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Neighborhood microclimates and vulnerability to heat stress

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Abstract

Human exposure to excessively warm weather, especially in cities, is an increasingly important public health problem. This study examined heat-related health inequalities within one city in order to understand the relationships between the microclimates of urban neighborhoods, population characteristics, thermal environments that regulate microclimates, and the resources people possess to cope with climatic conditions. A simulation model was used to estimate an outdoor human thermal comfort index (HTCI) as a function of local climate variables collected in 8 diverse city neighborhoods during the summer of 2003 in Phoenix, USA. HTCI is an indicator of heat stress, a condition that can cause illness and death. There were statistically significant differences in temperatures and HTCI between the neighborhoods during the entire summer, which increased during a heat wave period. Lower socioeconomic and ethnic minority groups were more likely to live in warmer neighborhoods with greater exposure to heat stress. High settlement density, sparse vegetation, and having no open space in the neighborhood were significantly correlated with higher temperatures and HTCI. People in warmer neighborhoods were more vulnerable to heat exposure because they had fewer social and material resources to cope with extreme heat. Urban heat island reduction policies should specifically target vulnerable residential areas and take into account equitable distribution and preservation of environmental resources.

Keywords: USA; Health inequalities; Climate; Neighborhood environment; Environmental justice

Introduction

Exposure to excessively warm weather is a global threat to human health and well-being (Patz, Campbell-Lendrum, Holloway, & Foley, 2005). Heat-related deaths are a chronic problem in arid climates (CDC, 2005). Summer heat waves, sporadic periods of elevated temperatures outside the normal range of climate variability, occur throughout the world and are projected to become more frequent and intense in the future (Meehl & Tebaldi, 2004). More deaths, in fact, are attributed to heat in temperate climates than in warm climates because people in temperate zones are less acclimated to high temperatures (Kalkstein & Davis, 1989; Kalkstein & Green, 1997). Climatically diverse cities, such as Toronto, Canada and Sao Paolo, Brazil report excess mortality attributable to

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extreme heat (Patz et al., 2005; Smoyer, Rainham, & Hewko, 2000). Notable recent events include the heat waves of 2003, which killed an estimated 35,000 Europeans in 2 weeks (Larsen, 2003) and more than 1900 people in India (IFRC, 2003); the 1995 Chicago, IL heat wave, which claimed over 700 lives (Semenza et al., 1996); and the summer of 1980, in which 10,000 US deaths were attributed to extreme temperatures (Sheridan & Kalkstein, 2004). In addition to elevated mortality, serious illnesses, such as heat stroke, heat exhaustion, cardiovascular, and respiratory problems, rise during the warmest spells of the year (ICLEI, 1998; Semenza, McCullough, Flanders, McGeehin, & Lumpkin, 1999). Deaths and illnesses from air pollutants and infectious diseases also increase during extremely warm weather (Easterling et al., 2000; Patz et al., 2005).

The highest morbidity and mortality associated with extreme heat appear to occur in cities and to fall disproportionately upon marginalized groups: the poor, minorities, and elderly (CDC, 2004; ICLEI, 1998). This article examines heat-related health inequalities within one city in order to understand the relationships between the microclimates of urban neighborhoods, population characteristics, thermal environments that regulate microclimates, and the resources people possess to cope with climatic conditions. We demonstrate that there are significant differences among urban neighborhoods in temperature and exposure to heat stress, and we investigate three important questions regarding potential heat-related health disparities: (1) Are socially and economically marginalized populations more likely to live in heat-stressed neighborhoods? (2) How are environmental properties of neighborhoods related to spatial inequalities in temperature and exposure to heat stress? (3) What resources do people have to cope with the risk factors associated with extreme heat? In other words, are marginalized groups at greater risk for heat-related illness and death because they live in warmer places and have fewer social and material resources to mitigate the effects of extreme heat?

Environment and risks of heat-related illness

Establishing who is most at risk for heat-related illness and death and how to reduce their exposure is a complex public health problem involving a combination of physiological variables and social and ecological variables related to spatial location. The elderly, young children, and people with chronic respiratory and cardiovascular diseases are physically more susceptible than healthy young adults to the dangers of prolonged exposure to excessive heat (McGeehin & Mirabelli, 2001). Social isolation—living alone without regular contact with others—is also a significant predictor of who succumbs to heat (Klinenberg, 2002; Semenza et al., 1996). Low-income and minority groups have higher health risks related to climatic conditions for a variety of social and economic reasons (CBCF, 2004). But a large number of people are vulnerable to warm weather because they live in urban areas where summer temperatures are more extreme than in suburban and rural communities. As Davis (1997, p. 35) wrote about deaths in the 1995 Chicago heat wave, the “unshaded asphalt jungles of our inner cities” are a major public health hazard.

Although periodic heat waves increase health problems in cities, temperatures in urban centers are also chronically higher than in adjacent outlying areas due to the urban heat island (UHI) (Oke, 1987, 1997). The UHI is created primarily by dense concentrations of heat-absorbing, impervious building materials that trap more heat during the day and release it more slowly at night than natural ground cover, such as soil and vegetation (Voogt, 2002). Thus urbanization elevates daytime temperatures and affords residents no relief during the nighttime at the warmest times of the year (Meehl & Tebaldi, 2004). Projections show that the heat differential between urban centers and surrounding areas will grow wider in the future, increasing the relative health risks for poor and minority populations who reside in cities (CBCF, 2004; New York Climate & Health Project, 2004).

Epidemiological research on climate and health is largely focused on cities, and some of these studies have evaluated individual or community characteristics that are markers of vulnerability (Curriero et al., 2002; O'Neill, Zanobetti, & Schwartz, 2003). Klinenberg's (2002) analysis differentiated rates of heat-related deaths during the 1995 Chicago heat wave according to where individuals lived *within* a city. He compared neighborhoods with different rates of heat-related deaths in order to determine if neighborhood-specific factors were implicated in higher rates of mortality. He found that degraded neighborhood physical environments altered social dynamics in ways that led to higher numbers of heat-related deaths and concluded that socio-ecological conditions in the Chicago neighborhoods where the most people died tended to isolate residents from crucial networks of social support. Smoyer's (1998) study of St. Louis also found citywide patterns of associations between the spatial distributions of neighborhood environmental quality, population characteristics, and heat wave mortality rates.

Environmental justice (EJ) research, a literature that documents the unequal burdens of environmental hazards on marginalized populations (Pellow, 2000), provides the framework for our analysis. Although many EJ studies have focused on the location of hazardous facilities, such as industrial plants, incinerators, and landfills (e.g., Bolin et al., 2002; Pellow, 2002), a related body of research examines neighborhood socio-ecological effects on health and disease (e.g., Corburn, Osleeb, & Porter, 2006; Cummins, Macintyre, Davidson, & Ellaway, 2005; Macintyre, Ellaway, & Cummins, 2002). Studies of asthma have made an important conceptual distinction between the *presence* of an environmental hazard (level of air pollution) and the human health *outcome* of the hazard (asthma rates) (Brown et al., 2003; Grineski, 2006). In our study, we measure both the presence of the climate hazard (neighborhood temperature) and outcome of the hazard, which is exposure to conditions that cause heat-related illness measured by an index of human thermal comfort. We also consider differences in the vulnerability of residents in diverse neighborhoods to extreme climate conditions. Vulnerability, an important concept in EJ research, is the absence of resources to cope with the impact of an environmental hazard (Grineski, 2006; Wisner, Blaikie, Cannon, & Davis, 2004).

We propose three hypotheses modeled on the EJ approach to answer our questions about climate and health: (1) Summertime temperature variations between urban neighborhoods are substantial and in those neighborhoods with warmer microclimates, residents will experience increased health risks from severe heat stress. (2) Higher summertime temperature and corresponding health risks will be associated with concentrations of marginal populations and inferior neighborhood environmental characteristics. (3) People in warmer neighborhoods will have fewer material and social resources to cope with or mitigate the effects of extreme heat.

Methods

This study is part of an interdisciplinary research project on human involvement in urban ecosystems that examined relationships between the characteristics of people, places, and UHI spatial variability in Phoenix. Human–climate relationships were investigated in the entire urbanized area of the Phoenix-Mesa Metropolitan Statistical Area (Jenerette et al., in press) and in the eight specific neighborhoods that are the subject of this article. Phoenix is an important site in which to investigate climate-related health issues because it has a semi-arid to arid climate that is similar to places where many of the world's fastest-growing cities are located (Golden, 2004). Phoenix is intensely hot in the summer—normal maximum summer temperatures are at least 38 °C (100.4 °F)—and Arizona leads the US in deaths from heat exposure (CDC, 2005). The city has an expanding UHI due to rapid population growth and experiences heat waves during the summer months (Brazel, Selover, Vose, & Heisler, 2000). The summer in which our study took place, 2003, was the city's warmest on record (NOAA, 2003).

Briefly, we collected a suite of social and biophysical variables for eight diverse neighborhoods in Phoenix. Human thermal comfort, a measure of people's exposure to conditions that cause heat-related illness, was simulated using an energy balance model with data from the sites. We used a mixed methodologies approach (Tashakkori & Teddlie, 1998), combining quantitative data and interviews with key informants in order to gain a nuanced understanding of the social and ecological dynamics of the neighborhoods.

Data sources

Seven of the eight neighborhoods in this study are among 206 sites in Maricopa County where field data are periodically collected by the Central Arizona–Phoenix Long-Term Ecological Research Project (CAP LTER) (Hope et al., 2003). Of those sites, which are 30 m^2 plots, 46 were in residential areas of the city of Phoenix. Placing census block group boundaries around the Phoenix sites, we selected a sample of neighborhoods that varied on important social and physical characteristics relevant to this study: median income, ethnic composition, age of housing stock, types of landscaping, and locations in the urban core, suburban areas, and the fringe of new development. The eighth site was chosen to represent an important type of neighborhood that was missing from the CAP LTER sites—a predominantly white, upper-income, older, and highly vegetated neighborhood near the central city. These neighborhoods are arrayed along a 48-km north-to-south arc that extends to the city limits (Fig. 1). *Black Canyon Freeway*, *Historic Anglo Phoenix*, and *Historic Mexican Phoenix* are in the urban core; *West Side* and *North Central* are suburban; and *North Desert Ranch*, *New Tract Development*, and *South Mountain Preserve* are on the fringe of urban development. Neighborhoods defined by census block groups yield socio-economically homogeneous populations in small areas (approximately 0.65 km^2) which can be matched to the boundaries of other datasets assembled with geographic coordinates.

Neighborhood population characteristics

We measured variation in the demographic composition of neighborhoods with population characteristics typically used in studies of social vulnerability to environmental hazards (Cutter, 2003). The block group variables from the 2000 US Census were: median income (US dollars), poverty rate (percent of population below the US government federal poverty guideline), educational attainment (percent with less than a high school diploma), ethnicity (percent Hispanic and Native-, African-, and Asian-American), and age (median, ages 5 and under, or ages 65 and older).

Neighborhood thermal environments

At the regional scale, land-use patterns and land cover are the strongest drivers of urban temperatures. Many interactive thermodynamic properties of biophysical and built environments resulting from changes in these systems determine the spatial distribution of the UHI (Grossman-Clarke, Zehnder, Stefanov, Liu, & Zoldak, 2005). We measured four basic properties at the neighborhood scale: distance from the central city; population settlement density; amount of open space; and vegetation density (Brazel et al., 2000; Carlson and Arthur, 2000; Karl, Diaz, & Kukla, 1988). Temperature decreases with distance from the central city because the core has higher population of density, less open space, and less vegetative cover.

Linear distance from the geographic center of Phoenix to centers of neighborhood block groups were measured in ESRI ArcView 3.3. Population density (number of people/km^2) was from the 2000 US Census. Percent open land within the block

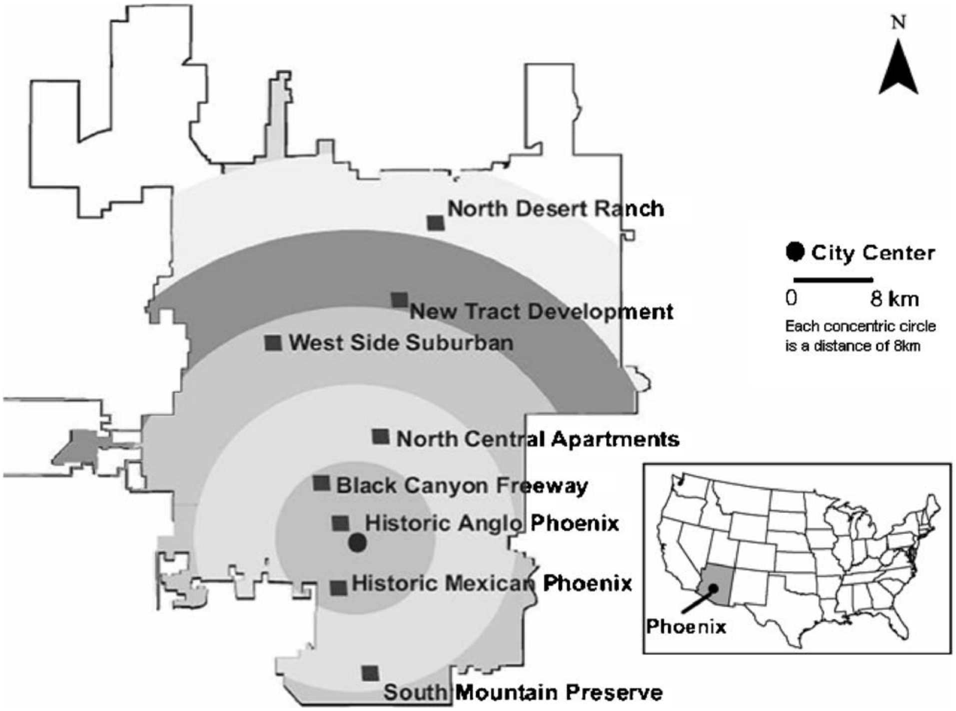


Fig. 1. Location of eight neighborhoods in Phoenix, Arizona.

groups was calculated from a land use classification study (Knowles-Yanez et al., 1999; updated in 2000). Parks and natural desert were classified as open land. Vacant land surrounded by development was not included because people do not use it for recreation or spend time there.

The Soil-Adjusted Vegetation Index (SAVI) (Huete, 1988) is a measure of vegetation density calculated from remotely sensed data acquired by the Landsat Enhanced Thematic Mapper Plus (ETM+) at approximately 10:00 am on May 21, 2000 and processed in the Geological Remote Sensing Laboratory at Arizona State University. SAVI measures the reflectance of actively photosynthesizing vegetation for each pixel ($30\,m^2$), correcting for the high soil reflectance in the desert. To obtain SAVI for the neighborhoods, we averaged all pixels within the boundaries of each block group and scaled the values between 0 and 1.0, with higher values indicating a greater concentration of vegetated ground cover. The pixel scale obtained by Landsat ETM+ is relatively coarse for small areas and thus obscures some of the differences in vegetation abundance between the neighborhoods.

Resources for coping with heat

Strong community networks signify social contexts in which residents are likely to cooperate, trust, and seek help from neighbors, and these contacts can buffer the grinding effects of individual poverty and isolation (Sampson, 1999). Klinenberg (2002) noted that neighborhoods with stronger ties had better social support and lower mortality rates during Chicago's 1995 heat wave. We measured the strength of neighborhood social ties in a 2001 telephone survey of 302 households in the eight neighborhoods. Responses to four questions were scored on four-point scales. How often (often, sometimes, seldom, never) do you or members of your household: visit informally with neighbors; invite neighbors over; help your neighbors. How well (very well, fairly well, not very well, not at all) do you feel you know your neighbors? High scores represent stronger social ties. Each respondent's score on the summated index ($\alpha = .87$) was standardized (z-sores) and averaged to compute a neighborhood score for social ties (Larsen et al., 2004).

Quality homes with features that mitigate excessive heat are another resource to reduce climate vulnerability, even in the warmest neighborhoods. We coded type of cooling system, presence or absence of swimming pool, and reflectivity of roofing material for a sample of detached houses in each neighborhood from the Maricopa County Assessor's website. Not included in the database were mobile homes and multiple dwelling units, such as apartments, which provided a sizable fraction of housing in three of the lower and lower-middle income neighborhoods. The generally lower quality of mobiles and multi-family dwellings in comparison to single-family houses means that we most likely under-estimated the exposure of lower-income and minority people, so any differences we found pointed to an even larger resource gap between socioeconomic and ethnic groups.

The total number of single family homes in 7 neighborhoods ranged from 195 to 447. We selected a systematic random sample of approximately 60 homes from each one for which we coded the housing quality variables. Since housing stock was fairly homogeneous in most of these neighborhoods, we felt this was an adequate sample size to capture variation. The majority of *Black Canyon Freeway* residents lived in small or large apartment buildings, other multi-family structures, and mobile homes and, therefore, we coded all single family homes in *Black Canyon* for which data were available ($n = 47$).

Most houses in Phoenix have either refrigeration (central air conditioning) or evaporative coolers as the primary cooling system. Access to air conditioning is the most effective method of preventing heat deaths (Kilbourne, 2002; Rogot, Sorlie, & Backlund, 1992). Evaporation is less effective, especially in the late summer humid conditions in Phoenix (Kalkstein & Kalkstein, 2004). A backyard swimming pool is also a beneficial way to "cool off." Construction materials with reflective surfaces that absorb less solar energy provide cooler indoor environments and reduce air conditioning loads in individual homes (Taha, 1997). We coded three common types of roofing material in Phoenix for our sample homes. Based on degree of solar reflectivity (Parker & Sherwin, 1998; Reagan & Acklam, 1979), we assigned the following values: wooden shakes (highest reflectivity = 3), concrete or clay tile (medium = 2), and asphalt shingles and rolls (lowest = 1). The percentages of homes in each neighborhood with central air conditioning and swimming pools were calculated along with a weighted mean value for roof type.

Outdoor temperature and human thermal comfort

Neighborhood microclimate data were obtained from a temperature/dew point logger system that was installed for at least 12 consecutive months in the backyard of one residence in each of the eight neighborhoods with permission of the owners (referred to as HOBOs, http://www.onsetcomp.com/index.html). We assessed the thermal and biophysical environmental characteristics for each neighborhood using high resolution remotely sensed and demographic data in an associated study (Stefanov, Prashad, Eisinger, Brazel, & Harlan, 2004). The results of this study guided selection of a representative area within each neighborhood and we then selected a yard with residential landscaping typical of each neighborhood. HOBOs were set to record temperature and humidity at 5-min intervals. In this analysis, we used temperatures recorded from June 1 through August 31, 2003 at 5:00 pm, an hour within the 10:00 am to 8:00 pm interval when NOAA's heat advisories/warnings may be in effect. Many people are likely to be outdoors in their neighborhoods at 5:00 pm as they return from work or transition between daytime and evening activities. Davis, Knappenberger, Michaels, and Novicoff (2003) found that mortality rates are closely related to afternoon high temperature. The subset of data for July 12 through 16, the longest 2003 heat wave in Phoenix, was also used in the analysis to illustrate the difference between normal summer temperatures and heat wave conditions.

Data analysis

Differences between neighborhoods in human physiological response to climate were simulated by OUTCOMES–OUTdoor COMfort Expert System (Heisler & Wang, 2002). OUTCOMES incorporates portions of a human-comfort model called COMFA by Brown and Gillespie (1995), which solves the energy balance index as

$$\mathrm{EB} = M + S + T_{\mathrm{a}} + C - E - T_{\mathrm{e}},$$

where M is the internal metabolic heat, S the absorbed solar radiation, T_{a} the absorbed thermal radiation, C the convective transfer, E the evaporative transfer, and T_{e} the thermal radiation emitted from the person.

The OUTCOMES index (herein called Human Thermal Comfort Index, HTCI) is based on the energy balance of a hypothetical person given the weather data from a site and the site's surrounding solar and thermal radiative environmental fluxes. Model inputs are air temperature, humidity, wind speed, solar radiation, pre-specified shading objects, reflectivity of the ground and nearby objects, the sky view, tree and building cover of the site, and clothing and human activity (Heisler & Wang, 2002; Hartz, Brazel, & Heisler, 2006). We input these parameters from the HOBOs and other data from our sites for the dates and time discussed above, and we assumed that a person was at rest and wearing a t-shirt and shorts, which would maximize human comfort in the summer. If the estimated energy balance is near 0 ($\pm 50\,\mathrm{W/m^2}$) most people will feel comfortable. Larger positive values equate with people feeling increasingly too hot (and conversely, negative values equate with people feeling increasingly too cold).

To establish benchmarks for HTCI that are related to the likelihood of a person experiencing heat stress, we quantified the relationship between estimated HTCI in our study and NOAA's National Weather Service Heat Index, the most frequently used indicator of probable human physical reaction to weather conditions (Watts & Kalkstein, 2004). The Heat Index is calculated from a model based on extensive biometric studies that measure the apparent temperature (AT), or how people actually feel outdoors based on the combination of air temperature with relative humidity (Steadman, 1984). NOAA's Heat Index also uses energy balance principles to model human comfort but Watts and Kalkstein (2004) have noted that it does not include all the relevant weather variables that affect how people feel. As noted above, OUTCOMES explicitly incorporates these inputs from the local environment near the person.

Table 1 shows HTCI values calculated by OUTCOMES corresponding to NOAA's Heat Index. The AT thresholds that trigger heat stress from prolonged exposure vary widely across geographic regions because people respond to relative changes in weather as well as to absolute conditions (Watts & Kalkstein, 2004). Kalkstein and Davis (1989) estimated that 38 °C is the threshold temperature for the southern US. Phoenix is a southwestern city where residents are accustomed to heat and, therefore, we suggest that 40 °C (104 °F) on NOAA's Heat Index (the "danger" zone) is an approximate threshold for severe heat stress in Phoenix. This corresponds to 200 on the HTCI (Table 1).

Table 1
Relationship between OUTCOMES Human Thermal Comfort Index (HTCI) and NOAA's Heat Index[a]

OUTCOMES	NOAA's National Weather Service		
HTCI (W/m^2)	Heat Index (apparent temperature)[b]	Label	Heat disorders
65–120	26.7–31.7 °C	Caution	Fatigue possible; discomfort
121–200	32.2–40.0 °C	Extreme caution	Sunstroke, heat cramps, heat exhaustion possible
201–339	40.6–53.9 °C	Danger	Sunstroke, heat cramps, heat exhaustion likely and heatstroke possible
340 or higher	54.4 °C or higher	Extreme danger	Sunstroke and heatstroke highly likely

[a]The corresponding relationship between NOAA's Heat Index and the OUTCOMES HTCI values were derived from data for the typical meteorological year (representative days each month on an hourly basis) at the Sky Harbor International Airport weather station in Phoenix (which were used to calculate the apparent temperature) and data from the neighborhood HOBOs, which were used with OUTCOMES to simulate HTCI for the same dates and times. Apparent temperature was regressed onto HTCI, which yielded the following predictive equation: HTCI = 5.58 (apparent temperature)−381.62, $R^2 = .86$.
[b]NOAA (2005).

No heat index can predict how many people will actually get sick or die from heat exposure because the threshold temperature and individual physiology that trigger illness vary according to many individual and contextual factors (ICLEI, 1998). Climate researchers, however, have documented a strong relationship between NOAA's Heat Index and mortality rates in cities (Davis et al., 2003). In this analysis HTCI is the indicator of exposure to climate conditions in neighborhoods that cause heat-related illness and death.

The associations between neighborhood HTCI and other variables are tested using one-way ANOVAs and Pearson correlations. In order to understand the neighborhoods as different interactive social and ecological contexts in which people live, we present case studies of three neighborhoods. These illustrate how social characteristics in advantaged and disadvantaged neighborhoods are closely related to the quality of the thermal environment and to the degree of people's exposure to heat stress.

Results

Descriptive statistics for each variable by neighborhood are shown in Table 2. Neighborhoods are arranged from left to right in descending order of median neighborhood income. Hispanics, mainly of Mexican origin, are the largest ethnic minority in Phoenix, comprising about 34 percent of the city's population in 2000. Ethnic composition varies widely among these sample neighborhoods, ranging from 89 percent to 9 percent Hispanic.

Neighborhood differences in human thermal comfort

In summer 2003 temperatures climbed to above normal values and set records in Phoenix. The daily average temperature at 5:00 pm for the eight neighborhoods was 39.5 °C at 5:00 pm (Table 3). For the entire summer period, ANOVA showed that neighborhood daily mean temperatures at 5:00 pm were significantly different from each other ($F = 16.39$, $p < .001$). (We also found that 5:00 pm temperatures generally characterize similar neighborhood differences for later in the evening.) The difference between the lowest (*Historic Anglo Phoenix*) and highest average summer temperatures (*Black Canyon Freeway*) was 4 °C. During the 5-day heat wave period in July, the ANOVA result for daily 5:00 pm mean neighborhood temperature differences was also significant ($F = 22.97$, $p < .001$). The mean temperature in *Black Canyon Freeway* during the heat wave increased twice as much as *Historic Anglo Phoenix* (+6.4°: +2.9 °C), indicating a larger disparity between the two at the warmest time of the summer.

The 5:00 pm HTCI values estimated by OUTCOMES were elevated far above the outdoor comfort level for residents of all neighborhoods during the whole summer and especially during the heat wave period (Table 3). For the entire period these scores fell into the "extreme caution" range where people are likely to feel extremely hot and prolonged outdoor exposure can result in sunstroke, heat cramps, and heat exhaustion. As with air temperature, ANOVA results indicated significant

Table 2
Population, thermal environment, and resources for coping with heat in eight Phoenix neighborhoods

Neighborhoods	South Mountain Preserve	North Desert Ranch	Historic Anglo Phoenix	New Tract Development	West Side Suburban	North Central Apartments	Historic Mexican Phoenix	Black Canyon Freeway
Population								
Income								
Median income	\$107,230	\$82,704	\$77,404	\$59,375	\$55,417	\$43,245	\$32,625	\$25,785
% in poverty	1.6	3.1	9.8	5.3	4.0	7.0	27.3	43.8
Education								
Less than high school	1.8	4.0	4.9	8.3	20.8	7.7	63.9	55.2
College graduate	23.5	29.1	41.7	4.6	3.0	11.3	1.3	0
Ethnicity								
% minority	14.7	9.3	25.8	15.5	19.5	20.1	88.6	90.9
Age								
Median age	34	33	38	37	33	36	25	23
% ages 5 and under	9.6	13.8	14.4	9.8	7.0	8.4	18.7	10.4
% ages 65 and over	1.9	5.2	5.8	15.6	6.2	21.4	0.8	6.8
Thermal environment								
Location								
Distance from city center (km)	15.5	33.5	2.6	24.6	22.7	11.4	5.0	6.6
Settlement density								
Population/km^2	720	314	1575	966	1988	2119	3083	8687
Land use								
% open space	18.0	12.0	10.0	0	0	3.0	0	0
Land cover								
Vegetation abundance (SAVI)	.474	.479	.569	.470	.483	.491	.502	.479
Coping resources								
Social ties index	.30	.30	.50	−.17	.09	.23	−.04	−.64
% air conditioned	100.0	100.0	98.0	100.0	86.0	78.0	28.0	6.0
% swimming pools	57.0	59.0	48.0	14.0	32.0	12.0	4.0	4.0
Roof reflectivity	2.00	1.81	1.59	1.88	1.02	1.00	1.00	1.04
% asphalt (low = 1)	—	24.1	48.1	12.1	98.2	100.0	100.0	95.7
% tile (medium = 2)	100.0	67.2	25.9	87.9	1.7	—	—	4.3
% wood (high = 3)	—	7.0	16.7	—	—	—	—	—
% other (mixed = na)	—	1.7	9.3	—	—	—	—	—

Sources: US Census 2000 block group data; CAP LTER Land Use Study; Landsat ETM+, Geological Remote Sensing Laboratory, Arizona State University, May 21, 2000; Maricopa County Assessor.

HTCI differences between neighborhoods for the entire summer ($F = 17.16$, $p < .001$). The 5:00 pm summer average marked a 39-point HTCI inter-neighborhood difference, with the warmer places approaching the 200 "danger" threshold (see Table 1, 40 °C on NOAA's Heat Index). During the July heat wave, HTCI values passed the threshold of the "danger" zone for seven of eight neighborhoods, and the range of mean differences between the neighborhoods increased to 73 points ($F = 5.94$, $p \leqslant .001$). *Historic Anglo Phoenix* offered its residents a singular advantage: during the heat wave the 5:00 pm HTCI was lower than in some of the other neighborhoods during normal summer days.

The last column of Table 3 shows the percentage of all hours during the 24-h/92-day summer period with 5:00 pm temperatures that passed the HTCI 200-point "danger" threshold. In the two neighborhoods with the lowest mean temperatures, only 4–6 percent of hours were classified above the threshold, but in *Black Canyon* and *New Tract*, the two neighborhoods with the highest mean temperatures, 1 of every 5 h (or 20 percent) was classified in the danger zone. Based on the analysis in this section, our first hypothesis was supported: there were statistically significant differences in temperature and exposure to heat stress among these neighborhoods.

Table 3
Average air temperature (C) and Human Thermal Comfort Index (HTCI), summer 2003 at 5 pm in eight Phoenix neighborhoods

Neighborhood	Mean (sd) air temp summer 2003 5:00 pm[a]	Mean (sd) air temp heat wave 2003 5:00 pm[b]	Increase in air temp during heat wave	Mean (sd) HTCI summer 2003 5:00 pm	Mean (sd) HTCI heat wave 2003 5:00 pm	Increase in HTCI during heat wave	Pct summer 2003 hours ⩾200 HTCI
Historic Anglo Phoenix	37.3 (2.5)	40.2 (3.1)	2.9	158 (26)	186 (35)	28	4.2
North Desert Ranch	38.4 (3.0)	43.3 (2.7)	4.9	166 (31)	215 (37)	49	5.9
West Side Suburban	39.0 (3.2)	43.7 (2.7)	4.7	175 (33)	220 (37)	45	11.0
South Mountain Preserve	39.3 (2.8)	44.4 (2.6)	5.1	176 (29)	226 (35)	50	15.9
North Central Apartments	39.5 (2.7)	44.5 (3.1)	5.0	178 (28)	226 (44)	48	18.4
Historic Mexican Phoenix	40.6 (2.8)	45.6 (2.9)	5.0	196 (31)	245 (37)	49	14.8
New Tract Development.	40.9 (3.0)	45.5 (3.1)	4.6	193 (32)	238 (44)	45	22.2
Black Canyon Freeway	41.3 (3.3)	47.7 (3.4)	6.4	197 (33)	259 (42)	62	19.8
Mean: All	39.5 (3.4)	44.4 (2.3)	4.8	180 (36)	227 (28)	47	14.0
Difference: highest–lowest	4.0	7.5	3.5	39	73	44	18.2
ANOVA	$F = 16.39^{***}$	$F = 22.98^{***}$		$F = 17.16^{***}$	$F = 5.94^{***}$		

Sources: HOBO climate weather stations and OUTCOMES.
$^{***}p < .001$.
[a]Summer dates were June 1–August 31, 2003. Neighborhoods ordered from lowest to highest mean summer temperature at 5:00 pm.
[b]Heat wave dates were July 12–16.

Neighborhoods and human thermal comfort

The correlations in Table 4 show that neighborhoods with lower median incomes, lower educational attainment, higher poverty rates, and more minorities had significantly higher HTCI scores. The very young and the elderly, however, were not more likely to live in neighborhoods with higher HTCI scores. Although median age was negatively correlated with HTCI, this is attributable to the fact that two predominately Mexican-American neighborhoods with high HTCI scores, *Black Canyon* and *Historic Mexican Phoenix*, had much larger young adult populations than other neighborhoods (Table 2).

There was no association between neighborhood distance from the urban center and HTCI (see also Table 2 and Fig. 1). Both the warmest, most uncomfortable neighborhood and the coolest, most comfortable one were located in the urban core. The urban fringe contained neighborhoods with large HTCI differences as well. Much more important than distance in determining temperature and residents' exposure to heat was the spatial and ecological configuration of the neighborhoods. Places that were less densely settled with some open space and more abundant vegetation were more comfortable environments in the summertime. The correlation between vegetation (SAVI) and HTCI was statistically significant for the eight sites (Table 4). This is primarily because SAVI identified *Historic Anglo Phoenix* as the "greenest" neighborhood, an important point to which we return below. The relationship between SAVI and HTCI was stronger during the heat wave. Our second hypothesis was supported: lower-income and minority populations were exposed to higher temperatures and the corresponding health risks associated with more crowded and less green neighborhood environments.

Resources for coping with extreme heat were severely limited in the neighborhoods with higher

Table 4
Correlation of human thermal comfort Index (HTCI) with population characteristics, thermal environment characteristics, and coping resources in eight Phoenix neighborhoods

Neighborhoods	Mean (sd)	Min/max	Correlation with mean HTCI summer 2003 5:00 pm	Correlation with mean HTCI heat wave 2003 5:00 pm
Population				
Median income	\$60,473 (\$27,436)	\$25,785/\$107,230	−.68**	−.65**
% below poverty line	12.3 (15.3)	1.6/43.8	.64**	.63**
% less than high school	20.8 (24.7)	1.8/63.9	.73**	.73**
% minority	31.8 (34.8)	9.3/90.9	.69**	.65**
Median age	32.3 (5.6)	22.5/37.7	−.66**	−.74**
% ages 5 and under	11.5 (3.8)	9.6/18.7	.06	.14
% ages 65 and over	8.0 (7.0)	1.9/21.4	.07	−.03
Thermal environment				
Distance from city center (km)	15.3 (10.9)	2.6/33.5	−.18	−.07
Population/km^2	2434 (2676)	314/8687	.58*	.64**
% open space	.05 (.07)	0/.18	−.65**	−.53*
Vegetation abundance (SAVI)	.493 (.032)	.47/.57	−.54*	−.63**
Coping resources				
Social ties index	.06 (.36)	−.64/.50	−.85**	−.88**
% houses with air conditioning	74.5 (36.8)	6.0/100	−.71*	−.68**
% houses with swimming pools	28.8 (23.4)	4.0/59.0	−.83***	−.73**
Mean roof reflectivity	1.4 (.45)	1.0/2.0	−.36	−.36

Sources: US Census 2000 block group data; CAP LTER Land Use Study, Landsat ETM+, Geological Remote Sensing Laboratory, Arizona State University, May 21, 2000; Maricopa County Assessor.
*$p<.10$.
**$p<.05$.
***$p<.01$ (one-tailed tests).

HTCI (Table 4). Social ties, the percentage of homes with central air conditioning, and with private pools were negatively correlated with the heat index. In our sample, 100 percent of the homes in upper-income and newer middle-income neighborhoods as well as the majority of homes in older middle class neighborhoods had central air conditioning. Almost all houses in the low-income Hispanic neighborhoods were without it (Table 2). Although every second house in the upper-income neighborhoods had a backyard swimming pool, most middle-income families and virtually all lower-income families did not. (Some people may have installed window refrigeration units or used community pools that were not recorded in the Assessor's database.) The correlation with roof reflectivity was in the expected direction but it was not significantly correlated with HTCI. Our last hypothesis was supported: residents in the most heat-stressed neighborhoods had inferior resources to cope with extreme heat.

Case studies of neighborhood environments and vulnerability to heat

The area with the highest HTCI value is the archetypical poor inner-city neighborhood with nearly three times the population density as the next most densely inhabited neighborhood in our sample. *Black Canyon Freeway* abuts an Interstate highway, and it is noisy, dusty, and crowded. It serves as a landing spot for many new arrivals from Mexico, virtually all of whom rent (or reside with family and friends who rent) a wide assortment of apartments in large buildings or detached and semi-detached houses built from the 1920s through the 1980s. The average length of residence in *Black Canyon* is about 1.5 years, which may be the reason they have by far the lowest level of social ties (z-score = −.64) among the eight neighborhoods. Residents have low educational attainment, low income, and many speak only Spanish.

An aerial photograph shows the proximity of the freeway, a source of anthropogenic heat from asphalt pavement and high vehicular traffic (Fig. 2a). Although there are some yards with grass and trees in the neighborhood, public alleys, non-landscaped yards, and vacant lots with exposed soil are prevalent. Fig. 2b is a map of the average SAVI value per pixel, in which darker shades indicate more abundant vegetation. It shows many areas of sparse vegetation in *Black Canyon Freeway*. This neighborhood is bordered by commercial land use and other dense residential development. There is no park or other green public space within the neighborhood, although at the time of the study, a small playground for children had recently been completed nearby. Almost no detached homes have air conditioning and, although most people lived in apartments that had central air installed, a neighborhood activist told us that it is often broken. She also said:

> I know that it's cooler to sleep outside than inside. And so a lot of families will be sleeping outside in the hot summer…. The fire department will come over and bring cases of water and fans and those sorts of things to facilitate families.

Historic Anglo Phoenix is 4 km from *Black Canyo*n *Freeway* and even closer to downtown, but it has the lowest HTCI value and is also the opposite of *Black Canyon Freeway* in almost every respect. *Historic Anglo Phoenix* contains some of the oldest homes in Phoenix (1920–1940) and, although the homes and lots are small by current upper-income standards, they have been renovated and are highly sought after by professionals who enjoy the convenience of a downtown location and the prestige of living in a historic preservation neighborhood near the largest green park in the city.

Residents live on palm tree-lined streets with single family houses that have grassy yards supplemented with shade trees, citrus, and dense tropical plantings (Fig. 3a). This neighborhood is ''flood irrigated,'' a formerly common but increasingly rare practice of opening city water mains to saturate lawns. A green park in the neighborhood provides open space in addition to the adjacent city park. The abundant greenery is evident in Fig. 3b, which shows high SAVI values everywhere but in the northwest corner of the neighborhood. The abundant greenery, which is a controlling influence on microclimates and is especially important during heat waves, was carefully cultivated by residents. In addition, residents have many resources to mitigate summer heat, including an active neighborhood association and the highest social ties in the sample (z-score = .50). An officer in the association offered this appraisal of local heat control:

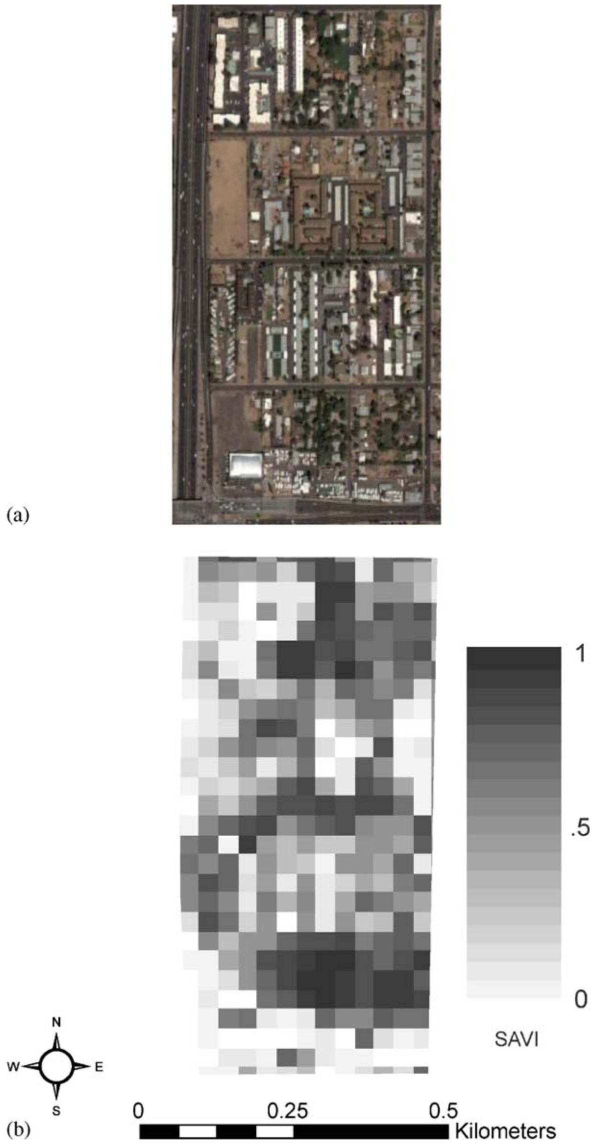
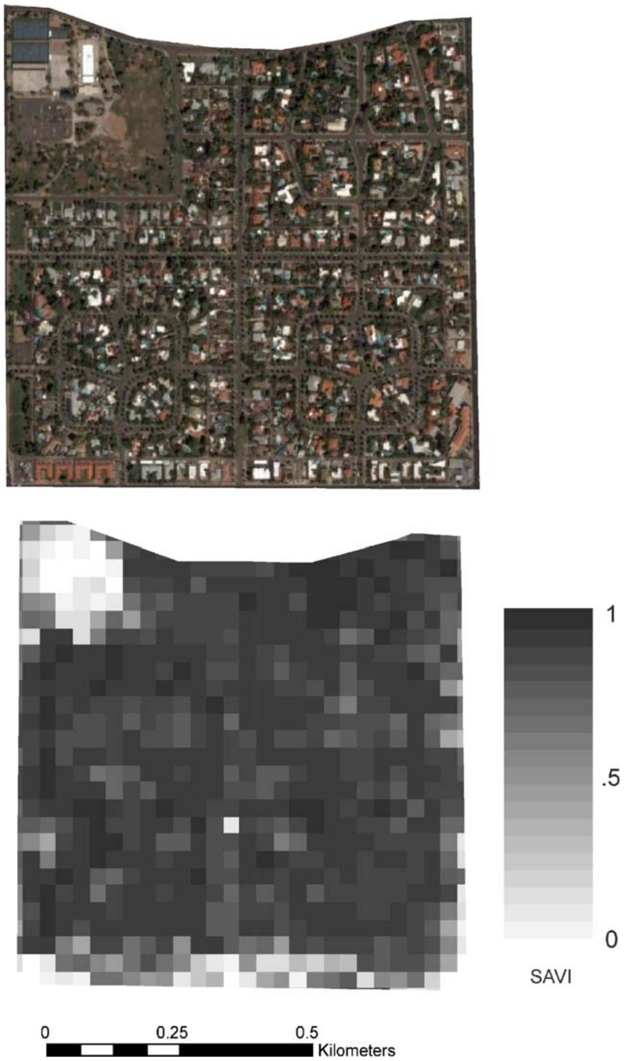


Fig. 2. (a) Aerial photograph of Black Canyon Freeway neighborhood, 2000 (Interstate highway extends along the left-hand side of the image), (b) map of average pixel values for the Soil-Adjusted Vegetation Index (SAVI) in Black Canyon Freeway, May 21, 2000, 10:00 am.

> I have air conditioning and swamp [evaporative] coolers. My house is really well-insulated. In the winter it doesn't get below 64 °F [17.7 °C] and in

(a)



(b)

Fig. 3. (a) Aerial photograph of Historic Anglo Phoenix neighborhood, 2000, (b) map of average pixel values for the Soil-Adjusted Vegetation Index (SAVI) in Historic Anglo Phoenix, May 21, 2000, 10:00 am.

> the summer it's 81 or 82 °F [27.2 or 27.7 °C] inside. The porch makes a big difference and I have fans.... The irrigation [flood lawn irrigation] has a cooling effect. When there's a breeze, the sprinklers create evaporative cooling. The irrigation and sprinklers in the park keep coolness in. There's a lot of shade... The older houses stay cooler because they're thick plaster with brick walls.

The middle-income *New Tract Development* neighborhood is located on the northern edge of the city. In contrast to the open spaces of wealthier urban fringe neighborhoods, *New Tract Development* represents middle class life in the newer housing developments. Despite its distance from the central city, it is the second warmest neighborhood in the sample and its HTCI and percent of summer hours above the ''Danger'' zone for heat stress are similar to *Black Canyon Freeway* (Table 3).

The ecological configuration of *New Tract Development* gives strong clues about why it is so hot. The aerial photo shows how closely spaced the homes are in the recently-built subdivisions where our HOBO measured the temperature (Fig. 4a). *New Tract Development* has the lowest lot to house size ratio of any neighborhood in the sample; it has 2 mobile home parks and is 3 times more densely settled than *North Desert Ranch*, an upper-income fringe neighborhood. Nearly half the land use in the block group is classified as ''vacant'' (as opposed to ''open'') because it is surrounded by dense development and not in active use. (The hilly, rocky butte that divides the neighborhood would be difficult—and hence more expensive—to build upon.)

New Tract Development and *Black Canyon Freeway* are the only neighborhoods that do not either have a park within their boundaries or share a border with a grassy park or native desert. Vegetation in this area is desert scrub and nearly 80 percent of the front yards are ''xeriscaped,'' a type of desert landscaping with crushed granite ground cover and drought-tolerant plants. The SAVI map in Fig. 4b indicates the overall sparse vegetation: most of the greenery in the neighborhood is in the schoolyard (southwest corner) and even the vacant land has more vegetation than the yards. With a great deal of exposed rocky ground cover and dense housing, *New Tract Development* would be expected to retain solar heat during the day. Social ties in this neighborhood are second lowest (z-score $= -.17$) and there are few swimming pools (14 percent), but most *New Tract Development* residents have some resources for mitigating outdoor heat: they live in relatively new homes with air conditioning and tile roofs.

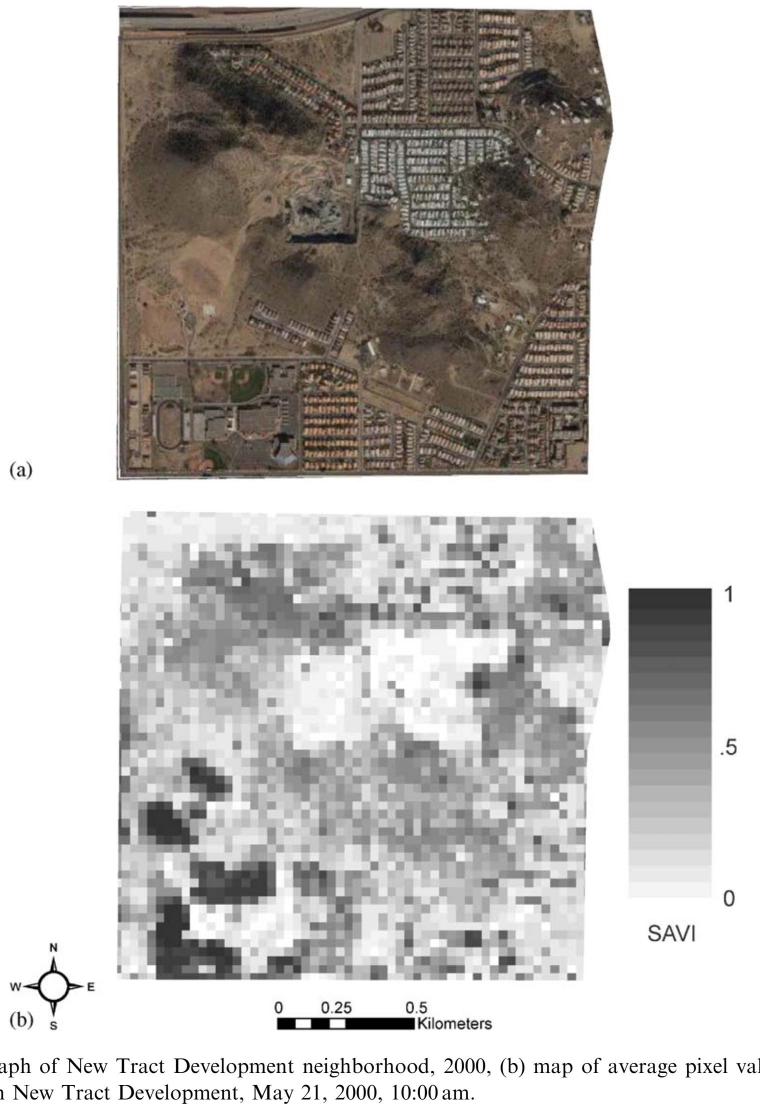


Fig. 4. (a). Aerial photograph of New Tract Development neighborhood, 2000, (b) map of average pixel values for the Soil-Adjusted Vegetation Index (SAVI) in New Tract Development, May 21, 2000, 10:00 am.

Conclusions

This study used multi-disciplinary data to address an important public health problem that is under intense scrutiny by international and governmental agencies seeking to reduce illness, mortality, and other costs of extreme heat experienced by cities in all types of climate regimes (ICLEI, 1998). We found significant 2003 summertime temperature variations among Phoenix neighborhoods. Simulated estimates of exposure to heat stress showed that the warmer neighborhoods more often exceeded the "danger" threshold in summer 2003. Unequal exposure was a chronic summer problem as well as an acute problem during a heat wave when differences in the heat index increased significantly.

In answering our first research question, we found a pattern of positive correlations between heat stress exposure and percentages of poor and minority inhabitants. Higher-income, predominately white neighborhoods were more comfortable places than lower-income, predominately Hispanic neighborhoods, and middle-income neighborhoods varied widely in HTCI values.

With respect to our second question, our findings challenged the idea that the heat island is a smooth urban-to-rural gradient in sprawling urban areas. Level of exposure to heat stress was highly correlated with place-specific measurements of ecological variables–vegetation density and open space—regardless of neighborhood locations. This is an important fact about the spatial distribution of the UHI, its relationship to the socio-ecology of neighborhoods, and its potential contributions to climate-related health inequalities in cities. Estimates of local temperature variation and human exposure to excessive heat in this study were far more spatially specific than the standard practice of reporting temperature from a single central weather station for a city, which may significantly over-estimate or under-estimate weather conditions in diverse parts of a region (e.g., Basu & Samet, 2002; Brazel et al., 2000).

The vulnerability of warmer neighborhoods was exacerbated by residents' lack of adequate social and material resources to cope with extreme heat. In answer to our third question, social networks were weakest in the warmest places. And contrary to the impression of many Phoenicians and summer visitors, desert-living does not come with an entitlement to air conditioning and a swimming pool. Warmer neighborhoods had fewer of these amenities because of the age or price of their homes. A much higher percentage of roofs in the poor neighborhoods were "rolled" roofs, an asphalt product that is even inferior to shingles. In sum, our research supports the fundamental environmental justice hypothesis: risks incurred from environmental hazards are greater for marginalized populations.

The practical use of this study is to suggest that reducing temperatures in vulnerable urban neighborhoods should be a priority driven by informed policy. Many cities and coalitions of cities, supported by national and international organizations, such as the US Environmental Protection Agency and the International Council for Local Environmental Initiatives, have initiated programs for heat island mitigation using three principle strategies: increasing vegetation cover in public spaces, adopting standards for reflective roofing and paving materials, and lowering anthropogenic emissions (City of Phoenix, 2004; Rosenfeld, Akbari, Romm, & Pomerantz, 1998; Rosenfeld et al., 1995). Heat/Health Warning Systems initiated by NOAA have also been instituted in Phoenix and many other cities (Sheridan & Kalkstein, 2004). More could be done, however, to target heat reduction resources and heat warnings to the specific places where they are most needed. Prime candidates for these programs are low-income inner-city neighborhoods and the burgeoning number of middle class communities being built on the urban fringes of development.

The poor, minority inner-city neighborhoods of Phoenix, similar to those in many cities, lack adequate housing, shade, and green open space. There is little new construction, so changing building requirements for new homes is not an option to improve conditions in those neighborhoods. However, public expenditures to improve the quality of existing housing and provide shade, green parks and community swimming pools would be effective heat mitigation measures and would increase the health and comfort of residents.

Neighborhoods built for the masses on the edges of metropolitan areas ultimately will house many more people than those in the inner-city. The agricultural fields and desert fringe surrounding Phoenix, once the province of a few wealthy settlements in natural settings, is being carved into smaller and smaller lots to house middle class families. As *New Tract Development* illustrates, dense settlements built to accommodate growth and demand for less expensive housing are enlarging the Phoenix UHI. Deforestation and heat island expansion are typical of many urban areas in the US that are losing trees at a rapid rate to the population pressure of urban sprawl (American Forests, 2005). In addition, the spread of development creates longer commutes to work and the increased traffic volume is a major source of anthropogenic heat that contributes to the UHI (Grossman-Clarke et al., 2005). Thus the total climate implications of urban sprawl cannot be remedied only by stricter building codes and heat-resistance materials. More holistic approaches to regional planning are needed that include alternative modes of transportation, mandates for increasing tree cover to replace native vegetation, and preservation of open space to moderate temperatures in modest neighborhoods on the urban fringe.

One great challenge for creating climate health equity in cities is the legacy of urban development that has left poor and minority populations in deteriorated urban spaces where there are structural constraints on improving environmental conditions. The locations of neighborhoods near transportation routes and industrial corridors result from historical patterns of enforced segregation, zoning regulations, and other municipal decisions, which are part of an on-going process of environmental inequality formation (Pellow, 2000). In order to reverse decades of disadvantage, a planned municipal and regional strategy for facilitating neighborhood social networks, granting greater community control over adjacent land use, and enforcement of environmental laws will be needed.

The second challenge is that future growth of cities in arid regions may exceed the supply of environmental resources necessary for human health and comfort. Land and water are two important resources for mitigating heat, but they are being used up rapidly. Phoenix is in a long-term drought, which is not uncommon in arid regions around the world. Although increasing tree cover and planting green open spaces are obvious responses to the UHI in a temperate city, such as Chicago, in arid climates the benefits of adding vegetation must be weighed against potential water shortages. Policies for UHI mitigation and the attendant health benefits of doing so must be carefully articulated with other urban environmental issues, such as long-term land preservation, water supply, and air quality. The distribution of these environmental amenities are justice issues that scientists, health researchers, engineers, planners, and the public must consider in creating healthier places for all people to live.

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