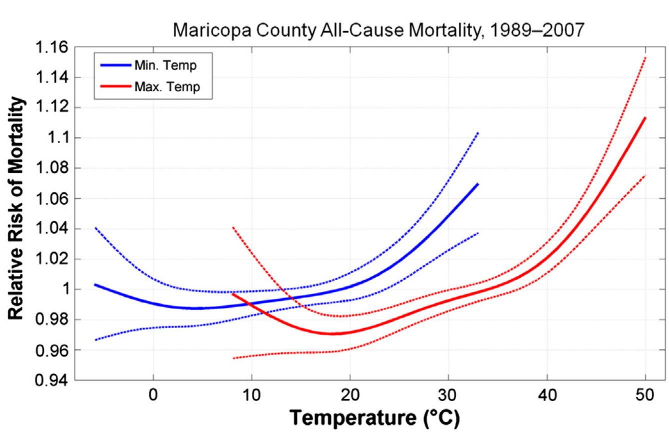

Fig. 2. The modeled relationship between daily mortality and temperature in Maricopa County, Arizona, United States, 1983–2007. The red line shows the relationship for daily maximum temperature and the blue line shows the relationship for minimum temperature. 95% confidence intervals are expressed with dashed lines. A penalized thin plate smoothing spline with a maximum of five degrees of freedom was used to estimate the temperature effect in generalized additive model that also accounted for seasonality and long-term time trends. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

as temperatures approach and exceed 40 °C the slope of the relationship increases substantially. A similar shape is observed for the minimum temperature–mortality relationship with a minimum mortality temperature near 5 °C and an upper inflection point near 25 °C. Estimates of excess mortality attributable to high temperatures during the ten year present-day period ranged from an average of 43.1 deaths per year (five-day average maximum temperature) to 94.5 deaths per year (three-day average minimum temperature). The mean across all nine temperature metrics was 63.6 deaths per year (results for all model runs and scenarios can be found in the Supplemental Material, Tables S2–S4).

Future temperature changes in the region varied across the three urbanization scenarios and exposure metrics considered (Fig. 3). Daily minimum temperatures increased substantially in all urbanization scenarios while daily maximums showed little change except for the SunCorrAdapt scenario in which daily maximums decreased.

Estimates of heat-related excess mortality varied considerably across temperature metrics and scenarios examined (Fig. 4 and Supplemental Material Fig. S6 and Tables S2–S4). In terms of the absolute and relative change in the number of heat-related deaths compared to present day, the largest increases in heat-related mortality were associated with minimum temperature projections for the SunCorrHi and SunCorrAdapt scenarios. All projections based on maximum temperature showed a decline in heat-related mortality in the future.

Comparing projections based on absolute changes (Fig. 4, left panel), the largest increases were associated with minimum temperatures for each scenario. Three-day minimum temperature projections for the SunCorrHi and SunCorrAdapt scenarios led to the highest heat-related mortality increases of 339 and 280 deaths per year, respectively (the number reported represents the mean of all four model runs). One-day and five-day minimum temperature projections for these scenarios also led to greater increases in mortality than any minimum temperature projections associated with the SunCorrLow scenario. Mean temperature projections led to the highest mortality increases with the SunCorrHi scenario, ranging from 117 to 151 additional deaths per year. The SunCorrLow and SunCorrAdapt mean temperature projections led to comparable mortality increases on the order of 50 additional deaths per year. Each model run using all possible combinations of urbanization scenarios and temperature metrics led to a projected decline in heat-related mortality with future urbanization. Maximum temperature projections for the SunCorrAdapt scenario led to the largest declines in heat-related mortality, the sharpest of which was a reduction of 46 deaths per year.

Evaluating the projections based on changes relative to the current period (Fig. 4, right panel) reveals a similar pattern. Again, the largest increases were associated with minimum temperature projections for the SunCorrHi and SunCorrAdapt scenarios. In terms of a relative increase, the difference between the one-, three-, and five-day temperature projections was much smaller than observed for the absolute numbers. The highest relative increase was found for the three-day average minimum temperature projection with the SunCorrHi scenario, with 359% more annual deaths associated with heat. Twelve of the 27 projection combinations were linked to a more than 100% increase in heat-related deaths in 2050, including all nine projections based on minimum temperature and three projections based on mean temperature with the SunCorrHi scenario. The relative decline in heat-related mortality using maximum temperature projections was largest for the SunCorrAdapt scenario, with reductions of 94–95% compared to present day.

4. Discussion

The climate of the desert southwest and Maricopa County in particular is expected to change in the coming decades as a result of urbanization and greenhouse gas forcing (Georgescu et al., 2013). Although the majority of heat-related mortality projections to date have focused on impacts owing to greenhouse gas-induced climate change (e.g., Hayhoe

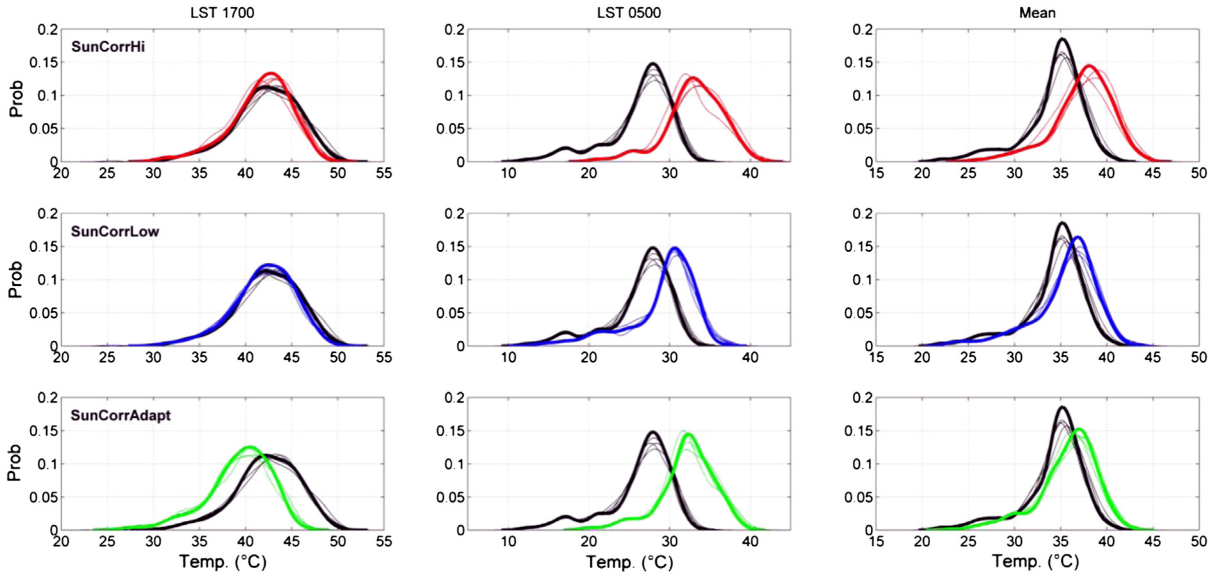

Fig. 3. Probability density functions of (left panels) daily summer temperatures at 1700 local standard time (used as a proxy for daily maximum temperature), (center panels) daily summer temperatures at 0500 local standard time (used as a proxy for daily minimum temperature), and (right panels) daily mean temperatures (average of 0500 and 1700 temperatures) for Maricopa County, Arizona, United States. The black lines show the density functions for a present-day control period. Density functions for year 2050 are shown for three different urbanization scenarios for Arizona's Sun Corridor: High growth (red lines), low growth (blue lines), and adaptation (green lines). Each thin line represents one of four separate model runs; the thick lines show the average of all four runs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 2004; Knowlton et al., 2007; Ostro et al., 2011; Petkova et al., 2013), recent results suggest that urban-induced climate change has similar order-of-magnitude climate effects on the spatial scales of human significance (Georgescu et al., 2013, 2014; Argüeso et al., 2014). Accounting for impacts due to large-scale climate change, while neglecting regional climate impacts owing to rapidly expanding urban areas, will therefore provide incorrect quantitative assessment of climate change consequences for heat-related mortality.

Projections of urbanization-induced heat-related mortality for Maricopa County for the middle of the 21st century based on minimum and mean temperatures show considerable increases relative to present day; even the most conservative estimate using these metrics was associated with more than a 50% increase in annual heat-related deaths. The most extreme estimates were associated with mortality increases exceeding 300%. The general direction and magnitude of these estimates is similar to those reported for other large metropolitan areas in the United States (e.g., Li et al., 2013; Sheridan et al., 2012).

A sharp contrast from most existing literature was found for projection based on maximum temperature. Results indicate that maximum temperature changes under all urbanization scenarios considered are associated with declining future mortality. Maximum temperature (or maximum apparent temperature) is among the exposure metrics most commonly used in heat-related mortality projection studies (Huang et al., 2011). With a few city-specific estimates in multi-city studies as exceptions (e.g., Sheridan et al., 2012), the bulk of the evidence to date suggests that changes in maximum temperature will be associated with increasing heat-related mortality. We did not find this to be the case in semiarid Maricopa County, because urbanization

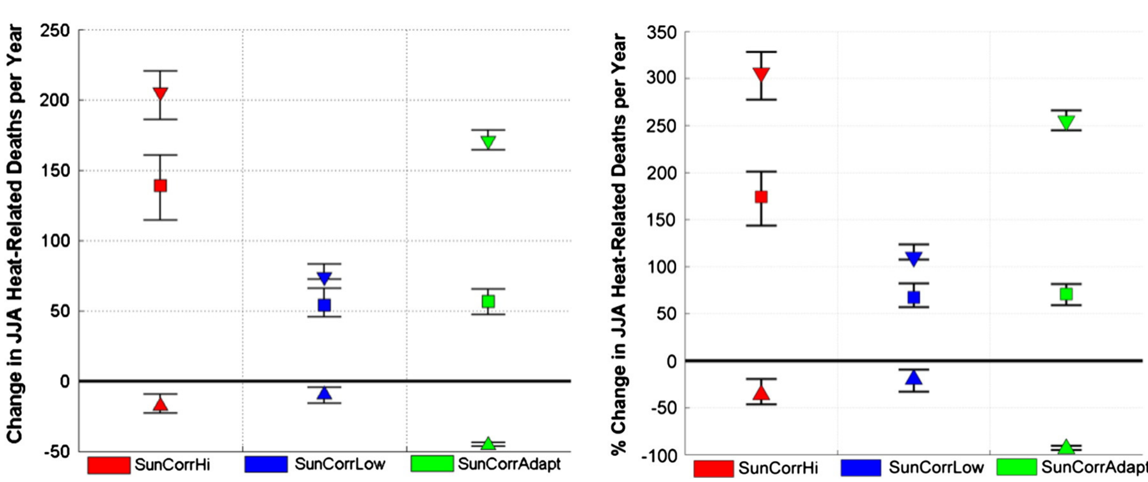

Fig. 4. Projected annual change in summer (June–August) excess all-cause mortality associated with heat in Maricopa County. The values shown reflect the (left panel) absolute differences and (right panel) relative differences between future heat-related mortality (based on the period 2045–2055) and calculated present-day heat-related mortality (based on the period 2002–2012). Red symbols represent the SunCorrHi urbanization scenario, blue symbols represent SunCorrLow, and green symbols represent SunCorrAdapt. Upward-pointing triangles represent daily maximum temperature, squares represent daily mean temperature, and downward-pointing triangles represent daily minimum temperature. The error bars show the range of changes across four different model runs; the symbol corresponds to the mean of four model runs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

patterns are expected to maintain, or slightly lower, daytime maximum urban temperatures within semi-arid regions (Imhoff et al., 2010; Georgescu et al., 2011).

Urbanization-induced climate change depends on the biome upon which the built environment resides (Georgescu et al., 2011). For example, mid-latitude urban areas exhibit a small positive urban heat island (UHI) effect during daytime hours followed by a large positive UHI effect during nighttime hours (Brazel et al., 2000; Imhoff et al., 2010), illustrating the classic warmer urban environment relative to rural (and consequently less developed) surrounding areas throughout the diurnal cycle. This is in contrast with the small, but negative, UHI effect during daytime hours followed by a significant positive UHI effect during the nighttime period, a prominent feature of semi-arid urban regions (Brazel et al., 2000; Georgescu et al., 2011; Imhoff et al., 2010).

Choice of exposure variable has a profound impact on estimates of future urbanization-induced heat-related mortality in the region we examined. Differences were more pronounced between minimum, mean, and maximum temperatures than between single day, three-day moving average, and five-day moving average temperatures. The *sign* of the change in heat-related mortality was different for maximum temperature projections than for minimum or mean, and considerable differences in magnitude were found among projections with the same sign. Barnett et al. (2010) reported that choice in exposure variable for temperature–mortality modeling should be guided by practical concerns because no one metric was found to be superior to others with respect to fitting the data. These results led Huang et al. (2011) to suggest that, when projecting future heat-related mortality, choice in temperature–mortality model is likely a more important determinant of variability in projections than the exposure metric used. Our findings offer a different perspective. Like Barnett et al. (2010), we found little difference in the statistical performance of different exposure metrics in relating temperature to mortality. All nine models developed were statistically significant and similarly fit the data. However, differing projected future changes in the exposure metrics we used – minimum temperatures generally increase by several degrees while maximum temperatures slightly decrease – results in large differences in heat-related mortality projections. Our analysis only tested differences between minimum, mean, and maximum dry bulb temperatures, but it could very well be the case that future changes in dry bulb temperature differ from those other metrics like apparent temperature or Humidex. Thus, we recommend that even if different exposure variables similarly fit mortality data, their impact on future mortality outcomes also be tested because the manner in which the exposure variables themselves evolve in the future may differ from one to another. In arid locations, home to over two billion people (Confalonieri et al., 2007), this is especially important.

The projections provided herein do not account for demographic changes, greenhouse-gas forced climate change, or population acclimatization to high temperatures. Population growth is accounted for in the urban expansion scenarios (determining future temperature changes) but mortality increases (both in absolute and relative terms) are provided for the current population size to provide a meaningful comparison with respect to risk. These variables are held constant so that we can specifically examine variability arising from urbanization and exposure variable choice. Population growth, demographic changes, greenhouse-gas forced climate change, and population acclimatization are all important elements of a comprehensive projection of heat-related mortality. This work highlights the need to include built environment expansion and its impacts on regional climate in such work.

5. Conclusions

Our results bring to light several dimensions of the challenge of projecting heat-related mortality that have been largely neglected to date. Heat-related mortality in the United States is widely projected to increase in the future as the climate warms, urban areas continue to grow, and the population ages. Research to date has not comprehensively examined the role that urbanization-induced climate change and choice in exposure variable play in these projections. Integrating historical weather and mortality data with climate projections for Maricopa County, Arizona, we have shown that both of these factors introduce large uncertainties. Substantial differences in heat-related mortality projections were evident across three different urbanization scenarios and choice of minimum, mean, or maximum temperature. All projections based on minimum and mean temperatures were associated with increasing heat-related mortality, with the largest projected increase exceeding 350% above present day. Conversely, all projections based on maximum temperatures were associated with declining heat-related mortality, and under an adaptation-oriented scenario these declines reduced mortality by more than 94%. The scale of these differences shows that critical evidence for policymakers is absent when projecting the health effects of climate change without considering the important role of urbanization and exposure variable choice.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2014.04.130.

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