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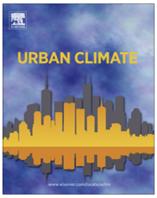

Sensitivity to heat: A comparative study of Phoenix, Arizona and Chicago, Illinois (2003–2006)

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ABSTRACT

Research on how heat impacts human health has increased as climate change threatens to raise temperatures to new extremes. Excessive heat exposure increases death rates, as well as rates of nonfatal, adverse health outcomes. This study used the negative binomial regression model to examine the relationship between daily maximum temperature, heat index, and heat-related emergency calls in Phoenix, Arizona and Chicago, Illinois, from 2003 to 2006. Using model results, we estimated call volumes in a warmer climate, with temperature increase from 1 to 5.5 °C. We found that: (1) heat-stress calls increase sharply when the temperature exceeds about 35 °C in Chicago and in 45 °C Phoenix; (2) warmer climate could seriously threaten human health and existing emergency response system in Chicago more than in Phoenix. Policies to reduce heat impacts in Phoenix should focus on reducing prolonged heat exposure, while Chicago should build a strong early-warning system for extreme heat events and provide sufficient resources and infrastructure to mitigate heat stress during those events.

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1. Introduction

Health and climatological researchers are concerned about the adverse health effects associated with warmer temperatures resulting from climate change, and the impact of climate change on heat-related morbidity and mortality (Huang et al., 2011; Thacker et al., 2008). In the United States of America (USA), the total number of deaths resulting from excessive heat far exceeds the number due to other natural hazards (Thacker et al., 2008). The health impacts of excessive heat are expected to increase with the more frequent, intense, and longer-lasting heat waves predicted to result from climate change (Huang et al., 2011; Knowlton et al., 2007; Meehl and Tebaldi, 2004; Patz, 2005). Indeed, the twelve months between June 2011 and May 2012 comprised the warmest year in the contiguous United States since 1895 (National Climatic Data Center, 2012). Heat waves will likely have the most significant impacts in urban areas, where large numbers of vulnerable people reside and where local-scale urban heat island effects (UHI) both retard nighttime cooling and increase city warmth.

To mitigate the health effects of increasing temperatures, we need to know: (1) which populations of a city are at greatest risk, (2) how sensitive these populations are to temperature increase, and (3) what measures can be taken to prevent heat-related illness and death. Research studies have evaluated and predicted how climate change influences the health of urban residents, both in cities throughout in the US (Kalkstein and Greene, 1997; Medina-Ramón and Schwartz, 2007; Sheridan et al., 2009, 2012; Greene et al., 2011; Hayhoe et al., 2010). These studies found that heat impact on mortality varies among cities and among different populations within cities. Large-scale studies that analyzed more than ten cities in different climate regimes confirmed that people in warm-climate areas are more acclimatized to heat (Medina-Ramón and Schwartz, 2007; Curriero et al., 2002), and predicted that the majority of heat-related deaths due to climate change will occur in Southeastern and Northeastern cities in the US (Greene et al., 2011). City-specific climate-mortality analyses complement research on regional and national scales. They emphasize sensitivity and adaptive capacities in a local context, yielding information that can help municipal governments implement interventions to reduce heat-related illness and death.

Little information is available to help municipal governments evaluate their current capacity for coping with heat or design adequate emergency-preparedness plans (although some researchers have suggested that increasing emergency-medical-service staffing is an effective heat mitigation strategy (Sheridan and Kalkstein, 2004). With climate change likely to exacerbate heat impacts on human health in the near future, cities need to become better prepared not only to respond to, but also to avoid, heat-induced emergencies. Our study used heat-related emergency calls as an indicator of heat-related illness in two cities in different climate zones (Phoenix, AZ, and Chicago, IL), to identify the temperature thresholds at which heat has widespread negative health impacts in each city. Because every city has unique social and physical environments, the temperature threshold varies among cities. If municipal governments were aware of the critical temperature at which heat causes health emergencies, they could plan more effectively to mitigate the effects of extreme heat on health, and to provide health- and life-saving responses to their residents. Planning for such measures as heat-wave warning systems, changes in the built environment, and care for vulnerable populations could be strengthened with knowledge of how often and when heat is likely to become a threat to health and life.

2. Theory and literature review

Although many researchers have examined the impact of heat on human health in case studies of individual cities (Vaneckova et al., 2010; Dolney and Sheridan, 2006; Metzger et al., 2010; Johnson and Wilson, 2009; Alessandrini et al., 2011), few have compared the heat slopes and threshold temperatures below which adverse health outcomes remain at a minimum, as we did in our study. Research on climate-related death and illness in urban areas seems to fall into three major categories. Studies in the first category investigated the historical exposure–response (or dose–response) relationship of temperature and health consequences (Curriero et al., 2002; Alessandrini et al., 2011; Braga et al., 2001; Davis et al., 2003; Medina-Ramón and Schwartz, 2007), and/or identified the *threshold temperature* at which death rates are lowest (Honda et al., 2006; Kosatsky et al., 2006). They identified the association between temperature and mortality and considered the effects of both heat and cold on human health. Most found the temperature-mortality relationship to be nonlinear, with U, V, or J shapes (Kinney et al., 2008; O'Neill and Ebi, 2009). The location of the low point of the curve, called the minimum mortality threshold, can be an indicator of adaptive capacity or acclimatization, and it varies by location. Higher minimum thresholds imply that the population is better adapted to heat, i.e., can tolerate a higher temperature while experiencing a lower number of adverse health outcomes. One study found that among 50 US cities, heat effects in the hottest cities were much lower than those in cities with mild summers (Medina-Ramón and Schwartz, 2007).

Studies in the second category concluded that not all urban populations are equally at risk from heat: human vulnerability to heat depends to some extent on the physical and social structure of the city. Humans can acclimatize to heat behaviorally (e.g., by foregoing outdoor activities) and culturally (e.g., by mitigating heat with air conditioning or changes in building design), as well as physiologically (Kovats, 2008); this thread of research examines how altering behavior or culture affects vulnerability. For example, Curriero et al. (2002) found that the proportion of a city's population without a high school degree and the proportion living in poverty both correlated with mortality during extreme-weather events. They also found that weather-related mortality decreased with a higher prevalence of air conditioning (or heating) and a lower number of elderly residents. A sociological study of the 1995 Chicago heat wave, which took more than 700 lives, found that elderly people who lived alone were at a higher risk of death during the heat wave than those living in a family or group environment (Klinenberg, 2002). Studies in the second category also found evidence that environmental, socioeconomic, and demographic risk factors affect the capacity of urban populations to *adapt to changes* in climate, and that these risk factors are not evenly distributed throughout the population (Bassil et al., 2009; Chow et al., 2012a; Harlan et al., 2006; Reid et al., 2009; Uejio et al., 2011). For example, a study in metropolitan Phoenix (Chow et al., 2012a) found heat vulnerability to be unevenly distributed, with a changing ''heat landscape'' from1990 to 2000, and increasing vulnerability of Hispanics to heat stress due to demographic-pattern change and intensified UHI effects in traditionally minority neighborhoods.

Studies in the third category predicted the health consequences of a warmer future climate (Knowlton et al., 2007; Greene et al., 2011; Hayhoe et al., 2010; Sheridan et al., 2012; Baccini et al., 2011; Cheng et al., 2008; Dessai, 2003; Doherty et al., 2009; Gosling et al., 2009; Jackson et al., 2010; Takahashi et al., 2007). For example, one study (Martens, 1998) used the projected mean temperatures of 20 cities from three General Circulation Models (GCMs) to estimate changes in mortality rate due to temperature exposure, and concluded that global climate change will likely reduce mortality rates by decreasing death rates in winter in most of the study cities. Elderly people in cold climates would especially benefit, because of lower cardiovascular mortality rates during warmer winters. But subsequent studies, using data from as many as 50 U.S. cities, argued that the predicted drop in winter mortality rate would not compensate for increased summer mortality (Kalkstein and Greene, 1997; Medina-Ramón and Schwartz, 2007).

Some studies have taken a synoptic climatological or spatial synoptic classification (SSC) approach, which classifies weather conditions into different air-mass categories, to predict future relationships between climate and mortality. These approaches use a suite of meteorological conditions, including humidity, cloud cover, and wind speed, to represent an environment's weather conditions more accurately than temperature alone does (Greene et al., 2011; Hayhoe et al., 2010; Sheridan et al., 2009; Kyselý and Huth, 2004; Kalkstein et al., 2008). Greene et al. (2011) simulated future climate conditions and mortality in 40 large US cites. Their results suggested that Southeastern and Northeastern cities would suffer a significant increase in both excessive heat events and heat-attributable mortality by the end of the twenty-first century, as the impact of climate change intensifies. Hayhoe et al. (2010) confirmed these findings in a case study of Chicago. They quantified the relationship between air mass and heat-related mortality in Chicago from 1961–1990, and applied three GCMs and two emission scenarios to estimate future mortality rates. Their results indicate that by the end of this century, Chicago's annual average heat-related mortality rate will be twice the 1995 level under the higher emission scenarios.

While such scenario-based research has helped policymakers to better understand the uncertainties surrounding heat-related mortality and to anticipate the range of possible future death rates, little research has studied the effect of a warmer climate on heat-related *illness,* which is a precursor of heat-related death. Heat stroke has a high case-mortality ratio, and progression to death can be rapid. If we could anticipate the incidence of heat-related illness, we could plan strategic and aggressive interventions to prevent such illness from progressing to mortality. Our cross-site comparison of heat slopes and estimates of heat-related illness provide a framework for assessing future heat impacts, and the need for context-based adaptation, in individual cities.

3. Materials and methods

3.1. Study areas

3.1.1. Phoenix, Arizona

The most populous city in Arizona, Phoenix is located in the Sonoran Desert in the southwestern United States. It has a hot, arid climate (Koppen classification *Bwh*) with extremely hot summers; the average maximum temperature in July is 41.0 °C(105.8°F). June is typically hot and dry, while July brings the monsoon season and increased humidity. Average annual precipitation (1971–2000) is low; about 21.1 cm (8.3 inches) at Phoenix Sky Harbor Airport (Arizona Department of Water Resources, 2012). The extreme desert climate has not, however, hindered the city's growth. The widespread use of air conditioning after 1950, along with a growing dependable water supply, made it possible for Phoenix to grow and take on characteristics of an oasis city. Phoenix was one of the first US cities to embrace evaporative-cooling and air-conditioning technologies, which became standard in housing built after World War II (Gober, 2005).

Phoenix's population grew rapidly after 1945, from 65,000 in 1940 to 582,000 in 1970 (Gober, 2005). Today, Phoenix is the sixth most-populous city in the US, with 1.5 million residents living within its 517 square miles. Phoenix has a low population density compared to most other major metropolitan areas in the US: in 2010 it was 2,798 people per square mile. Demographically, the population is nearly evenly divided between two groups, Hispanics (40.8 percent) and non-Hispanic whites (46.5 percent). The remaining population is comprised of African-Americans (6.5 percent), Asians (3.2 percent), American Indians and Alaska Natives (3.2 percent), and Native Hawaiians and other Pacific Islanders (0.2 percent) (US Census Bureau, 2012).

Since 1950, the Phoenix metropolitan area has undergone extensive land-cover and land-use change. Small individual city centers surrounded by agricultural land have merged into a large urban metropolis. Rapid urbanization has caused many environmental problems that threaten the area's long-term sustainability, including limited water resources, loss of native biodiversity, and an expanding urban heat island (UHI–the phenomenon of higher temperatures in the urban core than in outlying rural surroundings). Since 1990, the UHI effect has expanded and intensified, exacerbating already-extreme heat and raising nighttime temperatures by more than 6.0 °C(Baker et al., 2002).

3.1.2. Chicago, Illinois

Chicago is the largest city on the Great Lakes and the third largest city in the US; it has a hot-summer continental climate (Koppen classification *Dfa*). Although a much cooler city than Phoenix, Chicago was the site of a deadly heat wave in 1995, making it a useful area in which to study the relationship between heat and morbidity. As a cold-region city, Chicago provides a good counterpoint to Phoenix.

The average maximum July temperature is 29.4 °C (84.9°F), 11.6 °C lower than Phoenix. Average annual precipitation is about 93.7 cm (36.9 inches), four times greater than in Phoenix. The monthly average humidity in Chicago is constantly high, between 66 and 75 percent compared to 25 to 50 percent in Phoenix. Chicago's 2.7 million people reside on 234 square miles of land, resulting in a population density of 11,864 people per square mile, nearly four times that of Phoenix (US Census Bureau, 2012). Compared to Phoenix, Chicago is a relatively old city, with a high-density urban center and low-density suburban areas. Non-Hispanic whites comprise 31.7 percent of Chicago's population, African-Americans 33.0 percent, and Hispanics 28.9 percent. Chicago's UHI effect is milder than Phoenix's, due to the proximity of Lake Michigan. The temperature gradient between Chicago's western suburbs and core downtown area is, on average, 1.7 °C to 2.8 °C (3~5°F) (EPA, 2009).

Chicago has a long history of segregation, poverty issues, and high crime-rates in poor neighborhoods—all obstacles to strong social networks and support, which are critical factors when it comes to adapting to heat stress (Klinenberg, 2002; Harlan et al., 2006). In an analysis of deaths from the 1995 heat wave, Klinenberg, (2002) concluded that the social structure in Chicago exacerbated the outcomes of the heat wave. Those most vulnerable to the heat wave were low-income African-Americans, the elderly, and those living alone in high-crime areas.

3.2. Data

We used historical temperature and heat-stress emergency-call data to identify and compare patterns in the health impacts of heat in Phoenix and Chicago. We studied daily variation in temperature and heat-related 911 emergency dispatches in each city to identify temperature-response effects (heat slopes) and the critical thresholds at which heat begins to harm health, and to assess heat-stress risk under different climate-change scenarios. Two pilot studies have examined heat-related emergency dispatches in Chicago (Hartz et al., 2012a) and Phoenix (Golden et al., 2008), documenting annual, monthly, day-of-week, and time-of-day distribution of heat-stress calls and temperature metrics. Both studies found that high call volume was driven by high maximum temperature ($T_{\max}$) and apparent maximum temperature($AT_{\max}$), as well as maximum heat index, a combination of temperature and humidity. Hartz et al. (2012b) examined the association between a set of climatic factors and indices and heat-stress calls in Phoenix and Chicago, using cubic and stepwise regression. Though their method was suitable for estimating the relationship between climate and heat-stress calls, they were unable to estimate accurately the change in the number of calls. By using a systematic approach to evaluate temperature-health association, we were able to compare residents' sensitivity to temperature increase in Phoenix and Chicago and estimate how the number of heat-related emergencies would increase in the event of higher temperatures.

We used temperature and daily heat-stress-call data in a negative binominal model to generate curves that represent the relationships between temperature and heat-stress calls made. We then used these curves to identify heat slope and the threshold temperature beyond which the majority of heat-related health emergencies occurred. To evaluate the sensitivity of each city to heat, we estimated the number of heat-stress calls that would be made under maximum temperatures ranging from 1 to 5.5 °C higher than current temperatures—a plausible range predicted by two regional climate models (Lynn et al., 2007; Georgescu et al., 2013). The equations derived from the negative binomial models were used to calculate the number of heat-stress calls that would occur under warmer conditions in the two cities in July, the hottest month of the year. From these calculations, we estimated requirements for emergency medical support, and inferred measures that the cities could take to reduce vulnerability to heat stress in the future.

Research on the relationship between temperature and health has emphasized mortality (Curriero et al., 2002; Braga et al., 2001; O'Neill and Ebi, 2009; Kovats, 2008; O'Neill et al., 2003) because daily death statistics are collected on a national basis. However, an increase in the availability of local emergency-dispatch and hospital-admission records has stimulated research into morbidity patterns (Alessandrini et al., 2011; Bassil et al., 2009; Uejio et al., 2011; Hartz et al., 2012a; Golden et al., 2008). We used heat-related emergency-dispatch calls (made from May through September, 2003–2006) as the indicator of heat-related illness. Both Chicago and Phoenix report and define heat-related calls consistently because their diagnosis procedure is based on a national standard (NREMT, 2012). We obtained dispatch data from the City of Chicago's Office of Emergency Management and Communications, and from the Regional Dispatch Center of the Phoenix Fire Department. Each record contains the address of the dispatch destination and the date and time when the call was made. Records include no detailed information on the victims, but the data were sufficient to allow us to evaluate residents' sensitivity to temperature change, and to suggest how the two cities' governments might plan ahead to reduce heat impacts and increase the capacity of their emergency-response systems.

A variety of temperature metrics have been used in epidemiological and health geography studies (Braga et al., 2001; Davis et al., 2003; Golden et al., 2008; Basu et al., 2005; O'Neill et al., 2003; Stafoggia et al., 2006); we chose daily maximum temperature and maximum heat index as metrics of extreme-heat events. Heat index, which combines air temperature and humidity, is a measure of human comfort. The human body uses an evaporative cooling process, sweating, to cool itself. High humidity reduces the evaporation rate and thus increases thermal discomfort (NOAA, 2011).

There is no universally agreed-upon standard for heat waves, extreme-heat events, or temperature metrics that can be applied in human-health studies. Some researchers have argued that minimum temperature is more important than maximum temperature as a factor in heat-related mortality, because the human body benefits from cooling temperatures in the evening and nighttime (Kinney et al., 2008). If the minimum temperature is high at night, the body cannot recover from heat stress. However, studies in Phoenix and Chicago have shown that daytime maximum temperatures were slightly more correlated with heat-related morbidity than were nighttime minimums (Hartz et al., 2006, 2012a; Golden et al., 2008). A recently published paper on the association between heat-stress emergency calls and several climatic factors in Chicago and Phoenix noted that air-masstypes are not associated with daily heat-stress calls in Phoenix due to low variability in weather conditions during hot months (Hartz et al., 2012b). Based on these studies, we chose maximum temperature as a metric of heat stress. We also used daily maximum heat index because of the high humidity in Chicago, where the combination of temperature and humidity may have a more significant effect on the body than temperature alone.

We calculated the heat index using the definition of the US National Weather Service (Rothfusz, 1990):

$$\begin{aligned}\mathrm{HI} = & -42.379 + 2.04901523\mathrm{T} + 10.14333127\mathrm{R} - 0.22475541\mathrm{TR} - 6.83783 \times 10^{-3}\mathrm{T}^2 \\ & - 5.481717 \times 10^{-2}\mathrm{R}^2 + 1.22874 \times 10^{-3}\mathrm{T}^2\mathrm{R} + 8.5282 \times 10^{-4}\mathrm{TR}^2 - 1.99 \times 10^{-6}\mathrm{T}^2\mathrm{R}^2\end{aligned}$$

where T = ambient dry bulb temperature (°F); R = relative humidity (integer percentage).

We used historical weather information from the National Climatic Data Center (NCDC). For Phoenix, we used data from the weather station at Phoenix Sky Harbor International Airport in central Phoenix. Chicago data came from the weather station at Midway Airport in southwest Chicago, about 9.5 miles from the downtown "Loop." Although historical data from a single station may not fully represent the conditions for an entire city, data from these two stations are widely used by climatologists to represent the climate conditions of the cities.

3.3. Procedure

3.3.1. Extreme heat events and morbidity

Heat waves have been defined in various ways, but definitions are usually based on the temperature exceeding specific threshold conditions and persisting for several consecutive days, so that there is no relief from the heat. Threshold temperature is a designated upper percentile of the distribution of 30-year daily maximum temperatures (Meehl and Tebaldi, 2004; Reid et al., 2012; Ruddell et al., 2010). We used the thresholds and criteria from Meehl and Tabaldi (2004) that were also used in other climatological studies (Ruddell et al., 2010; Huth et al., 2000). We calculated T1 (upper 2.5th percentile) and T2 (upper 19th percentile) from the 30-year (1971–2000) distribution of daily maximum temperatures for Phoenix and Chicago between May and September, when most heat-related dispatchcalls occurred. Phoenix T1 = 45.0 °C (113.0° F); Chicago T1 = 35.0 °C (95.0° F). Phoenix T2 = 42.2 °C (108.0° F); Chicago T2 = 31.1 °C (88.0° F). The criteria for a heat wave are: (1) the daily maximum temperature reaches T1 for at least three consecutive days, (2) the average maximum temperature is above T1 during the entire heat event, and (3) the daily maximum is above T2 for every day of the entire period. According to these criteria, there were four heat waves in Phoenix and one in Chicago during the study period (Tables 1 and 2).

Table 1
Heat waves in Phoenix from 2003–2006.

Heat Waves	Date	T_{max} (°C)	Number of daily heat-stress calls	Average T_{max}
Event 1	Sunday, July 13, 2003	45.6	7	46.4 °C
	Monday, July 14, 2003	46.7	9	(115.5°F)
	Tuesday, July 15, 2003	46.1	20	
	Wednesday, July 16, 2003	47.2	8	
Event 2	Friday, July 15, 2005	45.0	11	45.1 °C
	Saturday, July 16, 2005	45.0	12	(113.2°F)
	Sunday, July 17, 2005	46.7	14	
	Monday, July 18, 2005	45.0	24	
	Tuesday, July 19, 2005	43.9	17	
Event 3	Thursday, July 13, 2006	45.0	17	45.2 °C
	Friday, July 14, 2006	45.6	17	(113.3°F)
	Saturday, July 15, 2006	45.0	9	
	Friday, July 21, 2006	47.8	17	46.4 °C
Event 4	Saturday, July 22, 2006	46.7	23	(115.5°F)
	Sunday, July 23, 2006	45.6	18	
	Monday, July 24, 2006	45.6	22	

T_{max} = Daily maximum temperature.

Table 2
Heat waves in Chicago from 2003–2006.

Heat waves	Date	T_{max} (°C)	Number of Daily heat-stress calls	Average T_{max}
Event 1	Monday, July 31, 2006	37.2	58	36.9 °C
	Tuesday, August 01, 2006	37.2	87	(98.3 °F)
	Wednesday, August 02, 2006	36.1	69	

T_{max} = Daily maximum temperature.

3.3.2. Evaluating temperature variables and heat-stress calls

Many longitudinal datasets with continuous dependent variables are modeled using Poisson regression, a model that is widely used for predicting continuous data in count format (D'Souza et al., 2004); however, if the data structure has a random dispersion pattern, the negative binominal regression could provide a better fit with the data than the Poisson regression (Bruno et al., 2007). The negative binomial regression model is ideal for an analysis that has a continuous and over-dispersed (the variance exceeds the mean value) dependent variable. The model is commonly used in biology and health studies to find patterns of a phenomenon, frequencies of events, disease spread, or change of population size over a period of time (Bruno et al., 2007; Mabaso et al., 2006; Rohr et al., 2008).

In Chicago and Phoenix, the number of heat stress calls varies enormously over the course of a year: 99.8 percent of Chicago calls and 93.6 percent of Phoenix calls occur between May and September. Therefore, we collected data for each day from May through September for our study (612 days in four years). The variances of heat stress-calls in the two cities far exceeded the mean value, indicating the problem of over-dispersion. We observed a large number of heat-stress calls made at the beginning of a heat wave, followed by a gradual decrease as the temperature returned to average. This data structure explained why the negative binominal model fit and predicted our data better than regular linear regression, quadratic regression, or Poisson regression, all of which are widely used in studies of temperature and health.

First, we used bivariance regression to examine relationships between heat metrics and heat-related dispatches in Phoenix and Chicago (Table 3). Air temperature is a stronger predictor of the daily variation in heat-stress calls in Phoenix than in Chicago. In Phoenix, T_{max}, T_{min} and Max heat index were good predictors of heat stress calls, with Pearson correlation values equal to 0.6 and p-values below 0.01. Phoenix is usually hot and dry, so air temperature alone had the strongest relationship with heat-stress calls. The heat index, which incorporates humidity, was the strongest predictor of

Table 3
Pearson Correlation Matrix of heat-stress calls and climate variables in Phoenix and Chicago, May–September, 2003–2006. (N = 612 days).

		Number of heat-stress calls in Phoenix	Number of heat-stress calls in Chicago
T_{max}	Pearson correlation	0.6[a]	0.3[a]
	Sig. (2-tailed)	0.00	0.00
Max_HI	Pearson correlation	0.6[a]	0.4[a]
	Sig. (2-tailed)	0.00	0.00
T_{min}	Pearson correlation	0.6[a]	0.3[a]
	Sig. (2-tailed)	0.00	0.00

[a] Correlation is significant at the 0.01 level (2-tailed). T_{max}, T_{min}, Max HI are daily maximum temperature, minimum temperature, and maximum heat index.

heat-stress calls in Chicago. The correlation coefficient between the heat-stress calls and the heat index in Chicago was 0.4. The correlations with T_{max} and T_{min} were lower than with the heat index in Chicago, but they were also statistically significant at the 0.01 level (Table 3).

We built two models for each city, one based on daily maximum temperature and the other based on maximum heat index using SAS 9.2, an integrated system of software product that perform statistical analysis. The models were designed to predict heat-stress calls and identify the temperature threshold at which heat-stress calls increase dramatically. Subsequently, we used the model to predict heat-stress calls under different future climate conditions.

The function of heat-stress calls and predictors is defined in Eq. (1), using the negative binomial regression analysis:

$$\hat{y} = \exp\{B_0 + B_1 X\} \tag{1}$$

where $\hat{y}$ = the average (mean) number of heat-stress calls in a day; B_0 = intercept; B_1 = beta value; X = Maximum temperature or maximum heat index (°C)

3.3.3. Climate change and heat impacts on human health

One approach to projecting future heat morbidity is to use results derived from downscaled global climate models (GCM), but any contribution to decision making from this approach would likely be limited due to various uncertainties. For instance, GCM scenario combinations yield different projections of the future, depending upon which model is used, the scale of analysis, and the region involved. Trenberth (2010) noted the high degree of uncertainty associated with IPCC Assessment Report 4 climate model projections, and anticipated even higher levels of uncertainty associated with IPCC Assessment Report 5 projections due out in 2013. He argued that as the models become more complex, incorporating a greater number of variables from the climate system as well as the interactions among these variables (e.g., the release of greenhouse gases from melting permafrost and the fertilizing effect of atmospheric carbon dioxide on vegetation), the uncertainty of model results will increase, especially in the short term. Wilby and Dessai (2010) have noted that the ability to downscale models to finer scales does not imply that resulting future scenarios will be more reliable, and that the envelope of uncertainty is impossibly large for vulnerability assessment and climate adaptation, especially for municipal stakeholders. They have argued against using GCM results for assessment, instead favoring an approach that focuses on identifying the vulnerabilities and the sensitivities in the current system to a plausible range of climate change. We employed that strategy, using “what if” changes in future climate based on a reasonable range of temperature increase.

Using results from the negative binominal model of temperature-heat stress relationships, we conducted a hypothetical experiment, assessing the volume of heat-stress calls across a range of temperature increase from two regional climate model simulations (Lynn et al., 2007; Georgescu et al., 2013), and using the volume as an indicator of vulnerability and sensitivity to climate change. Other researchers have used model simulations to predict future summer temperatures in Phoenix (Georgescu et al., 2013) and Chicago (Lynn et al., 2007). Their results indicated that in Phoenix in 2050, the local maximum near-surface temperature warming in a high-development scenario (based on urban and population growth) could reach 4 °C while Chicago could expect an increase in the average summer temperature of approximately 5.5 °C by 2080 as a result of anthropogenic climate change. Based on the results of these studies, we applied temperature increases from 1 to 5.5 °C to estimate the change in heat-stress calls from current status. As inputs into our model, we used each city's mean daily maximum temperature in July from 1980–1999, to represent the typical climatic experience of a city. Using this mean as a baseline, we then assessed the sensitivity of heat-stress calls to increases in maximum temperature. The goal of the analysis is not to project future morbidity, but to provide sensitivity analysis and vulnerability assessment for the two cities, as a basis on which they might enhance their current emergency-response systems.

4. Results and discussion

4.1. Extreme heat events and heat-stress calls from 2003–2006

Since 1970, large-scale urbanization and land conversion has resulted in increased summer temperatures in metropolitan Phoenix, and further urbanization is likely to exacerbate surface warming (Ruddell et al., 2013; Grossman-Clarke et al., 2010; Georgescu et al., 2009). A study of historical threshold temperature change and climatic trends in Phoenix (urban) and Gila Bend (desert) in central Arizona found that Phoenix's climatic trend has deviated from its historical path, and shows an increased warming pattern (Ruddell et al., 2013). Warming is also a threat to Chicago, especially in terms of an increase in extremely hot days. Historical records from 1961–1990 indicate that oppressive air masses over Chicago occurred, on average, about 16 days each year, but a set of AOGCM simulations predicted that the frequency of oppressive–mass events is likely to increase dramatically in high-emission scenarios (Hayhoe et al., 2010). While the temporal limitations of our data prevent us from identifying climate trends in the two cities, we did find that Phoenix experienced more and longer-lasting excessive heat events than Chicago did. During our four-year study period, we observed four extreme heat events in Phoenix, all in July (Fig. 1). In 2006, Phoenix experienced two heat waves in a single month, and the second one had a larger health impact than the first. We observed that numbers of heat-stress calls spiked in July, suggesting that more proactive interventions, medical services, and resources to mitigate heat stress are necessary in July than in other summer months. Chicago had only one extreme heat event in the four years studied. That event also occurred in July, and correlated with a four-year peak in daily number of heat-stress calls: 16.8 percent of total heat-stress calls in that year in Chicago occurred on a single day during this event (Fig. 2).

Although Phoenix has a smaller population than Chicago, more Phoenicians made heat-stress calls than Chicagoans (2560 versus 1104 calls) (Table 4). In Phoenix, heat-stress calls were made on 530 days of 612 days (May–September, 2003–2006), but only on 111 days in Chicago. However, the maximum number of calls in a single day in Chicago was 87 (August 1, 2006), about 3.1 times the maximum number in Phoenix (28 calls on July 21, 2005), suggesting that heat stress was more concentrated during extreme events in Chicago and more a fact of everyday life in Phoenix.

The daily distribution of heat-stress calls in the two cities was very different (Figs. 1 and 2). Distribution in Chicago was highly concentrated during extreme-weather days, while calls in Phoenix were more dispersed. In Chicago, the first cluster of calls occurred in June during three summers, suggesting that Chicagoans may lack of attention to the health effects of heat on residents in early summer. The city could use mass media to increase people's awareness of the possible negative effects of heat exposure starting in June. Annually, peak call numbers were observed in late July and early August in Chicago. That suggests during this time period, the city requires active plans to educate and inform people about heat stress, such as warning people in advance that high temperatures are going to occur and that they should stay indoors.

Despite the fact that Chicago experienced fewer and shorter extreme heat events than Phoenix, our findings indicated that Chicago residents were more vulnerable to extreme heat than Phoenicians, especially when they faced: (1) a heat wave, or (2) a large diurnal temperature increase, or (3) extreme temperatures outside of their normal range of experience. For example, a large diurnal temperature

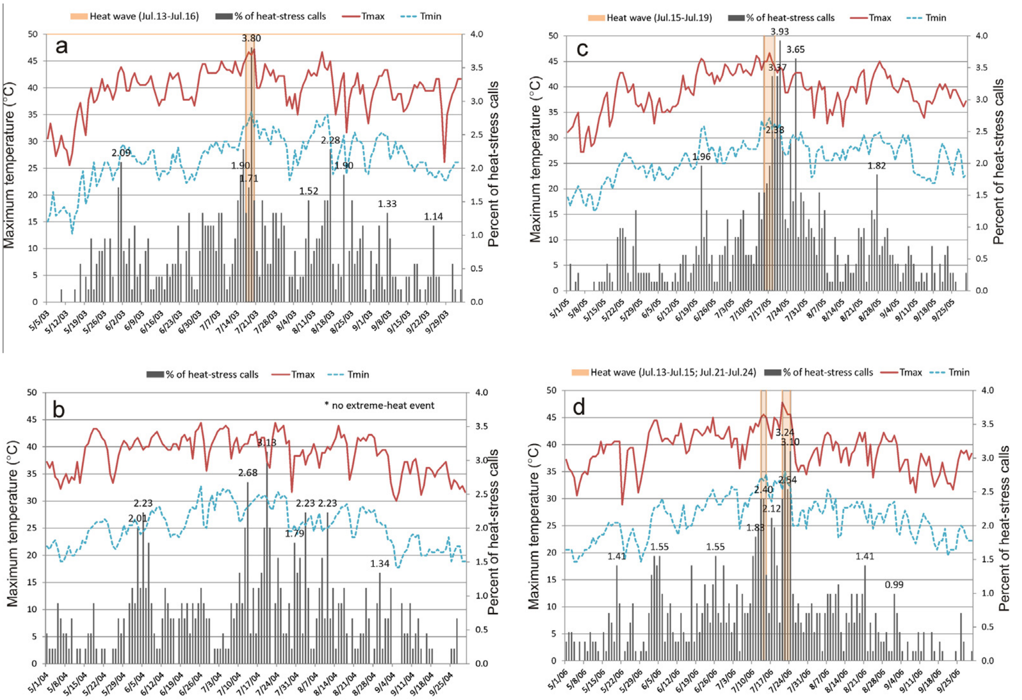

Fig. 1. Temperatures and heat-stress calls in Phoenix from May to September (a) 2003, (b) 2004, (c) 2005,(d) 2006. T_{max} and T_{min} are daily maximum temperature and daily minimum temperature.

Table 4
Descriptive analysis of heat-stress calls 2003–2006 (May–September).

	2003	2004	2005	2006	Daily average	Std.	Daily Maximum	Total
Phoenix	571	492	759	738	3.9	4	28	2560
Chicago	152	73	366	513	1.4	6.6	87	1104

increase in Chicago on July 24, 2005, with a dramatic temperature increase from 28.9 °C (84.0°F) to 40.0 °C (104.0°F), resulted in 48 calls in one day. The average maximum temperature for July over the past three decades was 29.5 °C (85.1°F) in Chicago. Our findings revealed that 88.5 percent of Chicago heat-stress calls were made when the temperature was above 30.0 °C (86.0°F), and call volume spiked when temperature reached 35.6 °C (96.1°F).

4.2. Model of heat-related illness

4.2.1. Phoenix models

Our negative binomial models describe the rate of heat-stress-call increases when temperature rises. They also identify the critical temperature at which heat-stress calls will occur. Model results for Phoenix passed the omnibus test, model-effect test, and goodness-of-fit test. The ratio of the deviance to the degree of freedom (DF), Value/DF, of our Phoenix model using maximum temperature as a predictor is 1.0, and the *p*-value of the omnibus test was less than 0.0001. The Phoenix model using

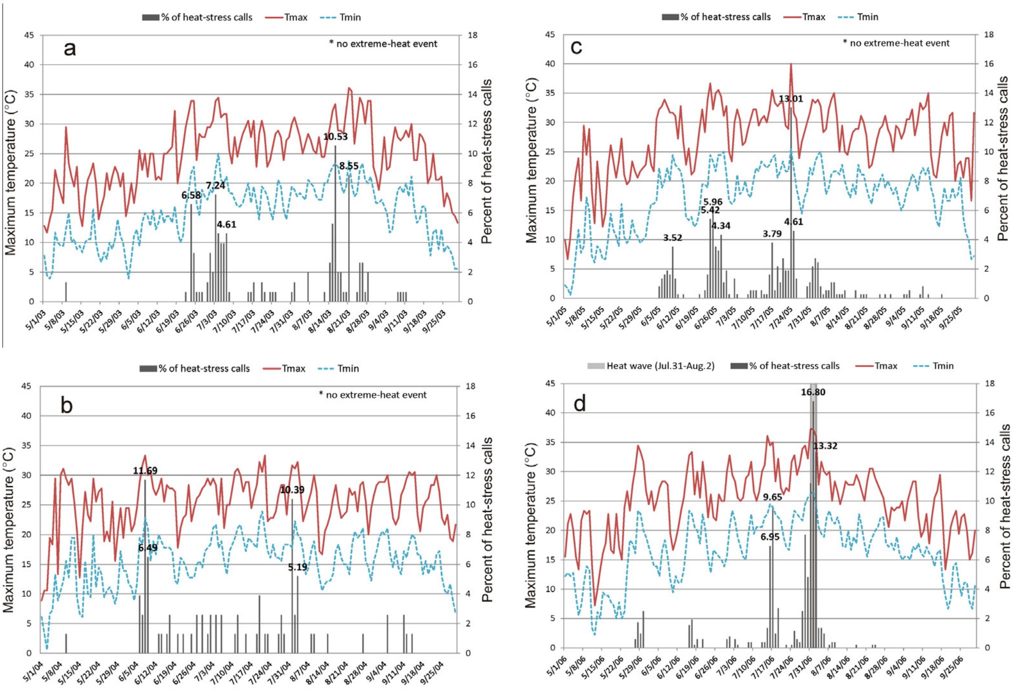

Fig. 2. Temperatures and heat-stress calls in Chicago from May to September (a) 2003, (b) 2004, (c) 2005,(d) 2006.

maximum heat index had the Value/DF of 0.9,[1] and the *p*-value of the omnibus test was less than 0.0001. The omnibus test provided a test of the overall model, comparing it to a model without any predictors. A low *p*-value for this test indicated that the model was significantly improved with the predictor.

- Using maximum temperature as a predictor of heat-stress calls

$$\hat{y} = \exp\{-6.84 + 0.203X_1\} \tag{2}$$

When Y = 1, X_1 = 33.7

- Using maximum heat index as a predictor of heat stress-calls

$$\hat{y} = exp\{-3.057 + 0.103X_2\} \tag{3}$$

When Y = 1, X_2 = 29.7

where: $\hat{y}$ = daily average heat-stress calls; X_1 = Maximum temperature (°C); X_2 = Maximum heat index (°C)

Our models predicted the number of heat-stress calls using maximum temperature Eq. (2) and maximum heat index Eq. (3). Based on model results, we predicted that the Phoenix Regional Emergency Dispatch Center would start receiving heat-stress calls when the maximum temperature exceeded 33.7 °C (92.7° F), or when the maximum heat index exceeded 29.7 °C (85.5° F).

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[1] The ratio of the deviance to DF, Value/DF, describes how well the model fits the data. If the model fits the data well, the ratio should be close to one.

4.2.2. Chicago models

The Chicago models described the relationship between temperature and the average daily number of heat-stress calls in Chicago, using maximum temperature Eq. (4) and maximum heat index Eq. (5) as predictors, respectively.

- Using maximum temperature as a predictor

$$\hat{y} = \exp\{-17.296 + 0.573X_3\} \tag{4}$$

When $Y = 1$, $X_3 = 30.2$

- Using maximum heat index as a predictor

$$\hat{y} = \exp\{-9.646 + 0.273X_4\} \tag{5}$$

When $Y = 1$, $X_4 = 35.3$

where: $\hat{y}$ = Daily average heat-stress calls; X_3 = Maximum temperature (°C); X_4 = Maximum heat index (°C)

The Chicago models fit the empirical data well, with the Value/DF ratios close to 1.0: the Value/DF ratio was 0.9 for the maximum temperature model and 0.8 for the maximum heat index model. Model results predicted that the Chicago Emergency Dispatch Center would receive at least one call per day when the maximum temperature was above 30.2 °C (86.4° F), or when the maximum heat index was

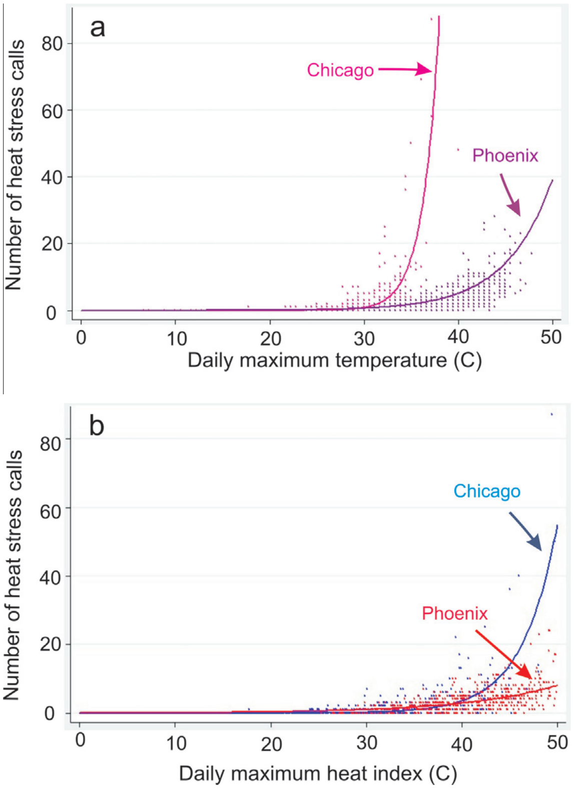

Fig. 3. The results of the negative binominal model (a) using daily maximum temperature as predictor (b) using daily maximum heat index as predictor.

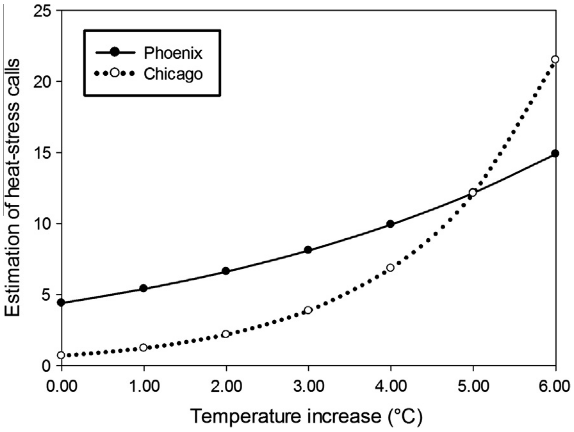

Fig. 4. Estimates of daily heat-stress calls with increase temperatures.

above 35.3 °C (95.5° F). Heat-stress calls in Chicago would increase sharply when maximum temperature was above 32.0 °C (89.6° F).

The model results, along with empirical data on the two cities, were plotted in Fig. 3. Chicago's steeper curves indicate that Chicagoans are more sensitive to temperature increases than Phoenicians. When daily maximum temperature exceeds 35.0 °C, heat-stress calls increase dramatically in Chicago. Heat-stress calls in Phoenix, however, gradually increase until the temperature reaches about 45.0 °C. This 10 °C difference in threshold temperature indicates that Phoenicians are indeed more acclimatized to high temperatures than Chicagoans; this finding echoes those of Curriero et al. (2002) and Medina-Ramón and Schwartz (2007).

4.3. Heat-stress calls under warmer climate conditions

Although our models showed that Phoenicians are more acclimated to heat than Chicagoans, they are not less *vulnerable* to heat. We used 20-year average daily maximum temperature in July as representative of residents' climatic experience in the hottest month of a year. The 20-year average for Chicago is 29.5 °C and for Phoenix, 41.0 °C. We used these temperatures as baselines, and calculated that Chicago and Phoenix would average 0.69 and 4.41 calls per day, respectively, at these temperatures (Fig. 4). Apparently, the prevalence of air conditioning in Phoenix (more than 90 percent of buildings are air conditioned) still cannot keep the number of heat-stress calls as low as in Chicago, which is a cold-climate city. Reducing the impacts of prolonged heat exposure in Phoenix would require proactive strategies to improve the city's current physical and social environments.

Despite the relatively lower number of heat-stress calls in Chicago, without adaptation, Chicagoans would suffer more negative health effects than Phoenicians if maximum temperatures increase substantially. With small increases in temperature, Phoenix would continue to outpace Chicago in the number of heat-related dispatches. However, if average temperatures were to increase by 4.8 °C Chicago would overtake Phoenix in the number of heat-stress calls (Fig. 4). A warmer climate could seriously threaten human health and the existing emergency-response system in Chicago during extreme heat events.

5. Proactive heat mitigation strategies for the two cities

Willows and Connell, (2003) have suggested that cities that fail to adopt new measures to cope with excessive heat in the future will become more vulnerable to temperature extremes. Our model results indicate that under current conditions, the critical threshold temperatures at which the

Emergency Dispatch Centers start receiving heat-stress calls are 33.7 °C (92.7° F) for Phoenix and 30.2 °C (86.4° F) for Chicago. With a 5.5 °C increase in temperature to 35.7 °C Chicago would experience an average of 16.2 heat-related calls per day. This number could climb higher because of the indirect influence of excessive heat on cardiovascular disease, cerebrovascular disease, electrolyte imbalance, renal failure, and respiratory illness (Reid et al., 2012).Because there are many kinds of emergency-dispatch requests other than heat-stress calls, and heat-stress calls will not be distributed at exactly the average rate on any given day, the capacity of Chicago's current Emergency Management Services (75 ambulances at 24 district stations (Chicago Fire Department, 2012) will likely be challenged by both direct and indirect heat-related calls. A deadly heat wave in 2006 challenged Chicago's emergency response system with 87 heat-related calls in one day. If no adaptive action is taken by the City of Chicago to cope with heat-related events, residents' health could be seriously impacted.

Although the prevalence of air conditioning in Chicago (including central air and window units) reached 90 percent in 2009 (US Census Bureau, 2013), it does not follow that Chicagoans will be less vulnerable to extreme heat events. Lack of adequate capacity in Chicago's power system could exacerbate the impacts of heat. During the heat wave that occurred in July 1995, electric demand due to air-conditioning use created a peak demand for electricity and resulted in power outages. On the second day of the heat wave, area hospitals were overwhelmed with heat-stress victims and unable to keep up with the continuing emergency because of patient volume (Klinenberg, 2002). The average duration of power outages in Chicago in 2011 was 89 minutes (not including storm-related blackouts). The overall duration was 366 minutes affecting 2.8 million people in the greater Chicago area (Daniels, 2011). To prevent overreliance on air conditioning that is vulnerable to power outages, Chicago (and municipal governments elsewhere) could enhance building codes to increase ventilation and require the use of materials that absorb less heat in building and housing design. We also suggest that Chicago's municipal government implement a two-stage strategy to reduce heat stress, based on the two threshold temperatures we found. Our model indicates that heat-stress calls start in Chicago when the temperature reaches 30.2 °C and that there is a 5 °C difference between the start of calls and an unmanageable proliferation of calls. The recommended first-stage strategy would use existing municipal capacity to provide residents with information about how to prevent heat injuries. Chicago already has an Extreme Weather Notification System that provides registered members with recorded phone messages that communicate official warnings and information about City services to help residents to cope with heat. The City's Office of Emergency Management and Communication also makes and distributes a booklet to educate people about how to prepare for extreme-heat events, including what to do during power outages (Office of Emergency Management and Communication, 2013). Our findings suggested that this warning information is especially important when the temperature is between 30 and 35 °C.The recommended second-stage strategy would be implemented when the temperature exceeds 35 °C and would require the city to take action to immediately reduce heat-stress by, for example, opening cooling centers and shelters, and providing support and care to vulnerable people living alone.

Chicago faces a set of challenges that results from the concentration of heat-stress calls during extreme-event periods, and from residents' greater sensitivity to increases in temperature, compared with Phoenix. Klinenberg , (2002) noted the many cases of heat-related death among those living alone in Chicago. Climate change will likely only worsen the health consequences of social isolation of the elderly; it will also worsen the health consequences of the city's disadvantaged populations, who suffer from inadequate housing and a diminished welfare system. We suggest that Chicago provide more resources and services to its most vulnerable residents, the poor and the elderly, during heat waves, to reduce heat-related illness and death in the future.

In Phoenix, there is 11.3 °C difference between the temperature at which the Emergency Dispatch Center starts receiving heat-stress calls (33.7 °C) and the temperature beyond which the number of calls received increases dramatically (45 °C). This suggests that Phoenix is more resilient to heat than Chicago because its residents have higher tolerance to temperature increases than do Chicagoans. Historically, Phoenix's summer daily maximum temperatures have changed little over time. Phoenix's challenge is that it routinely experiences high temperatures in the summer; in addition, the increasing UHI effect will have a significant impact on local climate. To cope with prolonged heat exposure in Phoenix, we recommend that the municipal government focus on UHI mitigation by providing daytime shade that reduces surface exposure to heat. The City of Phoenix has policies in place to reduce the UHI effect and enhance urban sustainability. By changing landscaping and using new building materials and designs, and by increasing shaded areas that help to mitigate the UHI effect and improve thermal comfort at street level, these policies aim to reduce UHI intensity and energy and water use in neighborhoods (Chow et al., 2012a). To provide direct assistance to residents to mitigate heat stress, the Phoenix Heat Relief Network operates when temperatures consistently rise above 38.0 °C (100.4) °F, and the National Weather Service issues heat warnings that are featured prominently in news outlets. During hot days, homeless service agencies and faith-based communities distribute bottled water, provide temporary refuge for cooling, and give lightweight clothing, hats, and sunscreen to those in need (City of Phoenix, 2012).

In Phoenix, interventions targeted at high-risk populations may be more effective in decreasing heat-related illness and death than interventions aimed at the general public. Baker et al. (2002) found that in Phoenix, heat mainly affects people in outdoor spaces (probably because most of the city's indoor spaces are air conditioned in hot seasons), and we suggest that Phoenix focus on heat-mitigation strategies for outdoor spaces, such as providing shaded areas, accessible drinking water, and warning signs. Research and statistics (Chow et al., 2012b; Harlan et al., 2006; Mrela and Torres, 2010) indicate that most of the vulnerable population in metropolitan Phoenix is either Spanish-speaking, or low socioeconomic status, in the US illegally, elderly, homeless, or some combination of the above.

6. Conclusion

We used the negative binomial regression model to determine how the volume of heat-stress calls in Phoenix and Chicago would be likely to change in response to temperature increase. Model results indicated that the threshold at which calls are likely to increase dramatically in Chicago is 35.0 °C and in Phoenix 45.0 °C. The higher threshold for Phoenix may be due to the city's lower humidity and/or wide-spread use of air conditioning in residences, work places, and public buildings. The gentler slopes of the Phoenix models suggest that Phoenix's physical and social capacity to withstand heat is put to the test regularly, as evidenced by the regularity of heat-stress calls throughout the summer. Our results are consistent with Curriero et al.'s (2002) research, which found that people in warmer regions are more adaptive to excessive heat than those in cold regions.

Our analysis identified the differences in the vulnerability and sensitivity of Phoenix and Chicago to heat stress. Our findings suggest that urban areas have different threshold temperatures at which heat-stress calls increase drastically, and that these differences are due not only to residents' physiological acclimatization, but also in some measure to the physical characteristics of a city's built environment and the demographic characteristics of its population. We conclude that both Chicago and Phoenix will need to increase adaptive capacity to cope with a warmer climate and reduce heat-related illness and death, especially among their most vulnerable populations. Phoenix needs to prioritize outdoor heat-mitigation strategies and protect its most vulnerable populations—the elderly, the homeless, Spanish speakers, those of low socioeconomic status, and those in the US illegally—from heat-stress. Chicago needs to strengthen *indoor* heat-mitigation strategies, such as improving building ventilation and opening more cooling centers, increase the effectiveness of the public warning system, and provide social support so that vulnerable individuals can get help from others during heat waves before their situation requires emergency assistance. This study empirically demonstrated the need for improved adaptive capacity and suggested future strategies for achieving this goal. Municipal governments, as well as service agencies and organizations, can use model to inform their planning to reduce heat-related illness and death in the future.

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