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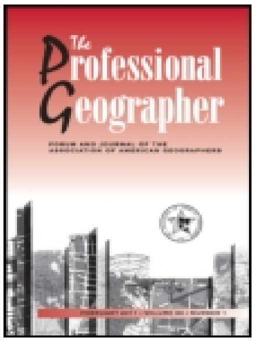

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# Vulnerability to Extreme Heat in Metropolitan Phoenix: Spatial, Temporal, and Demographic Dimensions*

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This study assessed the spatial distribution of vulnerability to extreme heat in 1990 and 2000 within metropolitan Phoenix based on an index of seven equally weighted measures of physical exposure and adaptive capacity. These measures were derived from spatially interpolated climate, normalized differential vegetation index, and U.S. Census data. From resulting vulnerability maps, we also analyzed population groups living in areas of high heat vulnerability. Results revealed that landscapes of heat vulnerability changed substantially in response to variations in physical and socioeconomic factors, with significant alterations to spatial distribution of vulnerability especially between eastern and western sectors of Phoenix. These changes worked to the detriment of Phoenix's Hispanic population and the elderly concentrated in urban-fringe retirement communities. **Key Words: adaptive capacity, physical exposure, urban heat island, vulnerability.**

本研究基于有关身体暴光和适应能力的七个测量值的一个平均加权指数，评估凤凰城大都会在 1990 和 2000 年极端高温脆弱性的空间分布。这些测量值来源于空间气候插值，归一化差分植被指数，和美国人口普查数据。从产生的脆弱性图，我们也分析了生活在高热脆弱性地区的人口群体。结果显示，热脆弱性景观对应于物理和社会经济因素的变化大大地改变了，特别是在凤凰城东部和西部之间，热脆弱性有重大改变。这些变化损害到凤凰城的西班牙裔人口和集中在城市边缘退休社区的老人。**关键词：适应能力，身体暴光，城市热岛，脆弱性。**

Este estudio evaluó la distribución espacial de la vulnerabilidad al calor extremo en 1990 y el 2000 dentro del área metropolitana de Phoenix, sobre la base de un índice de siete medidas igualmente ponderadas de exposición física y capacidad de adaptación. Estas medidas se derivan del clima interpolado espacialmente, del índice normalizado de vegetación diferencial, y datos censales de EE.UU. A partir de mapas de vulnerabilidad también se analizaron grupos de población que viven en zonas con vulnerabilidad a las altas temperaturas. Los resultados revelaron que los paisajes con vulnerabilidad al calor cambiaron sustancialmente en respuesta a variaciones en factores físicos y socioeconómicos, con modificaciones importantes en la distribución espacial de la vulnerabilidad, especialmente entre los sectores este y oeste de Phoenix. Estos cambios se dieron en detrimento de la población hispana de Phoenix y los ancianos concentrados en comunidades de jubilación urbano-marginales. **Palabras claves: capacidad de adaptación, exposición física, isla de calor urbano, vulnerabilidad.**

Metropolitan Phoenix, encompassing the City of Phoenix and twenty-six other municipalities and Native American communities in central Arizona (Figure 1), is one of the nation's largest and fastest growing urban agglomerations in both population size and land area (U.S. Census 2007). Its subtropical desert location presents an extreme climate with low total annual precipitation and high average maximum temperatures. Exposure to extreme heat is a potentially serious issue to its residents, especially during the summer months when daytime temperatures regularly exceed 43°C (110°F). Extreme heat is

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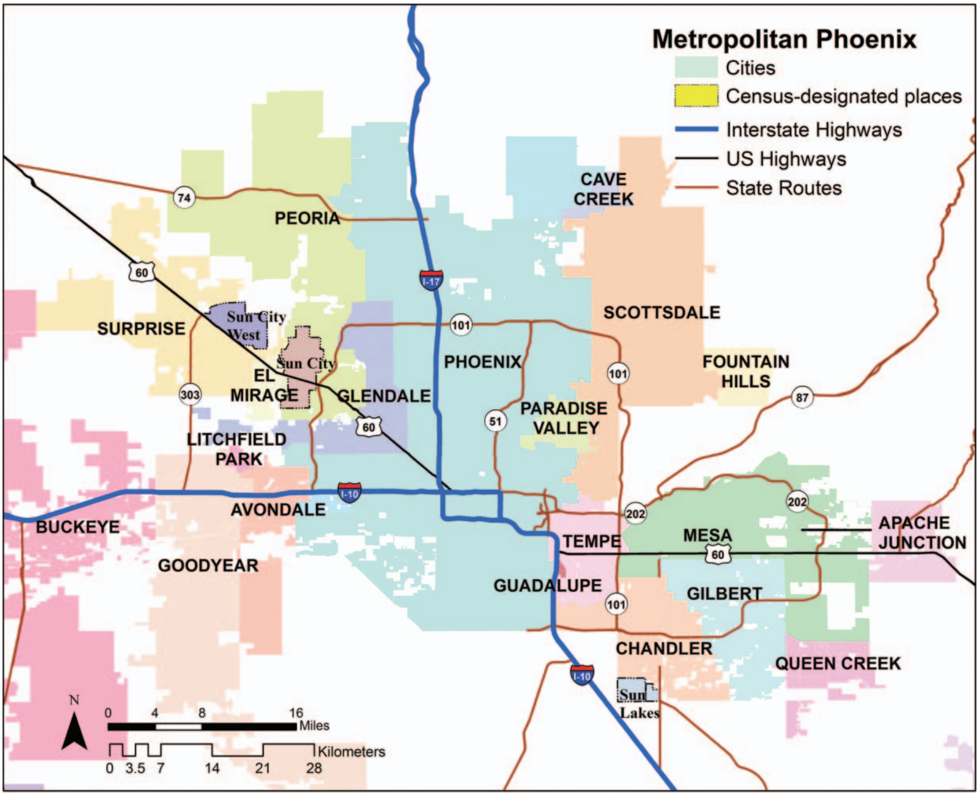

**Figure 1** *Metropolitan Phoenix and its constituent cities and census-designated places in 2000. (Color figure available online.)*

exacerbated by the growth of the city's strong near-surface urban heat island (UHI), which can raise nighttime temperatures by more than 6°C (10.8°F; Baker et al. 2002). Prolonged exposure to high temperatures has been shown to be hazardous to human health, especially when critical temperature thresholds are suddenly exceeded as, for example, during early onset of summer (Sheridan and Kalkstein 2004). Severe temperatures also have detrimental effects on human morbidity and mortality, as seen in the July 1995 Chicago heat wave that killed 700 (Semenza et al. 1996; Klinenberg 1999) and in the July and August 2003 Western European event that killed 35,000 (Stott, Stone, and Allen 2004). More than 250 deaths in Arizona were attributable to exposure to extreme heat between 1993 and 2002; the rate of age-adjusted deaths from heat exposure was the highest in the nation (Centers for Disease Control and Prevention [CDC] 2005).

The purpose of this article is to examine the spatial and temporal changes in vulnerability to extreme heat in Phoenix between 1990 and 2000. To this end, we (1) developed a metric for heat stress vulnerability based on measures of physical exposure (e.g., maximum and minimum temperatures) and adaptive capacity of the human population (e.g., income and social stability), (2) examined the spatial pattern of this metric in both 1990 and 2000, and (3) determined what proportion of different racial and ethnic minority populations lived above a critical threshold in vulnerability in both time periods. We refer to Phoenix as the entire metropolitan area and City of Phoenix as the municipality that constitutes the metropolitan core city.

## Urban Heat Island Research in Phoenix

The UHI is the most obvious, yet inadvertent, impact of urbanization on local-scale weather and climate. It is generally strongest at night when excess heat stored in urban surfaces during the daytime is released to the atmosphere. Its intensity is determined by factors such as surface material type, sky-view factor (exposure of urban surfaces to the sky), and synoptic weather conditions (Oke 1982). The large-scale urbanization of Phoenix has been accompanied by a UHI of growing intensity and expanse (Hsu 1984; Sun et al. 2009). Maximum magnitudes occur during summer nighttime hours and can exceed 8°C under ideal conditions (Balling and Cerveny 1987; Hedquist and Brazel 2006). Urban–rural temperature differences are either negligible (~1–2°C) during the day or lower in the city where irrigated residential landscaping and surrounding farmlands increase evapotranspiration, resulting in a cooling effect—a phenomenon called the "desert oasis effect" (Brazel et al. 2000). At night, temperatures are highest in the urban core and diminish with proximity to the urban fringe (Balling and Brazel 1987). UHI intensity also increases in response to land-use change from new home construction and land development (Hawkins et al. 2004; Grossman-Clarke et al. 2005; Brazel et al. 2007; Grossman-Clarke et al. 2008).

A parallel set of studies addressed the human consequences of UHI development in Phoenix, including increased "misery hours per day" where apparent temperatures exceed 37°C (100°F) and greater cooling degree hours per year (Baker et al. 2002). The UHI has also been shown to increase residential water use (Guhathakurta and Gober 2007), costs of cooling buildings during peak energy use summer months (Golden et al. 2008), and the increased potential for heat stress, especially among vulnerable segments of the urban population (Harlan et al. 2006).

Given these detrimental impacts, more attention is now being paid to physical and social indicators of vulnerability to extreme heat in Phoenix and elsewhere. These indicators can potentially guide mitigation strategies. These include replacing impervious surfaces with more porous materials (Stone and Norman 2006), modifying thermal characteristics of buildings by increasing albedo (Sailor 1995), and using materials with low thermal inertia for individual buildings (Emmanuel and Fernando 2007). A particularly fruitful UHI mitigation strategy in Phoenix is to increase the spatial coverage of irrigated vegetated surfaces (Gober et al. 2010), which has been shown to be effective in reducing near-surface urban temperatures in several City of Phoenix suburban neighborhoods (Stabler, Martin, and Brazel 2005).

## Assessing Vulnerability to Heat Stress

Vulnerability of human populations to extreme temperatures and other environmental hazards is usually defined as the degree to which they are likely to experience harm due to exposure (Turner et al. 2003). Such harm depends on both (1) physical exposure to extreme heat and (2) a population's adaptive capacity. The latter is the ability to mitigate risk through mechanisms such as air-conditioning or irrigated landscaping to cool areas surrounding the home and immediate neighborhood or through adjustments in behavior, such as staying indoors during excessive heat warnings or finding help in case of an emergency instead of remaining socially isolated. Conceptualizations of human vulnerability to any environmental risk thus require attention to the physical event itself and to social vulnerability, the capacity of the social system to respond and adapt to that risk (Cutter and Finch 2008).

The capacity to respond to hazards has been linked to racial and ethnic status, income level, gender, age (young children and the elderly), migration status, and housing tenure (Ngo 2001; Heinz Center 2002; Wisner et al. 2004; Mayhorn 2005; National Research Council 2006). Populations lacking in economic assets and access to public support systems, with diminished physical or cognitive capacities to respond to warnings and missing strong and enduring social support systems, are least able to adapt and thus the most vulnerable to a hazardous event.

Attempts to map vulnerability are fraught with data comparability and methodological and conceptual challenges. The onset of climate change has increased the imperative to map and explain social vulnerability at national and subnational levels and changes therein. In a U.S. county-level study, Cutter and Finch (2008) found that the quality of the built environment, age, race and ethnicity, and gender accounted for half of the spatial variation in social vulnerability in U.S. counties. Substantial changes in distribution occurred between 1960 and 2000, with high vulnerability becoming more focused on the U.S.–Mexico border region. High social vulnerability in 2000 was associated with urban development, race and ethnicity, and poverty. At the subnational scale, Cutter, Mitchell, and Scott (2000) included both biophysical and social indicators into an assessment of vulnerability in Georgetown County, South Carolina. They found that areas of the highest biophysical vulnerability did not overlap with areas of the highest social vulnerability. The most vulnerable places instead combined medium levels of biophysical vulnerability with medium to high levels of social vulnerability. The significance of this finding is that it would take only a moderate-level physical event to disrupt the livelihoods and well-being of many residents.

There have been numerous efforts to assess vulnerability to hazards in Phoenix from an environmental equity and social justice perspective (Bolin et al. 2000; Bolin et al. 2002; Grineski, Bolin, and Boone 2007). Bolin et al. (2000), for example, studied the population characteristics of those exposed to hazardous industrial and toxic waste sites and found that these were disproportionately located in areas where low-income, racial and ethnic minorities tend to live. The spatial concentration of hazardous facilities, in conjunction with the segregated nature of the City of Phoenix's disadvantaged populations, led to a highly unequal environmental burden borne by the region's lower income and racial minority populations.

The problem of heat stress as a hazard has gained currency in Phoenix in light of the intensifying UHI and in anticipation of a warmer climate associated with climate change. Harlan et al. (2006) recorded temperatures in eight City of Phoenix neighborhoods of differing socioeconomic characteristics and developed a human thermal comfort index (a measure of heat stress) based on the energy balance of a person exposed to the surrounding microclimate and thermal radiative environment. High heat stress exposure was significantly and positively correlated with high population densities and heavily Hispanic populations and negatively associated with access to open spaces and irrigated vegetation and income. Homes in areas with higher-than-average physical exposure to heat were, in the main, less well adapted to accommodate heat stress (i.e., no swimming pools and lower albedo roofs), as well as less well-developed social networks. Equally troubling was that many poor neighborhoods exposed to severe heat housed residents who spoke only Spanish and who were newcomers to the city. Thus, high physical exposure was coincident with high social vulnerability, rendering poor residents highly vulnerable to harm from extreme heat.

Given the importance of irrigated vegetation in UHI mitigation, Jenerette et al. (2007) used a path model to examine social determinants of surface temperature and vegetation patterns. They argued that social vulnerability to heat operates through the ability to (1) modify land cover by vegetation and (2) live at lower urban densities. In their view, well-off Phoenicians used superior social and economic status to maintain low-density housing units with much irrigated vegetation to reduce heat stress.

Golden et al. (2008) documented deleterious health consequences of heat exposure using information about 2001 through 2006 heat-related emergency dispatches (HRD) for most of Phoenix. Annual, monthly, and day-of-week distributions of HRD were correlated with several climate variables, including a human comfort index based on assorted climate data from several Phoenix climate stations. Heat-related health emergencies were strongly related to maximum temperature, elevated human comfort and heat indexes, and temporal exposure to excessively high solar irradiance, especially during summer.

Maximum temperature is one of the most important components in the physical exposure to heat vulnerability in Phoenix. Ruddell et al. (2009) developed a "riskscape" of heat stress across forty City of Phoenix neighborhoods during a four-day heat wave in July 2005 and found that (1) the distribution of extreme heat varied in space; (2) neighborhoods exposed to higher temperatures significantly correlated with results of survey respondents who perceived greater heat stress; and (3) elderly, minority, and low-income residents were more exposed to heat stresses than their younger, white, more affluent counterparts.

The substantial and growing literature dealing with heat stress in Phoenix has established that physical exposure is linked to reported health emergencies and human perceptions of discomfort. Moreover, the social and ecological structures are intimately intertwined with physical exposure as people with wealth and social status manipulate their immediate neighborhoods (i.e., through planting trees, maintaining lawns, and living at lower densities) to reduce temperatures. Physical exposure thus affects social groups unequally, with socially vulnerable populations experiencing the most heat. Lacking from these studies, however, is a systematic spatio-temporal assessment of vulnerability to heat stress for metropolitan Phoenix, incorporating both biophysical variables and measures of social sensitivity and resilience.

## Study Area and Methodology

Between 1990 and 2000, Phoenix experienced rapid growth in both population (2.24 to 3.25 million; increase of 45 percent) and land area (1,223 to 2,069 km$^2$; increase of 69 percent). Changes in surface conditions accompanying rapid urbanization profoundly changed the local landscape, demography, and ecosystem, with potential consequences for heat vulnerability (Keys, Wentz, and Redman 2007). Our study specifically focused on the Phoenix urbanized area as defined by the 2000 U.S. Census. We derived a composite heat vulnerability index ($VI_{\mathrm{total}}$) from seven measures that are proxies for physical exposure and social vulnerability or adaptive capacity (Table 1). Given the complexities of mapping vulnerability with disparate data sets reviewed in the previous section, it is difficult to determine a priori if any one measure is of more importance than others. We thus assumed that each measure is of equal importance in estimating extreme heat vulnerability.

Near-surface (2 m) maximum ($T_{\max}$) and minimum ($T_{\min}$) air temperatures in June are indicators of physical exposure. These data were obtained from thirty-seven meteorological stations distributed across different land-use types throughout Phoenix. These stations are part of several well-established, professionally operated meteorological networks used for prior UHI analysis (Brazel et al. 2007). June was selected because average monthly weather conditions were favorable to UHI development, with numerous hot, clear and calm days and nights. Further, extreme heat events occurring in June as opposed to late summer are more likely to result in heat-related injuries because residents are less adapted to early-summer "shocks" (Environmental Protection Agency [EPA] 2006). Mean June temperatures were averaged over five years from 1990 to 1994 and 2000 to 2004 to even out the effects of annual synoptic weather variations. June maximum temperatures ($T_{\max}$) usually occur between 4 and 5 p.m. Conversely, $T_{\min,}$ the minimum temperature, tends to occur around sunrise, and spatial variations in $T_{\min}$ reflect UHI effects. Higher $T_{\max}$ and $T_{\min}$ magnitudes are indicators of greater heat vulnerability.

The normalized differential vegetation index (NDVI) from multispectral satellite imagery has been widely used for measuring and monitoring plant growth, vegetation cover, and biomass production (Lillesand, Kiefer, and Chipman 2004). It utilizes the fact that healthy vegetation has high (low) reflectance to near-infrared (visible) bands. NDVI ranges between ±1, with positive values indicating denser surface vegetation. NDVI was derived from Landsat ETM+ images acquired on 19 June 1990 and 14 June 2000 at a resolution of 28.5 m per pixel, and these represented vegetation density during the summers of 1990 and 2000, respectively. Areas with high NDVI are assumed to have more effective cooling properties and would reduce exposure and potential vulnerability.

We selected four measures of social vulnerability to characterize the human system's capacity to adapt to extreme heat conditions. These measures were extracted from U.S. Census data at the census tract level. They reflect an individual's capacity to adapt to heat as well as the likelihood that the social setting will support the adaptation process. In terms of individual characteristics, the elderly have been shown to be more sensitive to heat stress than younger populations because of a biological predisposition to harm (Smoyer, Rainham, and Hewko 2000). We thus selected the total population above the

***Table 1*** *Measures for vulnerability index to extreme heat, their sources, and what they indicate*

| Measure | Source | Indicator of/relationship to total vulnerability |
|---|---|---|
| Physical exposure | | |
| 1. Mean summer maximum temperature ($T_{\max}$) from June 1990–1994 and 2000–2004 | 37 meteorological stations (Brazel et al. 2007) | Daytime heat stress from regional climate change/ positive |
| 2. Mean summer minimum temperature ($T_{\min}$) from June 1990–1994 and 2000–2004 | | Nocturnal heat stress from urban heat island/positive |
| 3. Mean normalized difference vegetation index (NDVI) | Landsat ETM+ data | Cooling potential from vegetation evapotranspiration/negative |
| Adaptive capacity | | |
| 4. Population > 65 years of age (Pop_over65) | U.S. Census | Population most vulnerable to heat stress/positive |
| 5. Median household income (Med_inc) | | Wealth or poverty/negative |
| 6. Population of foreign-born noncitizens (Pop_FBNC) | | Social integration/positive |
| 7. Population living in different residences from 5 years prior (Diff_hous_5) | | Social instability/positive |

age of sixty-five years (Pop_over65) to account for this tendency to extreme heat vulnerability. We also used household income (Med_inc) as a surrogate for a household's ability to use refrigeration or irrigated landscaping to manage heat stress, as Jenerette et al. (2007) showed that greater wealth enables Phoenix households to mitigate heat stress.

The third and fourth indicators measure the social structure's ability to mitigate risk when individuals are physically exposed. The size of a census tract's foreign-born, noncitizen population (Pop_FBNC) is a proxy for populations with difficulty in heeding warnings and seeking help in case of medical emergencies. Harlan et al. (2006) showed that immigrant status deters integration within minority neighborhoods. A notable number of Phoenix's noncitizen immigrants are illegal migrants from Mexico and thus often lack health insurance and access to the public health care system. Whereas immigrant groups elsewhere have been shown to have strong internal social networks that foster social cohesion and community rebuilding in the face of disaster (e.g., Chamlee-Wright and Storr 2009; Li et al. 2010), we believe that the illegal and short-term status of many of Phoenix's foreign-born residents weigh in favor of social isolation, resulting in difficulty in obtaining resources from established channels of relief. A final vulnerability indicator measures the recentness of residence and population mobility. We assumed that people who changed residences in the past five years before the census period (Diff_hous_5), such as short-term renters, were more likely to lack social support in their neighborhoods, hindering personal access to help during heat-wave events (EPA 2006). Lack of local surveillance and support combined with social isolation were major factors in heat deaths in the European heat wave of 2003 (Fouilett et al. 2006). To summarize, we assumed that high social vulnerability in a census tract stems from large numbers of elderly, foreign-born noncitizens, newcomers to the neighborhood, and low-income residents.

The data were mapped through ESRI ArcGIS 9.3 mapping software and analyzed at the census tract scale. Whereas measures 4 through 7 in Table 1 were already formatted for spatial analysis, raw measures of $T_{\max}$ and $T_{\min}$ had to be spatially interpolated through ordinary kriging, a geostatistical technique that interpolates the value of a random field for unobserved locations based on observations at nearby locations. Subsequently, these kriged temperature fields were spatially joined to the census data. We used ENVI 4.6.1, a software program for processing and analyzing geospatial imagery, to process layerstaking and atmosphere correction on raw raster data

***Table 2*** *Correlation coefficient (*r*) and variance inflation factor (*VIF*) matrices for raw* $VI_{total}$ *measures in both 1990 (top,* $n = 458$*) and 2000 (bottom,* $n = 646$*).*

| | **Med_inc** | **Pop_over65** | $T_{min}$ | $T_{max}$ | **Diff_hous_5** | **Pop_FBNC** | **NDVI** |
|---|---|---|---|---|---|---|---|
| 1990 | | | | | | | |
| Med_inc | *1.272* | | | | | | |
| Pop_over65 | **−0.149** | *1.048* | | | | | |
| $T_{min}$ | −0.003 | −0.079 | *1.114* | | | | |
| $T_{max}$ | −0.042 | 0.089 | **−0.300** | *1.127* | | | |
| Diff_hous_5 | −0.040 | 0.093 | 0.060 | −0.072 | *1.131* | | |
| Pop_FBNC | **−0.368** | 0.017 | 0.058 | −0.052 | 0.301 | *1.288* | |
| NDVI | **0.251** | −0.015 | **−0.127** | **0.139** | −0.094 | −0.120 | *1.108* |
| 2000 | | | | | | | |
| Med_inc | *1.581* | | | | | | |
| Pop_over65 | **−0.112** | *1.221* | | | | | |
| $T_{min}$ | **−0.218** | **−0.204** | *1.219* | | | | |
| $T_{max}$ | **−0.110** | **0.155** | **−0.198** | *1.138* | | | |
| Diff_hous_5 | 0.043 | **0.260** | **−0.187** | −0.026 | *1.291* | | |
| Pop_FBNC | **−0.476** | −0.098 | **0.227** | −0.021 | **0.236** | *1.571* | |
| NDVI | **0.260** | −0.004 | −0.035 | **0.172** | −0.064 | **−0.142** | *1.133* |

*Note:* Values in bold are statistically significant at $p = 0.01$; *VIF* are italicized. Med_inc = median household income; Pop_over65 = population over 65 years old; $T_{min}$ = mean summer minimum temperature; $T_{max}$ = mean summer maximum temperature; Diff_hous_5 = population living in different residences from 5 years prior; Pop_FBNC = population of foreign-born noncitizens; NDVI = normalized difference vegetation index.

from the Landsat ETM+ images. Thereafter, NDVI was computed by Equation (1):

$$\mathrm{NDVI} = \frac{Band4 - Band3}{Band4 + Band3}. \qquad (1)$$

where Band 3 is the red band (0.63–0.69 mm) and Band 4 is the near-infrared (0.63–0.69 mm) of the ETM+ image data. Subsequently, we used the zonal statistics function in ArcMap 9.3 to obtain both mean temperatures and NDVI for each census tract.

Once all raw data were geo-referenced and converted to shapefiles, we examined both correlation coefficient ($r$) matrices and variance inflation factors (*VIF*)[1] during both periods for possible multicollinearity among component variables (Table 2). Six (sixteen) variable pairs had statistically significant correlations ($p = 0.01$) in 1990 (2000), although magnitudes of each bivariate correlation were consistently low with the exception of Med_inc and Pop_FBNC in both periods. The increase in significant correlations between variables over time is most evident between $T_{min}$ with social vulnerability indicators, possibly indicating that minor intervariable redundancies exist, particularly with respect to the social vulnerability component of $VI_{total}$ (especially in 2000). Although we are aware of this issue, it should be stressed that the generally low magnitudes of both $r$ ($< 0.5$) and *VIF* ($< 1.581$) for all pairs strongly suggest that such impacts were kept to a minimum and would not largely affect interpretation of $VI_{total}$.

Raw vulnerability measures for each tract were normalized against the entire study area for both 1990 and 2000 in a ratio treatment used by Cutter, Mitchell, and Scott (2000) and tested for normality using the D'Agostino–Pearson $K^2$ test. Med_inc, however, showed significant positive skewness after treatment by Equation (2), and were instead normalized via a ratio of mean residuals (Equation 3):

$$y_i = \frac{x_i / \sum_{m=1}^{n} x_i}{x_{\max}} \qquad (2)$$

$$y_i = z_i / z_{\max};\; z_i = (x_i - \bar{x}) + |x_{\max}|. \qquad (3)$$

where $y_i$ = normalized vulnerability measure score in census tract $i$, $x_i$ = raw data of vulnerability measure, $\bar{x}$ = mean vulnerability measure for entire study area, $x_{\max}$ = maximum raw vulnerability measure in study area, $z_i$ = intermediate vulnerability measure score, and $z_{\max}$ = maximum intermediate vulnerability score for entire study area.

Normalized measure scores for each tract varied from 0 to 1, with higher magnitudes indicating more vulnerability for five of the component measures (i.e., tracts with higher raw temperature or greater elderly population add to total vulnerability). Tracts with higher raw Med_inc (i.e., more wealth) and NDVI (i.e., more green-space cooling), however, are negatively related to vulnerability. To account for this inverse relationship in computing total vulnerability, we used a simple data transform function for normalized data of both variables (i.e., $1 - y_i$). $VI_{\text{total}}$ (Equation (4)) was subsequently defined as the linear sum of all seven normalized vulnerability measures of equal weight:

$$\begin{aligned} VI_{totali} &= y(T_{\max})_i + y(T_{\min})_i \\ &\quad + (1 - y(NDVI)i) + (1 - y(Med\_inc)_i) \\ &\quad + y(Pop\_over65)_i + y(Diff\_hous\_5)_i \\ &\quad + y(Pop\_FBNC)_i \qquad (4) \end{aligned}$$

## Results

### Assessing Spatial Distribution of Vulnerability

In mapping $VI_{\text{total}}$, we divided the metropolitan area into four quadrants, using the central business district (CBD) of the City of Phoenix as the reference point. This is a suitable landmark as downtown Phoenix remains the primary economic and transportation node of the region, which dominates many of the political, social, economic, and cultural aspects of metropolitan life (Gober and Burns 2002; Keys, Wentz, and Redman 2007). $VI_{\text{total}}$ maps for 1990 and 2000 revealed distinct spatial trends in vulnerability to extreme heat within Phoenix (Figure 2). $VI_{\text{total}}$ was high in two urban neighborhood types during both periods: (1) the inner core both in the City of Phoenix and in several suburban cities in the eastern metropolitan area (e.g., Tempe, Guadalupe, Mesa) and (2) within several retirement communities with high concentrations of elderly (e.g., Sun City, Sun Lakes, and downtown Mesa). In contrast, several relatively high-income enclaves had persistently low $VI_{\text{total}}$ (e.g., Paradise Valley, Cave Creek, and North Scottsdale).

Several urban areas underwent significant changes in $VI_{\text{total}}$ between 1990 and 2000 (Figure 3), notably in northwest and southwest cities, which had increasing $VI_{\text{total}}$ trends, especially along the diagonal northwest–southeast U.S. 60 highway corridor stretching from the City of Phoenix CBD to the retirement community of Sun City West. Most northeast and southeast cities, with the exception of isolated tracts in Scottsdale, South Phoenix, and South Chandler, experienced decreasing $VI_{\text{total}}$ over the study period, especially in the fast-growing suburbs of Gilbert and Queen Creek. A substantial increase of $VI_{\text{total}}$ in the southeast quadrant occurred at Sun Lakes, a notable elderly enclave where people were aging into the older than sixty-five years age cohort.

To explain these patterns, we plotted maps of normalized scores for individual vulnerability components to illustrate changing spatial patterns of physical exposure and adaptive capacity measures in Phoenix (Figures 4 and 5). A strong desert oasis effect in central Phoenix is seen for $T_{\max}$ in both time periods, with expected higher $T_{\max}$ observed at the urban fringe. UHI growth is easily discerned with the gradual expansion of higher $T_{\min}$ away from the urban core from 1990 to 2000, with larger than average UHI intensities documented in central and western Phoenix. The general expansion of the UHI also corresponded with rapid land-cover change resulting from urbanization documented throughout the metropolitan area. Although the central areas of the City of Phoenix had consistently below-average NDVI, notable increases in green space were observed in Paradise Valley and North Scottsdale; these are cities with high-income populations, suggesting possible residential landscape modification proposed by Jenerette et al. (2007). Conversely, the gradual conversion of agricultural to suburban land-use, and the resulting decrease in green space within several southeast and western cities, can also be seen from the 1990 to 2000 NDVI data.

Changing trends in normalized scores for each adaptive capacity component of $VI_{\text{total}}$ also revealed interesting geographic patterns. Retirement communities, with many out-of-state elderly migrants (e.g., Sun City, Sun Lakes, East Mesa), dot the urban fringe on the Pop_over65 map. Several high-income

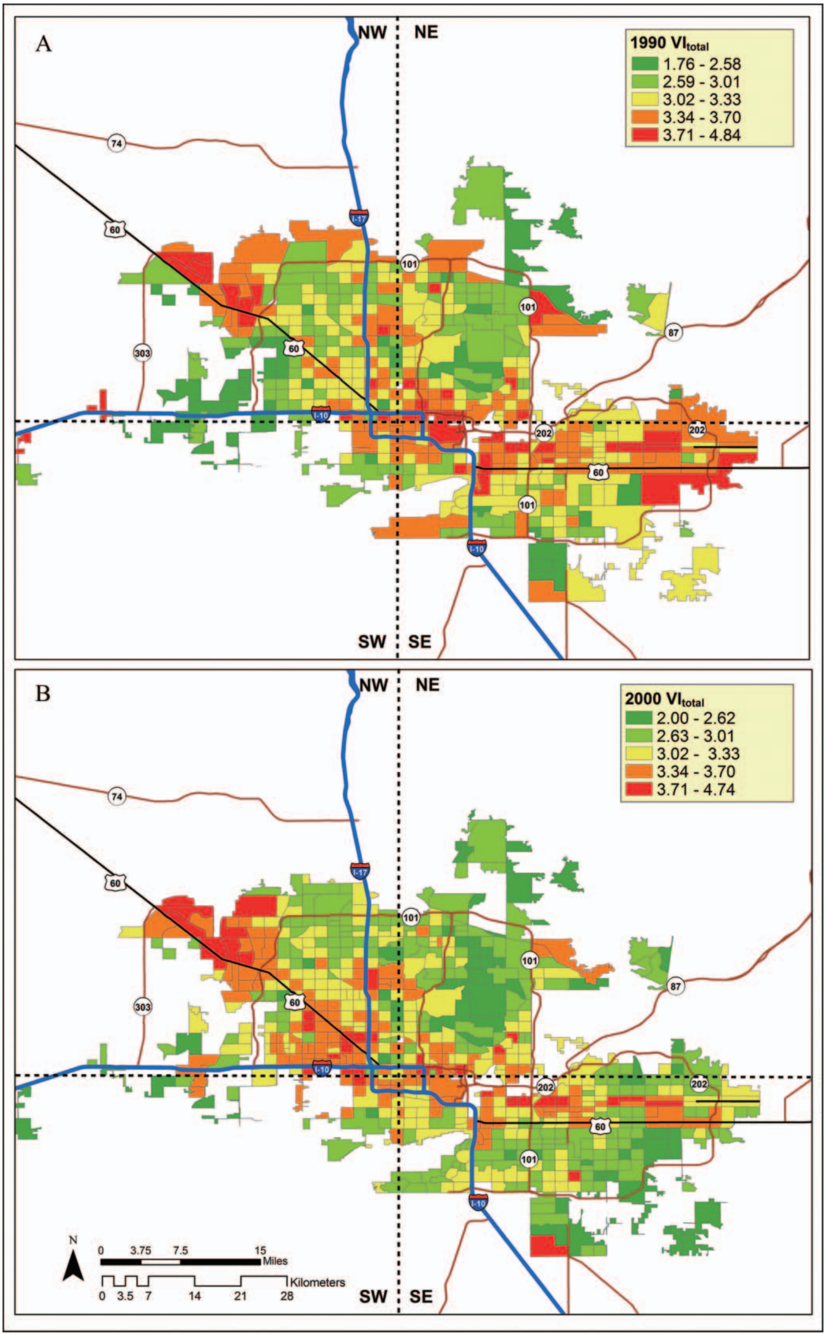

**Figure 2** *(A) 1990 and (B) 2000* $\mathrm{VI}_{total}$ *for metropolitan Phoenix. Interval classes are based on standard deviation of* $\mathrm{VI}_{total}$*. (Color figure available online.)*

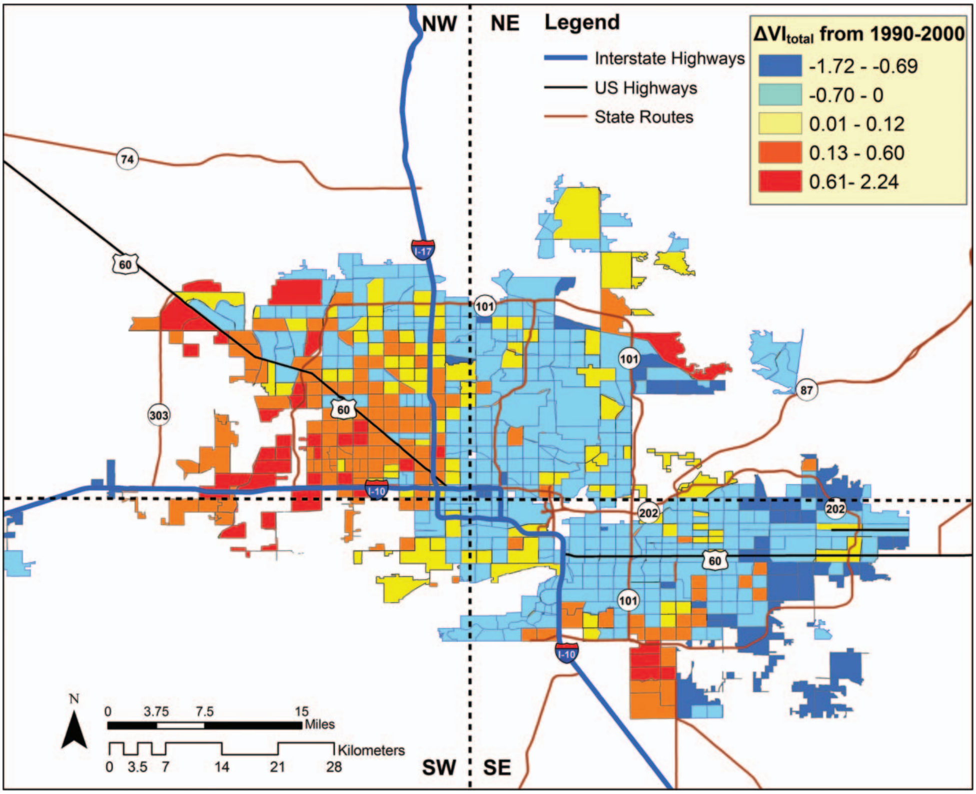

**Figure 3** $\Delta\mathrm{VI}_{total}$ *from 1990 to 2000 for metropolitan Phoenix. Interval classes are based on standard deviation of* $\mathrm{VI}_{total}$*. (Color figure available online.)*

northeast cities, such as Paradise Valley and North Scottsdale, stand out on the Med_inc map in both 1990 and 2000. Several southeast neighborhoods (e.g., especially in Chandler and Gilbert) experienced substantial increases in Med_inc as the farming communities, mobile homes, and retirement villages that once dominated the landscape were replaced with master-planned communities appealing to more affluent households. Low-income areas of the central core persisted and expanded toward the west from 1990 to 2000.

Sun City, El Mirage, Tempe, central Phoenix, and Queen Creek were migration foci for Phoenix's growing foreign-born, noncitizen population in 1990, and except for Queen Creek, they were points of settlement for new immigrants to the region in 2000, with a notable expansion of predominantly Mexican-Hispanic neighborhoods in central and west Phoenix (Gober 2006). Cities at the urban fringe, especially in the northeast and northwest, generally had higher concentrations of Diff_hous_5 in both periods, reflecting the concentration of new development there.

$VI_{\mathrm{total}}$ declined in the east for a variety of reasons. First, the sum total of higher income residents increased; second, it contained a smaller proportion of foreign-born residents who concentrated in inner-city neighborhoods such as within central Phoenix; and third, it became more stable demographically as urban growth shifted westward. Residential areas in the west were also affected more by larger $T_{\mathrm{max}}$ and $T_{\mathrm{min}}$ increases relative to eastern cities, thus increasing physical exposure.

**Figure 4** *1990 and 2000 normalized* VI *maps for physical exposure* $VI_{total}$ *components.* $T_{max}$ = *mean June maximum temperatures;* $T_{min}$ = *mean June minimum temperatures; NDVI = mean June normalized differential vegetation index. (Color figure available online.)*

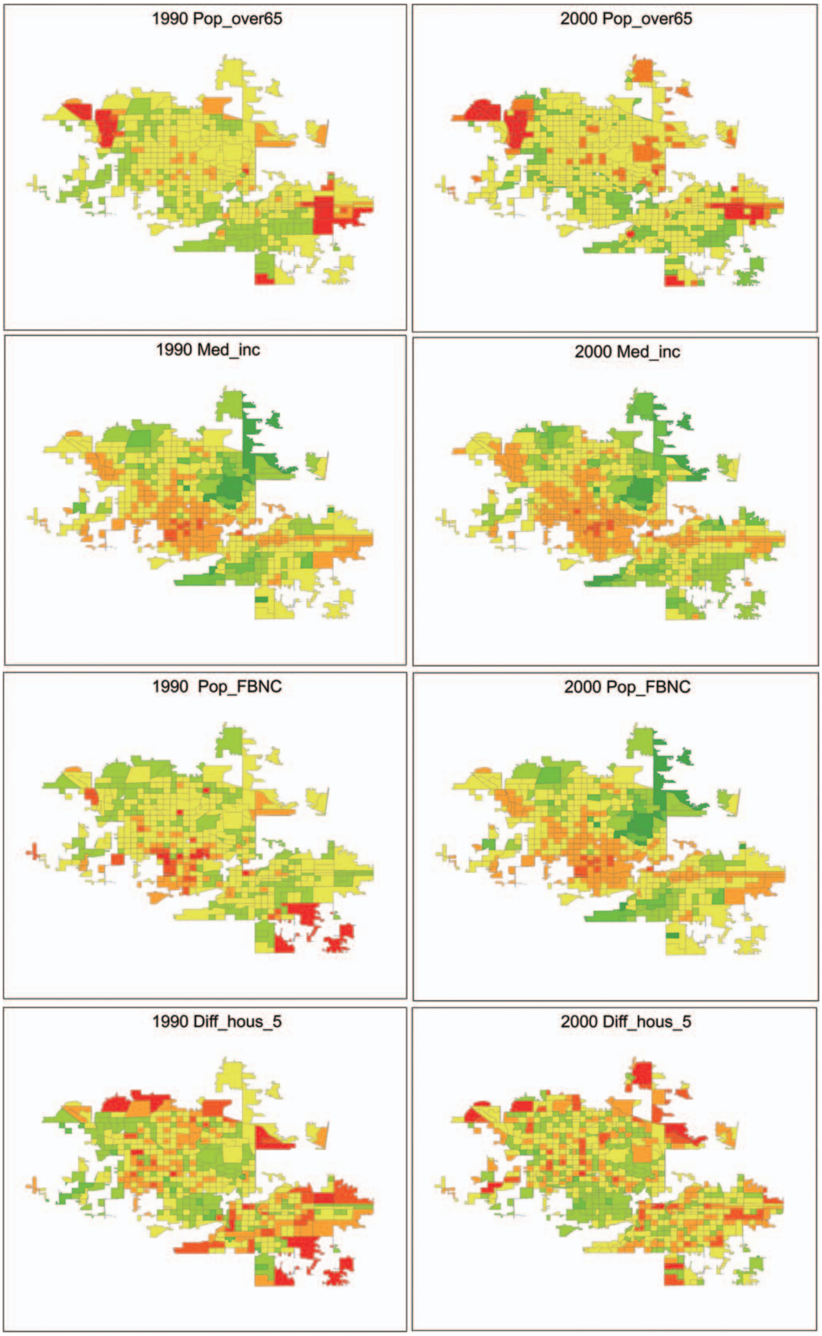

**Figure 5** *1990 and 2000 normalized* VI *maps for adaptive capacity* $\mathrm{VI}_{total}$ *components. Pop_over65 = total population over age 65; Med_inc = median household income; Pop_FBNC = total population of foreign born noncitizens; Diff_hous_5 = population living in different residences from five years prior. (Color figure available online.)*

***Table 3*** *Vulnerable (defined as $+1\sigma$ about mean $\mathrm{VI}_{total}$) and total population in Phoenix during 1990 and 2000 according to ethnicity*

| | **African American/ Black** | **Hispanic/ Latino** | **Indian/Alaska Native** | **Asian** | **Non-Hispanic/ Latino White** | **Total** |
|---|---|---|---|---|---|---|
| Vulnerable population | | | | | | |
| 1990 | 13,310 | 69,687 | 8,097 | 6,695 | 285,022 | 382,811 |
| 2000 | 19,703 | 176,471 | 10,308 | 8,682 | 227,838 | 443,002 |
| Net % change compared to 1990 baseline | +48.0 | +153.2 | +21.5 | +29.7 | −20.1 | +15.7 |
| Total population | | | | | | |
| 1990 | 73,777 | 337,540 | 37,570 | 35,113 | 1,627,350 | 2,111,350 |
| 2000 | 113,925 | 758,176 | 52,412 | 66,269 | 2,008,475 | 2,999,257 |
| Net % change compared to 1990 baseline | +54.4 | +124.6 | +39.5 | +88.7 | +23.4 | +42.1 |

### *Demographic Variations in Vulnerability*

We subsequently examined what these changed vulnerability maps mean for the region's racial and ethnic minorities. We specifically targeted tracts with $VI_{\mathrm{total}}$ one standard deviation above the metropolitan mean (mean $VI_{\mathrm{total}} + 1\sigma$). This threshold level of high vulnerability was 3.6 in both 1990 and 2000 (Table 3). The sum of vulnerable tracts was also similar in number during both time periods (sixty-one in 1990 vs. sixty-two in 2000). The total metropolitan area population living in vulnerable areas rose by 16 percent from 1990 to 2000, with the ethnic Hispanic population having the largest rate of growth at 153 percent, followed by African Americans with a 48 percent increase. Although the number of vulnerable people increased for all minority groups between 1990 and 2000, the number of vulnerable non-Hispanic Whites declined from ~285,000 to ~228,000, a 20 percent decrease.

These increases in vulnerable populations must also be compared to corresponding increases in total population within the study area to examine proportional demographic changes over both periods. The proportion of vulnerable to total population for the entire metropolitan area decreased from 18.1 to 14.8 percent (Figure 6); non-Hispanic Whites experienced the largest proportional decrease of 6.2 percent, followed by a 6 percent decrease among ethnic Asians, a 1.9 percent drop among African Americans, and a 0.7 percent reduction among Native Indian/Alaskan ethnicities. In contrast, the proportion of Hispanics living above the $VI_{\mathrm{total}}$ threshold of 3.6 increased from 20.6 to 23.3 percent of the total population, reinforcing the interpretation that Hispanics were increasingly vulnerable to heat stress as result of the complex interplay of physical and social factors.

## Discussion

The maps of $VI_{\mathrm{total}}$ and its changes between 1990 and 2000 illustrate how climate, urban ecology, social status, and changing demography interact to create and change the spatial and temporal patterns of vulnerability to heat stress. The largest increases of $VI_{\mathrm{total}}$ occurred in western cities within the metropolitan area where the growth in low-income, foreign-born populations coincided with increased physical exposure. High vulnerability increased also in elderly urban-fringe retirement communities that were enveloped by the expanding UHI. Declining vulnerability occurred across eastern metropolitan cities where population growth stabilized and UHI development was relatively weak. These evolving vulnerability surfaces disproportionately affected the region's Hispanic population because of the strong indirect relationships between the four social vulnerability indicators with race and ethnicity. This was combined with the residential segregation of Hispanics into neighborhoods with increasing exposure. For instance, historic patterns of population growth for different ethnic groups in Phoenix show that Hispanics (mostly Mexican American) concentrated around *barrios*

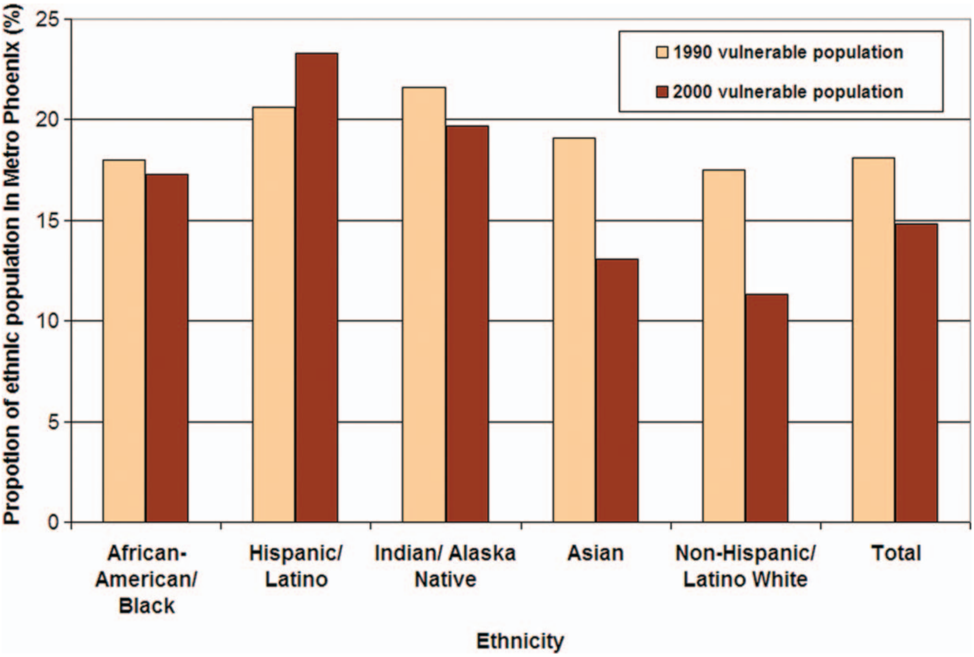

**Figure 6** *Proportion of vulnerable ethnic population to total population in 1990 and 2000 within metropolitan Phoenix (Color figure available online.)*

(generally lower class, lower income neighborhoods with a high proportion of Spanish-speaking residents) close to Sky Harbor airport in the City of Phoenix. To accommodate the rapid growth of Hispanics, these *barrios* spread outward and encompassed much of central and west Phoenix (Gober 2006). These racial and ethnic disparities would have been exacerbated if not for non-Hispanic elderly whites continuing to migrate to Phoenix and settling into age-segregated retirement communities, where physical exposure to nighttime heat was growing from rapid urbanization of the metropolitan fringe. These communities are ethnically homogenous areas where more than 98 percent of residents are non-Hispanic whites (McHugh and Larson-Keagy 2005).

Despite the influx of this population segment into retirement neighborhoods, far fewer total non-Hispanic whites in 2000 were exposed to vulnerability at above-average thresholds for heat stress when compared to other ethnic minorities. Younger, non-Hispanic whites predominantly settled in several northeast and southeast cities within the metropolitan area. These cities experienced declining vulnerability due to (1) low exposure to physical stresses of high maximum and minimum temperatures, (2) more neighborhoods with higher income residents, (3) increased surface green space through landscape modification (e.g., in Paradise Valley), and (4) more social stability from longer term residents. These physical and social characteristics validate previous, smaller scale findings from Harlan et al. (2006), who first noted a correlation between physical exposure and social vulnerability to heat stress; Jenerette et al. (2007), who linked socioeconomic status and urban vegetation with heat stress levels; and Ruddell et al. (2009), who discerned strong social inequalities with respect to heat exposure in Phoenix.

Finding that Hispanics in Phoenix are both socially and physically disadvantaged is consistent with previous research on toxic hazards, which have also shown the unequal burden carried by minorities who are generally located adjacent to hazardous places (Bolin et al. 2000;

Bolin et al. 2002; Bolin, Grineski, and Collins 2005; Grineski, Bolin, and Boone 2007). These studies argue that the burden of minorities is a function of institutional racism; we do not draw causal interpretations but note how profoundly the social and geographic characteristics of minorities interact to heighten urban vulnerability. These interactions are particularly worrisome under circumstances of potential climate change, where the thresholds of extreme heat and resulting harm to health in the American Southwest will be approached, if not exceeded more frequently. Vulnerabilities in the physical system could lead to vulnerabilities in the social system, as increasing exposure to extreme heat would require development of stronger social networks and support systems, which might not keep pace with changes in magnitudes of physical exposure.

## Conclusion

This study assessed the vulnerability of Phoenix residents in 1990 and 2000 to extreme heat based on a composite index of vulnerability ($VI_{\text{total}}$) based on normalized indexes of physical exposure to heat and several socioeconomic adaptive capacity measures of equal weight. We demonstrated that vulnerability varied significantly over space and time and that it is unequal across different demographic segments in Phoenix, with Hispanic populations having a disproportionate exposure to extreme heat versus other ethnic groups. This marked disparity is especially apparent in both the increasing total Hispanic population and the ratio of Hispanics to total Phoenix population that were residing in more vulnerable areas from 1990 to 2000. In contrast, the proportion of non-Hispanic whites exposed to extreme heat decreased, despite a large increase in total elderly migrants in urban-fringe retirement communities with high $VI_{\text{total}}$.

The need for climate adaptation in Phoenix is particularly acute, as our research suggests that many Hispanics in inner-city neighborhoods, and some elderly in retirement communities, live at loci of heat vulnerability. The study's results thus have several policy implications. First, given the disproportionate vulnerability to extreme temperatures, policymakers and emergency responders based in cities or neighborhoods with a large proportion of vulnerable populations should anticipate increased HRD calls during heat wave events, and tailor effective measures for them (e.g., more Spanish-speaking responders or specialized elderly medical aid centers). Second, by identifying areas with high vulnerability, city officials and policymakers could design more effective urban adaptation strategies, such as policies to improve social cohesion and integration within neighborhoods via widespread dissemination of heat-stress mitigation information in different languages. ■

## Note

[1] *VIF* is a measure of the impact of collinearity among variables in a regression model. $VIF > 10$ indicates definite problems of multicollinearity; $VIF > 2.5$ indicates potential areas of concern. As *VIF* magnitudes in Table 2 are between 1.0 and 1.6, this suggests that the collinearity problem among our independent variables is relatively minor.

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