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Heat Death Associations with the built environment, social vulnerability and their interactions with rising temperature

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ABSTRACT

In an extreme heat event, people can go to air-conditioned public facilities if residential air-conditioning is not available. Residences that heat slowly may also mitigate health effects, particularly in neighborhoods with social vulnerability. We explored the contributions of social vulnerability and these infrastructures to heat mortality in Maricopa County and whether these relationships are sensitive to temperature. Using Poisson regression modeling with heat-related mortality as the outcome, we assessed the interaction of increasing temperature with social vulnerability, access to publicly available air conditioned space, home air conditioning and the thermal properties of residences. As temperatures increase, mortality from heat-related illness increases less in census tracts with more publicly accessible cooled spaces. Mortality from all internal causes of death did not have this association. Building thermal protection was not associated with mortality. Social vulnerability was still associated with mortality after adjusting for the infrastructure variables. To reduce heat-related mortality, the use of public cooled spaces might be expanded to target the most vulnerable.

1. Introduction

In the face of climate change and more frequent and severe extreme heat events, it has become more important to understand which neighborhoods and populations are at risk of death from extreme heat and how properties of the urban environment contribute to or mitigate the risk of heat related death (United Nations, 2014). Heat related deaths can be prevented if individuals can cool themselves. Air conditioning is the most important form of cooling available in most cities and its absence from homes is a factor in heat mortality and morbidity (Blum et al., 1998; Semenza et al., 1996). In its absence, the U.S. Centers for Disease Control and Prevention recommend people "reduce their risk for heat-related illness by spending time in public facilities that are air-conditioned", specifically suggesting shopping malls and public libraries as public venues for accessing cooled space (U.S. Centers for Disease Control and Prevention, 2015). Local public health departments and emergency managers open and provide access to air-conditioned, cooling shelters in extreme heat events, as this is commonly believed to be helpful in reducing heat-related deaths, and neighbors are asked to check on elderly neighbors (Mees, 2015). There is indirect evidence that heat-health warning systems which couple early warnings with a broad array of emergency response measures save lives, though it is unknown which of the measures contribute to any reduction (Ebi et al., 2003).

A community's vulnerability to extreme heat can be understood as a function of its heat exposure, population characteristics and adaptive capacity. Exposure, in the form of increasing temperature, is related to mortality: in one study for every 10 °F increase in ambient temperature, there was a 2.6% increase in cardiovascular mortality (Basu, 2009). The temperature-mortality relationship may be non-linear so that longer duration heat events

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may have more population effects (Anderson and Bell, 2011). Population characteristics including socio-economic and health factors contribute to heat-mortality relationships. Age is commonly cited as a risk factor with some studies finding that populations are at higher risk of mortality as well as persons under age five (Luber and McGeehin, 2008). Minority groups are frequently at greater risk of heat mortality too, though studies are not consistent in this finding (Hondula et al., 2012; Uejio et al., 2011; Golden et al., 2008). Poverty, chronic health conditions and social isolation can be risk factors (Harlan et al., 2013; Kovats and Hajat, 2008, McGeehin and Mirabelli, 2001, Le Tertre et al., 2006; Klinenberg, 2002). Which populations are at risk varies between and within cities likely due to differences in environment, climate, culture, demography and adaptations (Harlan et al., 2013; Reid et al., 2012; Hondula et al., 2015; Davis et al., 2003b).

Less well studied are adaptations to the effects of climate change that might reduce heat wave mortality. Adaptation is "adjustment in natural or human systems in response to actual or expected stimuli or their effects, which moderates harm or exploits beneficial opportunities" (Huang et al., 2011; Hess et al., 2012). Adaptive capacity refers to the resources available for adaptation and the ability to use them effectively and efficiently. These resources can come in many forms including social, educational, physical or financial and together form the inputs for adaptation interventions, programs and community actions (White-Newsome et al., 2014; Huang et al., 2011). Access to cooled space may be the most important physical resource imparting adaptive capacity and reducing the risk of heat-related health effects (Harlan et al., 2013; Reid et al., 2012; Ostro et al., 2010; O'neill et al., 2005b). It can come from several sources including air-conditioning at work and home and from publicly accessible cooled spaces such as libraries, commercial venues and public transportation. But simply getting more people to use home air-conditioning is not a panacea as estimates of increasing heat and water shortages may strain the electricity grid's ability to provide power during extreme heat events (Sathaye et al., 2012). Buildings with thermal properties that allow it to heat slower in the sun and maintain cool air within may, besides contributing to environmental sustainability and reducing strain on the power grid, provide further adaptive capacity in the face of extreme heat. Similar to social vulnerability, adaptive capacities and their potential for reducing mortality could vary between regions. For instance, cooling centers that are integrated into a community may be more broadly useful in an extreme heat event than cooling centers that carry the stigma attached to primarily serving the homeless or senior population (Hayden et al., 2011; White-Newsome et al., 2014).

This study focuses on the relationship between social vulnerability and adaptive capacity in Maricopa County, Arizona. Maricopa County includes Phoenix, the second most populous city in the southwestern United States (Los Angeles is the most populous), where summertime temperatures frequently exceed 105 (40.5 °C) F, as well as Mesa, Glendale, Chandler, Scottsdale and Tempe. The daily mean summer temperature in Phoenix, 33 °C (91.4 F), is the highest of all major metropolitan areas in the United States (Petitti et al., 2016). Several studies have addressed aspects of adaptive capacity in Phoenix and Maricopa. One study of three socioeconomically vulnerable Phoenix neighborhoods at potential high risk from extreme heat found access to cooled space was more nuanced than simply having an air conditioner in the home (Hayden et al., 2011). The cost of electricity prevented over 36% of survey respondents from using their air conditioner and an additional 6% reported having a nonfunctional air conditioner. 38% of participants endorsed feeling too hot inside their homes and home renters and Hispanic respondents were significantly more likely to experience this. The authors observed that air conditioner use was "often limited to simply reducing the extreme heat but not necessarily providing relief" [p275]. Hydration and cooling centers were not well used by this sample: Only 9 of 359 respondents had ever used a heat refuge station. Other Phoenix-based surveys, and multi-city studies report that residential air-conditioning may be installed but residents may not turn them on due to the costs of electricity or disliking the feel (Sheridan, 2007; Lane et al., 2014).

Thus, while characteristics of the urban infrastructure such as the availability of residential air conditioners can contribute to heat's impact on health it is necessary to examine other sources of adaptation such as building thermal properties that maintain cool air and retard heating and access to public air-conditioned spaces where one may cool down. For instance, residents living in communities with air-conditioned spaces and buildings that heat slowly might experience less risk as temperatures increase than residents without these protections. Though the thermal properties of buildings, which in this context means the ability of buildings to keep the indoor space cool, has also been offered as a factor in heat mortality we know of little research that has tested this connection (Kovats and Hajat, 2008; Mavrogianni et al., 2012; Anderson et al., 2013). Similarly, individuals cope with extreme heat in a variety of ways. Kalkstein and Sheridan reported that 72% of respondents in their Phoenix survey "went to an air-conditioned location or stayed indoors" on excessively hot days (Kalkstein and Sheridan, 2007). This suggests that one way individuals may cope is by going to publicly available cooled spaces, though the compound nature of their survey question limits any estimation of frequency. On the one hand, the senior centers, libraries, community centers and other community sites that are designated as cooling centers may be distributed sparsely, unevenly and loosely tied to the neighborhoods most in need. Fraser reported that only 2% of Maricopa County, Arizona residents are within walking distance of an official cooling center (Fraser et al., 2016). On the other hand, individuals may seek non-residential, publicly available air conditioned spaces such as shopping malls and libraries. Still, we know of no research examining how differential access to air conditioned public spaces relates to health outcomes, a question we ask in this study. Examining the spatial variation of social vulnerability to heat, a common approach in heat-vulnerability studies, should examine these adaptive capacities that may mitigate vulnerability.

This paper explores the contributions of exposure, susceptibility and adaptive capacity to extreme heat mortality. Specifically, it investigates how susceptibility and adaptive capacity, operationalized as social vulnerability and infrastructure factors respectively, contribute to mortality from extreme heat and whether the relationships between mortality and the social vulnerability and infrastructure factors are sensitive to increasing temperature in Maricopa County, Arizona. The infrastructure factors examined are access to publicly available air conditioned space, home air conditioning and the thermal protective properties of residential buildings. We hypothesized that census tracts with increased social vulnerability, less home air conditioning, less access to publicly available cooled space and lower scores on an index of building thermal protection would have excess heat mortality.

2. Methods

Two outcomes were evaluated: mortality from all internal causes and mortality from heat-related illnesses. All internal causes of mortality is the most frequent overall mortality outcome studied because it is broad enough to capture the full range of causes of death from heat (excessive heat can exacerbate chronic medical conditions thereby leading to death), it provides sufficient power to detect associations and it allows comparison to a wider range of health risk factors. These other causes of death may be more consistently applied by coroners than heat-related illnesses, especially if coroners are more likely to consider heat-related causes during official heat waves than on non-heat wave days (Shen et al., 1998). Studying heat-related illness mortality may capture a different health risk profile than does all-internal causes of mortality since it captures deaths directly attributed to the acute effects of heat exposure or to specific demographic profiles including outdoor workers.

Mortality data came from the Arizona Department of Health Services for 2005–2010. Each record included date of death, the underlying cause and the secondary causes of death. We excluded external causes of death, such as homicide or suicide, except heat related causes. Heat-related mortality was defined as any death which had code X30, exposure to excessive natural heat, and T67, effects of heat and light, listed as either the underlying cause of death or other causes of death (up to 20) on the death certificate. All internal causes of death were those who died of heat-related causes or any of the following causes of death listed as either the underlying cause of death or other causes of death (up to 20): cardiovascular (I00–I99), respiratory (J00–J99), acute kidney failure and chronic kidney disease (N17–N19), disorders of fluid, electrolyte, and acid-base balance (E87), dehydration (E86) and diabetes (E08–E13). These causes increase during heat waves (Basu, 2009; Knowlton et al., 2009; Reid et al., 2012). Frequencies of death from all internal causes and heat-related illness were generated for each census tract per day on the heat days and control days which are defined below (see Fig. 1).

Thirteen census variables previously shown to contribute to social vulnerability during heat waves were selected as the socioeconomic predictor variables (Knowlton et al., 2009; Basu, 2009; Reid et al., 2009; Semenza et al., 1996; Harlan et al., 2006; Petitti et al., 2013; Cooley et al., 2012; Uejio et al., 2011; Chow et al., 2012). The 2012 American Community Survey's 5-year estimates were used to extract census-level data for the 911 census tracts in Maricopa County. The following socioeconomic variables were considered for analysis: percent female householder (no husband present), percent householder living alone, percent householder living alone (>65 years old), percent foreign born, percent who work in construction, percent who work in agriculture, forestry, fishing and hunting, and mining, percent of people whose income in last 12 months is below poverty level, percent of households with no vehicles available, percent 65 years or older, percent Hispanic or Latino, percent uninsured, percent female and percent renter households.

Three infrastructural variables were studied as predictor variables: access to public cooled spaces, home air-conditioning and thermal protection of residential buildings. Fraser et al. (2016) developed an index which describes neighborhood access to publically available cooled space in Maricopa County. This access to cooled spaces index, developed for individual households, considers walkable access to different types of spaces which could provide air-conditioning and heat relief to large numbers of people including official cooling centers, public libraries, shopping malls, museums and restaurants (American Library Association, 2012). The index was based on pedestrian access in order to address the potential challenges those without motorized transportation, a particularly vulnerable population subset, may face in finding air-conditioned relief. In brief, the accessibility metric is based on the distance between any pair of publicly accessible cooled space and individual residential parcels and is defined by three parameters: walking time, walking speed and the existing street network. The 75th percentile for walking duration for non-leisure trips based on data from the National Household Travel Survey, 15 min, was selected as the maximum time for this analysis along with an average walking speed of 3.5 km/h, representing the average walking speed of an elderly adult. Thus, a distance of 0.89 km assessed within a regional road network established the catchment area for each publicly accessible cooled space. ArcGIS's Network Analyst tool generated the catchment areas for every publicly accessible cooling location assuming individuals would select the shortest path. Household-level accessibility measurements were aggregated at the census tract and the mean of household accessibility scores characterizes neighborhood level accessibility. Higher numbers are associated with greater access. Aggregated to the census tract scale, the index demonstrates wide variation in access to cooled spaces with accessibility greater in the older, inner city core of Phoenix and lower in the surrounding suburbs (see Fig. 2). Household central air conditioning was determined using the Maricopa Assessor's database.

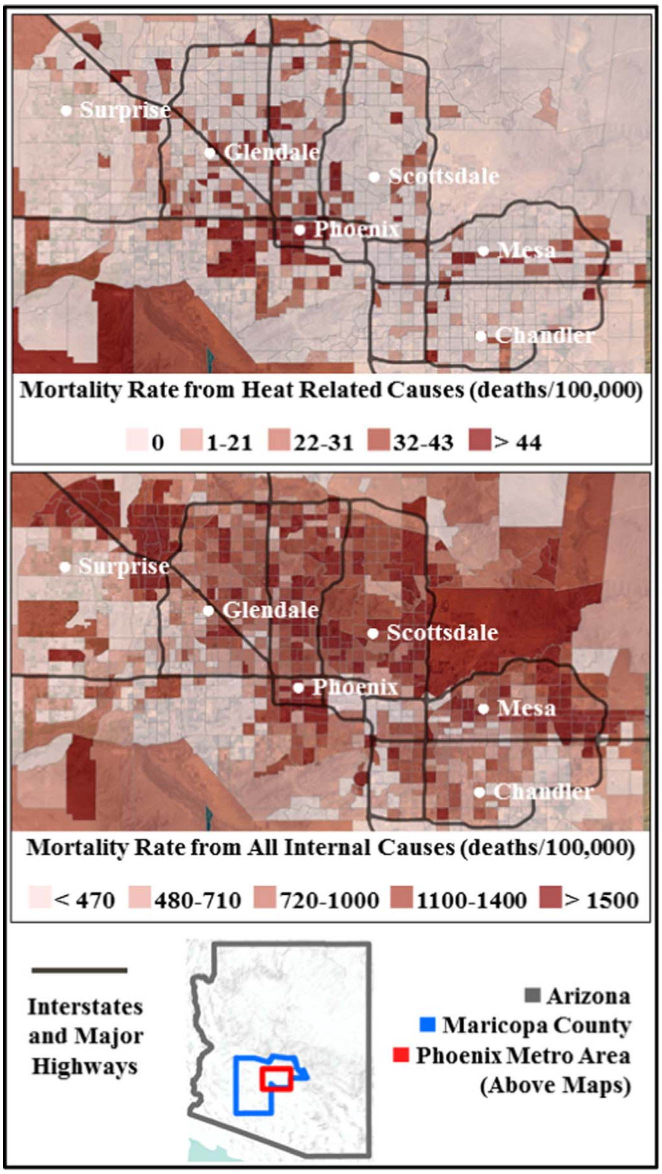

Fig. 1. Mortality rate from heath related causes of death and all internal causes of death by census tract in Maricopa county, 2005–2010.

The thermal protection of residential buildings was measured using a building thermal index of Nahlik et al. The building thermal index can be described as the number of hours it takes for the indoor temperature to reach an unsafe temperature in response to outside air temperature, measured as degrees Celsius per hour. The thermal properties of 39 housing prototypes were assessed

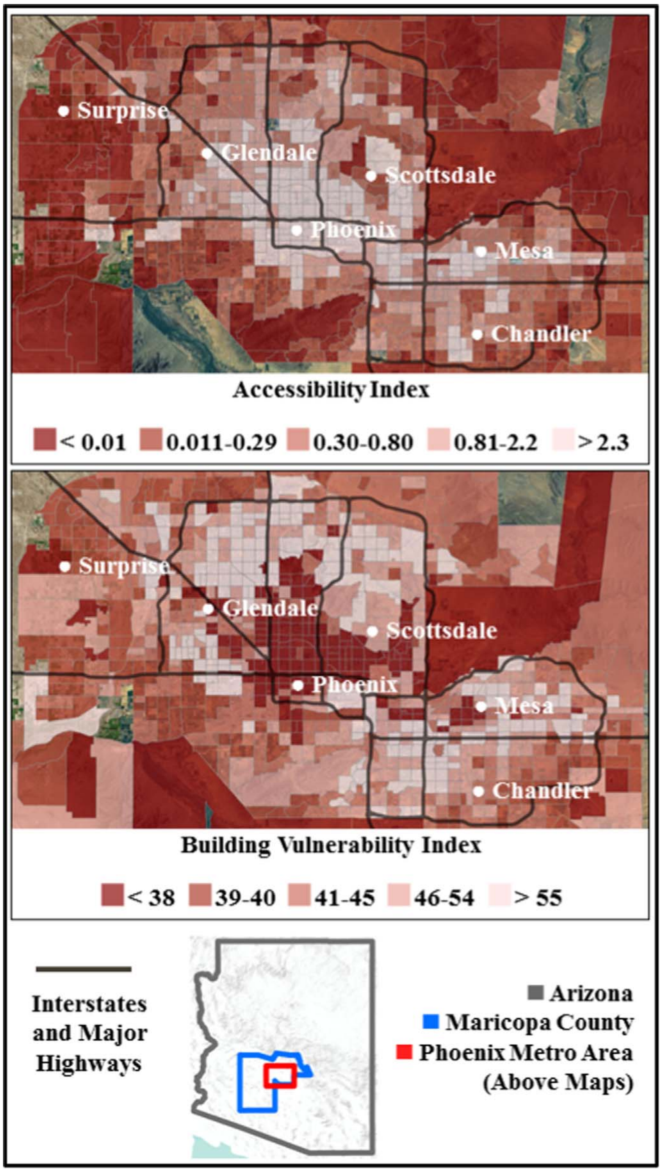

Fig. 2. Accessibility index and building vulnerability index scores by census tract, Maricopa county.

using simulation modeling that measured how building internal temperatures increase in response to outside heat, when air conditioning is not used, in an extreme heat event. A numerical index of building vulnerability was computed and assigned to each of the building prototypes based on the hours elapsed for each structure to increase from 25 to 32 °C (78–90 °F). A greater index value indicates buildings that take longer to warm up during periods of extreme heat and are therefore more protective against extreme heat. Wall materials (concrete block, wood frame), insulation thickness, window panes, attic insulation, roofing material and size of home contribute to its thermal characteristics. The building prototypes were then matched to every equivalent existing building based on building type and vintage to assign a building vulnerability index. Finally, results were aggregated to the census-tract level. Census tracts with the highest building thermal index score are mostly characterized by single family homes, with the census tracts with the highest score, on average, located in the older areas of Maricopa county (see Fig. 2).

Heat events were defined consistent with the simplest definition of extreme heat, which is summertime temperatures that are substantially hotter and/or more humid than the historic average for that location at that time of year (U.S. Centers for Disease Control and Prevention, 2013). We used maximum temperatures since they are well associated with a heat-mortality response, though investigators have also found heat effects with mean daily temperature so it is also likely that the various temperature metrics produce similar results (Chow et al., 2012; Basu, 2009; Anderson and Bell, 2009; Baccini et al., 2008; Michelozzi et al., 2006; Davis et al., 2016). Gridded historical daily temperature data reported at 1/8° (12 km) published by Maurer et al. (2002) were used. Maurer et al. (2002) provide the gridded data through 2010 on a project website. They estimated the gridded temperatures from readings at NOAA Cooperative Observer stations. The station readings were gridded to 12 km cells using the synergraphic mapping system (SYMAP) algorithm. They fit the data using an asymmetric spline to estimate daily maximum and minimum temperatures. Extreme heat events were identified based on the methodology by Meehl and Tebaldi (2004): (a) the 97.5th historical percentile of daily maximum temperature for summertime months (hereafter referred to as T1), and (b) the 81st historical percentile of daily maximum temperature for summertime months (hereafter referred to as T2). Summertime months are June through August. For each grid cell, extreme heat events are identified based on: 1) Maximum daily temperature must be above T1 for at least three consecutive days; 2) The average maximum daily temperature for the period must be greater than or equal to T2; and 3) The maximum daily temperature must be above T2 for every day in the period.

As studies find that heat-health associations diminish after a lag period of three days, we added a lag three days to the end of each heat event to capture any deaths which may have been related to the heat event but did not occur during the heat event (Baccini et al., 2008; Curriero et al., 2002; O'neill et al., 2005a; Davis et al., 2016). If the time between two heat events was three days or less, the lag days would therefore join the two heat events, and it was treated as one single event. For each heat event, a corresponding control period was defined as the period of time in the weeks prior to the heat event of the same number of days on the same days of the week. In the analysis we used the maximum temperature of the day to evaluate the association between outcomes and heat exposure. Only data from heat events and control periods were used in the analysis.

Principal components analysis with varimax rotation was used to construct composite variables from the 13 socio-economic variables. This reduces collinearity and helps avoid over-fitting the regression models. Components were retained based on the Kaiser criterion (eigenvalue > 1).

First, we examined the relationships between the principal components, the three technical infrastructure predictor variables and the two mortality outcomes. Second, we performed regression modeling of mortality from heat-related illnesses and mortality from all internal causes. Because the outcomes are non-negative count variables, Poisson log-linear models based on generalized estimating equations method were used to model the number of deaths per day per census tract in each outcome. No formal spatial correlation was considered in this analysis, however, within census tract correlation was included to account for the repeated measures in the data from the same census tract, similar to previous heat-mortality studies (Ostro et al., 2009; Medina-Ramon and Schwartz, 2007; Uejio et al., 2011). To determine if the relationship between the independent variable and mortality is modified by maximum temperature, the models included the variable, the maximum temperature on that day in that census tract and an interaction between the independent variables and the maximum temperature:

$$\log(\mu_{ij}) = \alpha + \beta_1 * t_{max} + \beta_2 * comp_x + \beta_3 * t_{max} * comp_x$$

where μ_{ij} is the expected number of heat related mortalities in tract i on day j, t_{max} is the maximum temperature in tract i on day j and $comp_x$ is the calculated component score ($x \in 1,2,3,4$).

Using the maximum temperature in the models, instead of an indicator of extreme heat day versus control day, increases the power of detecting the association between outcomes and heat exposure. All models were offset by population size of the census tract to convert to per capita rate. The estimates from the main effect–only models predict the estimated change in expected mortality for a unit risk factor change. For example, a predictor with an estimated IRR of 1.5 indicates that for each one unit increase in the predictor (e.g. Building Thermal Property Index, percent of households with air conditioning, etc.), expected mortality increases by 50%. We standardized the components such that a one unit change in the component is the change of one standard deviation for the component in the study population. For the models considering the interaction of temperature, a positive IRR indicates that the mortality rate increases faster as the maximum temperature increases in census tracts with a higher value of the predictor. For example, an estimated IRR of 1.5 resulting from the interaction between a variable and temperature indicates that as maximum temperature increases by one degree, the rate of mortality increases 50% in census tracts with higher scores for that variable. All results presented are interaction effects, except in the Poisson regressions where all variables are presented.

Stepwise regression of the component scores was used to create the model predicting the relationship of the principal components of the social vulnerability variables to the number of deaths per day. Technical infrastructure variables were added into the model one at a time before building a full model. QIC (quasi-likelihood under the independence model criterion) was calculated to facilitate model comparison. Models with lower QIC are considered better models (Pan, 2001).

3. Results

The final data set of 49,394 census-tract/days (24, 697 census-tract/heat days and an equal number of census-tract/control days) yielded1584 deaths from all-internal causes (814 on heat days and 770 on control days) and 40 deaths from heat-related illness (35 on heat days and 5 on control days).

Four factors were extracted from the social vulnerability variables and together they explained 77% of the variability in the dataset (Table 1). Factor One can be understood as a socioeconomic vulnerability component with the addition of lacking health insurance, working outdoors in construction and female headed households. Factor Two contains persons living alone, renters, and those without vehicles. The commonality among these variables is that they indicate persons at risk for social isolation due to living alone with less connection to their community as renters and potentially less mobile transportation. The first two components explained 60% of the variance. Factor Three is an older aged, female living alone component and Factor Four is an agricultural and extraction industry workers component.

Table 2
Incident Rate Ratios (IRR) with 95% confidence intervals for interaction of variable with maximum temperature,[a] by cause of mortality, Maricopa county, 2005–2010.

Variable	Mortality from all internal causes		Mortality from heat related illness	
	IRR (95%C. I.)	P-value	IRR (95% C. I.)	P-value
Socioeconomic vulnerability (factor 1)	**1.03 (1.00, 1.06)**	**0.03**	**1.17 (1.00, 1.38)**	**0.05**
Renters living alone, without vehicle (factor 2)	0.99 (0.97, 1.01)	0.54	0.91 (0.80, 1.02)	0.11
Older aged, female, living alone (factor 3)	0.99 (0.97, 1.01)	0.29	**0.83 (0.75, 0.92)**	**0.0004**
Agriculture, extraction industry (factor 4)	**0.97 (0.94, 1.00)**	**0.08**	**1.3 (1.01, 1.69)**	**0.04**
No air conditioning	**1.02 (1.00, 1.03)**	**0.01**	1.02 (0.99, 1.04)	0.16
Public cooled space accessibility	1.00 (0.99, 1.01)	0.34	**0.99 (0.98, 1.00)**	**0.03**
Building thermal protection	1.00 (0.99, 1.00)	0.97	1.02 (0.99, 1.04)	0.25

[a] Maximum temperature centered at 40 degrees; IRR=incidence rate ratio; 95% C.I=95% Confidence interval. Each model included predictor variable, maximum temperature, and interaction of variable with maximum temperature. Only the results of the interaction term are presented.

3.1. All-internal causes of mortality

As shown in Table 2, cooled space accessibility did not modify the effect of temperature on all internal causes of mortality (IRR 1.00 95% CI 0.99, 1.01; p=0.34) nor did the building thermal protection index modify the effect of temperature on all internal causes of mortality (IRR 1.00 95% CI 0.99, 1.00; p=0.97). The

Table 1
Principal components from socioeconomic variables.

	Factor 1: socioeconomic vulnerability	Factor 2: renters living alone without vehicle	Factor 3: older age/ female/living alone	Factor 4: agriculture or extraction industry
Percent Hispanic/Latino	**0.90**	0.09	−0.18	0.10
Percent foreign born	**0.84**	0.17	−0.12	0.07
Percent uninsured	**0.82**	0.31	−0.20	0.09
Income below poverty level	**0.76**	0.50	−0.10	0.07
Work in construction	**0.74**	−0.09	−0.06	0.13
Female householder, no husband present	**0.70**	0.10	−0.23	−0.27
Householder living alone	−0.17	**0.84**	0.33	0.01
Percent renter households	0.40	**0.78**	−0.25	−0.08
No vehicles available	0.42	**0.76**	0.05	0.04
Householder living alone > 65 years old	−0.16	0.28	**0.90**	0.08
Percent > 65 years old	−0.28	0.02	**0.88**	0.10
Percent female	−0.05	−0.24	**0.62**	−0.37
Works in agriculture, forestry, fishing, hunting, mining	0.11	−0.03	0.00	**0.88**
Percent of variance explained	41%	19%	9%	8%

Table 3
Incident Rate Ratios (IRR) with 95% confidence intervals for interaction of significant social vulnerability components at given percentiles with maximum temperature.[a]

Mortality cause	Component with percentiles	IRR (95% CI)	P-value
All internal causes	Socioeconomic vulnerability (factor 1)		
	(25th percentile)	0.99 (0.97, 1.01)	0.43
	(75th percentile)	1.02 (0.99, 1.05)	0.08
	(90th percentile)	**1.05 (1.00, 1.09)**	**0.04**
Heat-related illness	Socioeconomic vulnerability (factor 1)		
	(25th percentile)	1.16 (0.90, 1.49)	0.24
	(75th percentile)	1.38 (1.15, 1.66)	0.79
	(90th percentile)	1.58 (1.25, 1.99)	0.27
	Older aged, female, living alone (factor 3)		
	(25th percentile)	**1.51 (1.24, 1.83)**	**< 0.001**
	(75th percentile)	**1.36 (1.12, 1.63)**	**0.002**
	(90th percentile)	**1.20 (0.97, 1.48)**	**0.06**
	Agriculture, extraction industry (factor 4)		
	(25th percentile)	**1.30 (1.06, 1.60)**	**0.01**
	(75th percentile)	**1.43 (1.18, 1.75)**	**< 0.001**
	(90th percentile)	**1.73 (1.31, 2.29)**	**< 0.001**

[a] Maximum temperature centered at 40°.

interaction between maximum temperature and absence of home air conditioning was significantly associated with risk of death from all internal causes (IRR 1.02 95% CI 1.00, 1.03; p=0.01). This means that a one percent rise in the proportion without air-conditioning increases the incidence rate ratio of deaths from all internal causes due to increased maximum temperature by two percent. Socioeconomic vulnerability (factor 1) was also positively associated with all internal causes of mortality in the interaction model (IRR 1.03 95% CI 1.00, 1.06; p=0.03). Table 3 provides the IRR at the 25th, 75th, and 90th percentiles for the factors that have a significant interaction with temperature. As shown in Table 3, the increase is most apparent in census tracts at the 90th percentile of the distribution of factor 1 scores (IRR 1.05 95% CI 1.00, 1.09; p=0.04).

In the multivariable analyses for all internal causes of mortality (Table 4), Model One shows that the interaction between the socioeconomic vulnerability factor and temperature is significantly associated with an increased mortality (IRR=1.02, 95% CI 1.00, 1.05; p=0.047). In other words, as maximum temperature increases, deaths from all internal causes increase more in census tracts with higher index of socioeconomic vulnerability (factor 1). In the full model, as the building thermal protection index increases mortality increases (main effect IRR=1.01, 95% CI 1.00–1.02; p=0.001) but there is no association with the interaction between maximum temperature and building thermal protection. The QIC indicates that the full model has the best fit.

3.2. Heat-related illness mortality

When the outcome was mortality from heat-related illness, there was a significant negative interaction between cooled space accessibility and maximum temperature (IRR=0.99, 95%CI 0.98, 1.00; p=0.03) indicating that mortality from heat related illness increases faster as the maximum temperature increases in census tracts with less cooled space accessibility (Table 2). This is illustrated in Fig. 3.

In census tracts at the 25th percentile of cooled space accessibility, that is census tracts at the lowest end of the distribution, the IRR is 1.38 (95% CI=1.12, 1.69; p=0.002), indicating that for every increase in maximum temperature by one degree Celsius, there was a 38% increase in deaths from heat-related illness. In census tracts at the 75th percentile, that is census tracts with

Table 4
Mortality from all internal causes: Incident Rate Ratios (IRR) with 95% confidence intervals from Poisson multivariate regression, Maricopa county, 2005–2010.

	Model 1: socio-vulnerability+air conditioning		Model 2: socio-vulnerability+cool space access		Model 3: socio-vulnerability+building thermal protection		Model 4: full model	
Variable[a]	IRR (95% CI)	P-value	IRR (95% CI)	P-value	IRR (95% CI)	P-value	IRR (95% CI)	P-value
Socioeconomic vulnerability (factor 1)	0.92 (0.82, 1.02)	0.106	**0.90 (0.82, 1.00)**	**0.043**	**0.89 (0.80, 0.98)**	**0.024**	0.90 (0.81, 1.00)	0.054
Renters living alone, without vehicle (factor 2)	**1.35 (1.25, 1.47)**	**< 0.001**	**1.31 (1.19, 1.44)**	**< 0.001**	**1.40 (1.29, 1.52)**	**< 0.001**	**1.40 (1.29, 1.52)**	**< 0.001**
Older aged, female, living alone (factor 3)	**1.74 (1.63, 1.85)**	**< 0.001**	**1.75 (1.64, 1.86)**	**< 0.001**	**1.71 (1.60, 1.82)**	**< 0.001**	**1.71 (1.61, 1.82)**	**< 0.001**
Agriculture, extraction industry (factor 4)	1.06 (0.94, 1.19)	0.334	1.05 (0.94, 1.18)	0.420	1.03 (0.92, 1.15)	0.613	1.04 (0.93, 1.16)	0.542
Tmax[b]	1.00 (0.98, 1.02)	0.831	1.00 (0.98, 1.02)	0.975	1.01 (0.92, 1.11)	0.854	1.00 (0.98, 1.02)	0.971
Factor 1 × Tmax	**1.02 (1.00, 1.05)**	**0.047**	**1.03 (1.00, 1.06)**	**0.024**	**1.03 (1.01, 1.06)**	**0.012**	**1.03 (1.00, 1.06)**	**0.040**
Factor 4 × Tmax	**0.96 (0.93, 0.99)**	**0.003**	**0.96 (0.93, 0.99)**	**0.005**	**0.97 (0.94, 1.00)**	**0.034**	**0.97 (0.94, 1.00)**	**0.020**
No air conditioning	0.95 (0.89, 1.01)	0.103					0.96 (0.91, 1.02)	0.202
No air conditioning × Tmax	1.01 (1.00, 1.03)	0.093					1.01 (1.00, 1.03)	0.118
Cooled space accessibility			1.01 (0.99, 1.05)	0.349				–
Cooled space accessibility × Tmax			1.00 (0.99, 1.01)	0.752				–
Building thermal protection					**1.01 (1.00, 1.02)**	**0.002**	**1.01 (1.00, 1.02)**	**0.001**
Building thermal protection × Tmax					0.99 (0.99, 1.00)	0.895		–
QIC	13,760.3		13,794.0		13,730.1		13,700.1	

[a] Missing components and variables were not chosen by model building procedure.

[b] Maximum temperature (Tmax) centered at 40°.

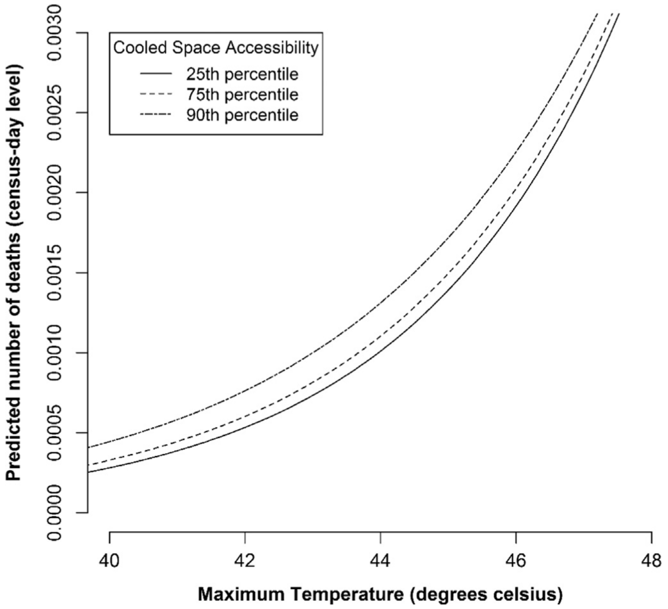

Fig. 3. Effect of cooled space accessibility and temperature on heat-related deaths in Maricopa county.

relatively greater accessibility, the IRR was 1.36 (95% CI = 1.11, 1.66; p = 0.003) and at the 90th percentile of cooled space accessibility, the IRR was 1.31 (95% CI = 1.07, 1.60; p = 0.007). In contrast, we found no association between the interaction of maximum temperature with households without air-conditioning and mortality from heat-related illness (Table 2).

There was a significant negative interaction between the older aged female living alone factor, and maximum temperature (IRR = 0.83; 95%CI 0.75-0.92; P-value < 0.001) indicating that the rate of mortality from heat-related illnesses increases *more slowly* as the maximum temperature increases among census tracts with more older aged females living alone (Table 2). In other words, census tracts with a larger proportion of older aged females living alone experienced less of a rise in fatalities as maximum temperatures increased than did tracts with smaller proportions of this group. As shown in Table 3 and illustrated in Fig. 4, in census tracts at the 25th percentile of the older aged female living alone factor, the IRR was 1.51 (95% CI = 1.24, 1.83; p < 0.001), indicating that for every degree Celsius increase in maximum temperature, there was a 51% increase in deaths from heat-related illness. In census tracts at the 75th percentile, the IRR was lower, 1.36 (95% CI = 1.12, 1.63; p = 0.002), and in census tracts at the 90th percentile of the older aged female living alone factor—that is census tracts with the greatest proportion of older aged females living alone, the IRR was still lower, 1.20 (95% CI = 0.97, 1.48; p = 0.06).

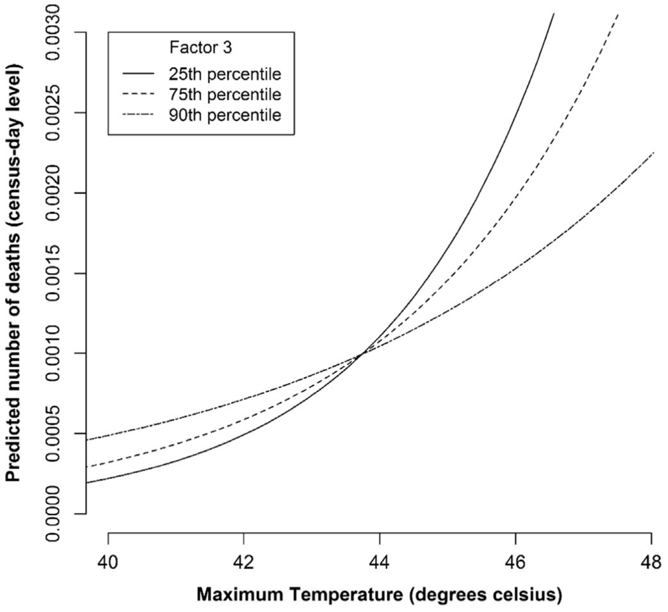

Fig. 4. Effect of factor 3 and temperature on heat-related deaths in Maricopa county.

The interactions between maximum temperature and the socioeconomic vulnerability factor (IRR = 1.17, 95%CI 1.00, 1.38; p = 0.05) and agriculture/extraction industry factor (IRR = 1.30, 95% CI 1.01, 1.69; p = 0.04) were associated with increased mortality from heat-related illness (Table 3). As shown in Table 3, census tracts in the 90th percentile of the distribution of the agriculture/extraction industry factor have significantly greater death from heat-related illnesses compared to census tracts in the 75th and 25th percentiles.

In the multivariable analysis of mortality from heat related illnesses (Table 5), Model One shows socioeconomic vulnerability and advanced aged females living alone are positive main effect predictors of heat related illness mortality and that the interaction between agricultural/extraction worker and temperature leads to increased mortality from heat-related illnesses (IRR = 1.33, 95%CI 1.05, 1.69; p = 0.020). As maximum temperature increases mortality from heat related illnesses increases more in census tracts with higher agricultural/extraction worker indices. In contrast, as maximum temperature increases, mortality from heat related illnesses increases less in census tracts with higher advanced aged females living alone indices (IRR = 0.86, 95% CI 0.79, 0.95; p = 0.002). The direction and magnitude of the factors three and four interaction results do not change as further infrastructure variables are added into the model. Model Two shows that the interaction between accessible cooled spaces and temperature reduces the risk of death from heat-related illnesses (IRR = 0.98, 95%CI 0.96, 1.00; p = 0.024). In other words, as maximum temperature increases, increasing access to public cooled spaces is associated with slower increases in the mortality rate from heat related illnesses, controlling for the social vulnerability of a census tract. The QIC indicates that Model Two has the best fit. Model Three shows that building thermal protection is not a predictor of mortality from heat related illness when controlling for social vulnerability. The importance of all the social vulnerability factors to heat-related illness mortality did not change across all models.

4. Discussion

We found mixed support for the hypothesis that three infrastructure resources that could provide adaptive capacity in Maricopa County reduce mortality in extreme heat events. As maximum temperature increases, mortality from heat-related illness increased less in census tracts with more publicly accessible cooled spaces, controlling for social vulnerability (IRR 0.98, 95% CI 0.980, 0.999; p = 0.027). This suggests that publicly accessible cooled space provides adaptive capacity when the metric is mortality from heat-related illness.

However, publicly accessible cooled space is not significantly associated with all internal causes of mortality as maximum temperatures increase. Indeed, throughout our analyses, the results differed based on the cause of mortality used as an outcome, consistent with research showing that the heat-health relationship depends on the health outcome assessed (Kovats et al., 2004; Petitti et al., 2016). One explanation for these discrepant findings is that the all-internal cause grouping may be too non-specific to sensitively detect heat-related protective factors (Petitti et al.,

Table 5
Mortality from heat related illness: Incident Rate Ratios (IRR) from Poisson multivariate regression. Maricopa county, 2005–2010.

	Model 1: socio-vulnerability + air conditioning		**Model 2: socio-vulnerability + cool space access**		**Model 3: socio-vulnerability + building thermal protection**		**Model 4: full model**	
Variable[a]	**IRR (95% CI)**	**P-value**	**IRR (95% CI)**	**P-value**	**IRR (95% CI)**	**P-value**	**IRR (95% CI)**	**P-value**
Socioeconomic vulnerability (factor 1)	**1.64 (1.17, 2.30)**	**0.004**	**1.70 (1.24, 2.31)**	**0.001**	**1.71 (1.22, 2.39)**	**0.002**	**1.73 (1.23, 2.44)**	**0.002**
Renters living alone, without vehicle (factor 2)	1.20 (0.80, 1.80)	0.380	1.12 (0.72, 1.73)	0.627	1.11 (0.75, 1.63)	0.598	1.05 (0.68, 1.61)	0.823
Older aged, female, living alone (factor 3)	**2.27 (1.50, 3.44)**	**0.001**	**2.40 (1.58, 3.64)**	< **0.001**	**2.53 (1.68, 3.82)**	< **0.001**	**2.52 (1.66, 3.84)**	< **0.001**
Agriculture, extraction industry (factor 4)	**0.17 (0.03, 0.97)**	**0.045**	0.17 (0.02, 1.19)	0.073	**0.18 (0.03, 1.00)**	**0.050**	0.16 (0.02. 1.11)	0.064
Tmax[b]	**1.42 (1.16, 1.72)**	**0.001**	**1.49 (1.22, 1.81)**	< **0.001**	0.84 (0.43, 1.65)	0.620	**1.50 (1.23. 1.83)**	< **0.001**
Factor 3 × Tmax	**0.86 (0.79, 0.95)**	**0.002**	**0.85 (0.77, 0.94)**	**0.002**	**0.85 (0.77, 0.94)**	**0.001**	**0.85 (0.77, 0.94)**	**0.002**
Factor 4 × Tmax	**1.33 (1.05, 1.69)**	**0.020**	**1.34 (1.03, 1.75)**	**0.028**	**1.33 (1.06, 1.67)**	**0.016**	**1.34 (1.04, 1.74)**	**0.023**
No air conditioning	1.05 (0.92, 1.21)	0.450						
No air conditioning × Tmax	1.00 (0.98, 1.03)	0.792						
Cooled space accessibility			**1.12 (1.04, 1.22)**	**0.005**			**1.11 (1.00, 1.22)**	**0.042**
Cooled space accessibility × Tmax			**0.98 (0.96, 1.00)**	**0.024**			**0.98 (0.96, 1.00)**	**0.030**
Building thermal protection					0.92 (0.85, 1.00)	0.052	0.97 (0.94, 1.01)	0.146
Building thermal protection × Tmax					1.01 (1.00, 1.03)	0.146		
QIC	603.9		593.1		597.6		620.2	

[a] Missing components and variables were not chosen by model building procedure.

[b] Maximum temperature (Tmax) centered at 40°.

2016). Mortality from heat-related illness will be directly dependent on increasing maximum temperature whereas all-internal causes of mortality may be exacerbated by high heat but may not be directly dependent on it. Another possibility is that “officially” designated extreme heat events may prompt urban residents to use cooled spaces such as libraries and malls at the same time as official announcements alert coroners to heat-related deaths that would be otherwise misclassified (Shen et al., 1998). However, one survey of public responses to extreme heat found only 14% of respondents from Phoenix reported going to a “cooler place” on a hot day (Sheridan, 2007). Therefore, while use of publicly accessible cooled spaces cannot be inferred from these results, our results hint that access to this resource can reduce risk to socially vulnerable populations.

The building thermal protection index was not associated with mortality in our analyses. In the multivariate models, census tracts with buildings that are slower to heat up showed a decrease in heat-related illness mortality (fixed effect IRR 0.92, 95%CI 0.85, 1.00; $p=0.052$) and an increase in all internal causes of mortality (fixed effect IRR 1.01, 95%CI 1.00, 1.02; $p=0.002$) but the interactions with maximum temperature were not significant, thereby calling into question the meaning of the fixed effect findings. We would expect that the relationship between building thermal properties and heat-related mortality would be sensitive to increasing maximum temperature; the environmental benefits of buildings maintaining cool temperatures longer might translate to mortality benefits, too. Research has shown a correlation between older and poorer housing stock and increased mortality from extreme heat (Uejio et al., 2011; Klein Rosenthal et al., 2014). And Hayden's report that 89% of their survey respondents had air conditioning but 38% still experienced their homes as too hot inside suggests a protective benefit in improving thermal properties (Hayden et al., 2011). But studies addressing the relationship of the thermal envelope of a building to adverse events have not been conducted until now. The buildings that heat up the quickest in Maricopa County are the older single family homes that are concentrated in the older, central neighborhoods where poverty is also concentrated, which may explain the fixed effect relationship to all-internal causes of mortality. The relationship between this adaptive functioning of a building's thermal protection and social vulnerability at the census tract level is likely complex and may include factors we did not measure such as the willingness to use air-conditioning in the home. Also, the building index does not consider the contributions of building orientation or tree cover to potential cooling (Jenerette et al., 2011; Jenerette et al., 2007).

The interaction of not having air conditioning with increasing temperature was a significant predictor of all internal causes of mortality in the bivariate but not the multivariate models. In the multivariate models predicting mortality from all internal causes, the protective benefit of air conditioning was moderated by the social vulnerability factors. One implication is that any effort to reduce heat-mortality in Maricopa County by increasing air-conditioning availability must focus on the barriers to using air-conditioning. Previous research in Phoenix supports this (Hayden et al., 2011; Sheridan, 2007). Current programs to provide air conditioning to residents on fixed incomes are reported to reach less than half of those requesting service (White-Newsome et al., 2014).

Factors 1, 3 and 4 were associated with mortality though sometimes in surprising directions. Socioeconomic vulnerability (factor 1) was associated with mortality from all internal causes and heat related illnesses as temperature increases and it was robust to adjustment in the multivariate models. In contrast, the interaction of maximum temperature with the older aged/living alone factor reduces the risk of mortality from heat-related illness, an interaction effect not previously demonstrated. The effect of increasing maximum temperature on heat-related illness mortality declines as the proportion of a census tract that is female, age over 65 and living alone increases; census tracts with higher proportions have less sensitivity to increasing heat than census tracts with lesser proportions. Few studies have investigated if the relationship between a predictor variable and mortality is dependent on temperature, which has the advantage of addressing relationships to continuous temperature that would be missed by restricting the analysis to the absolute categories of heat days and control days. This captures how sensitive the variables are to increasing temperature. For example, regarding the fixed effect IRR, the older aged/living alone factor was positively associated with increased mortality from all internal causes and heat-related illness in the multivariate analyses. This is consistent with Harlan and colleagues' finding that a factor made up of advanced age, living alone and the interaction of age and living alone predicted heat-related death in Phoenix (Harlan et al., 2013). Hondula also reported that a factor comprised of percent living alone, percent living alone over age 65 and medium intensity development predicted excess mortality in Phoenix (Hondula et al., 2015). Lastly, Chuang's study in Phoenix also found that a factor containing proportion of elderly and rate of hospitalization for diabetes predicted heat-related hospitalizations(Chuang and Gober, 2015). But, our interaction results are also consistent with findings that the number of heat distress calls was inversely related to the proportion of older residents in a census block group in Phoenix (Uejio et al., 2011). These results suggest that adaptations in Phoenix may be having some benefit, though which adaptations cannot be discerned. For instance, as part of the city's heat health warning system, emergency managers contact assisted living facilities with warnings. Also, Phoenix has many retirement communities including communities where age specific zoning restrictions mandate every household must include an older adult (Gober, 2006). The city has a public information campaign each summer in which “the big thing with the seniors is watch out for your neighbors so you know if you don't see your neighbor” (White-Newsome et al., 2014). It is possible that some combination of protective behaviors (including traveling to cooler climates, so called “snowbirds”), social networks and social service resources among Phoenix's seniors, retirement communities and assisted living facilities may explain these findings. Thus, this study raises all new questions for research into adaptations for extreme heat.

As for the agricultural/extraction industry worker factor, our study confirms and extends prior findings of an association between heat-related mortality and outdoor workers (Petitti et al., 2013; Davis et al., 2003a). Not only was mortality from heat-related illness higher in census tracts with more such workers, but as maximum temperature increased excess mortality from heat-related illness increased too. This association remained robust adjusting for the other social vulnerability components. We were surprised to find a negative interaction between the agricultural/extraction industry worker factor and maximum temperature in the multivariate models of all internal causes of mortality. As with the results of the older aged/living alone factor, further inquiry is needed to understand the finding.

There are several limitations to our analysis. We did not assess the predictive ability of our models, though vulnerability models have mixed success in predicting heat-related mortality (Reid et al., 2012). The small number of deaths from heat-illness further limits our ability to make meaningful predictions. However, the relationship between heat and health is complex such that temperature-mortality relationships may differ depending on the health event measured. Petitti and colleagues found that mortality from the direct effects of heat consistently occurred at lower temperatures than did all-cause mortality in Maricopa County (Petitti et al., 2016). Accessible cooled spaces and official cooling centers may be particularly important for the homeless and our measure of accessibility, based on residential parcels, cannot capture accessibility for the homeless. It is not uncommon in Phoenix for homeless persons to ride the air-conditioned public transit for heat relief (Sanchez, 2011). The census variables used to define vulnerability are also coarse indicators of vulnerability. While being older than 65 years may confer statistically significant risk, clinically meaningful risk may occur mostly to frail elderly over 75, or older ages, such as 85 and older. Living alone may be an inadequate proxy for the level of social isolation that elder "shut-ins" face (Klinenberg, 2002; Bassil and Cole, 2010; Foroni et al., 2007). Lastly, while this analysis provides census-level associations that may be useful for community planning, it does not necessarily explain individual-level factors. Nesting individual factors inside group level factors would provide a more nuanced understanding of the interaction between vulnerable residents and vulnerable neighborhoods.

This study has implications for public health adaptation planning. To reduce heat-related mortality, the use of public cooled spaces might be expanded to target the most vulnerable. More research is needed to understand how publicly accessible cooled spaces might become a feasible and acceptable element of adaptation planning. Community programs that mobilize residents to public spaces, such as occurs in city parks and during bicycle events are increasingly used in public health and civic engagement. Such programs might hold the ingredients for designing a private-public partnership program that gets people from vulnerable neighborhoods into public cooled spaces such as shopping malls during extreme heat days. Getting more people to use their home air-conditioning during extreme heat days is a worthy adaptation for short-term responses to these events but it is coming under increasing scrutiny as a long-term adaptation (Hess et al., 2012). Extreme heat of increasing frequency, duration and severity combined with predictions of Southwest water shortages raises the danger of grid failure. The risk increases still further when one considers the hazards posed by wildfires at the urban-wilderness interface occurring during times of drought and extreme heat and threatening electrical grids. The protective effect of increasing the concentration of older aged adults living alone in a census tract raises interesting possibilities that adaptive behaviors are at work that have not previously been captured. Understanding the adaptive behaviors could enhance public health and safety programs for extreme heat.

5. Conclusions

We studied three elements of the infrastructure of Maricopa County to examine their potential benefit as adaptive resources to extreme heat and found mixed results. As temperatures increase, mortality from heat-related illnesses in a census tract decreases with increasing accessibility to publicly available cooled spaces. However, the mortality from all-internal causes was not associated with improved access. Nor did an index measuring the thermal ability of a building to remain cool in the heat relate to mortality with increasing temperature. Mortality rates increase as temperature increases in Maricopa County census tracts that have higher proportions of Hispanic households living in poverty and without health insurance. This association is not ameliorated as the proportion of households with air-conditioning increases, which further supports the need to remove social and financial obstacles to air-conditioner use in these neighborhoods. As the proportion of a census tract that is older aged females living alone increases, the effect of increasing temperature on mortality rates from heat-related illness decreases and this relationship is similarly true for agricultural workers and all-internal causes of mortality. These two surprising findings call for more fine-grained studies looking for the potential adaptive mechanisms at work. Overall, this study highlights the value of research on the interplay between vulnerability and adaptive capacity at the city-level and the need to uncover the adaptive capacities already in play in our cities.

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