Health & Place 17 (2011) 498–507

Contents lists available at ScienceDirect

Health & Place

journal homepage: www.elsevier.com/locate/healthplace

Intra-urban societal vulnerability to extreme heat: The role of heat exposure and the built environment, socioeconomics, and neighborhood stability

Christopher K. Uejio [a,*], Olga V. Wilhelmi [b], Jay S. Golden [c], David M. Mills [d], Sam P. Gulino [e], Jason P. Samenow [f]

[a] Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin-Madison, 1710 University Ave. #246, Madison, WI 53726, USA
[b] Integrated Science Program and Research Applications Laboratory, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000, USA
[c] Nicholas School of the Environment and Pratt School of Engineering, Duke University, P.O. Box 90335, 2117 Campus Drive #103, Durham, NC 27708, USA
[d] Stratus Consulting Inc., P.O. Box 4059, Boulder, CO 80306, USA
[e] Medical Examiner's Office, Philadelphia Department of Public Health, 321 University Avenue, Philadelphia, PA 19104, USA
[f] Weather Editor, Washington Post, 1150 15th St. NW, Washington DC 20071, USA

ARTICLE INFO

Article history:
Received 30 April 2010
Received in revised form
5 October 2010
Accepted 1 December 2010
Available online 13 December 2010

Keywords:
Heat
Environmental health
Geographic information systems
Built environment
Racial disparities
Socioeconomic disparities

ABSTRACT

Extreme heat is an important weather hazard associated with excess mortality and morbidity. We determine the relative importance of heat exposure and the built environment, socioeconomic vulnerability, and neighborhood stability for heat mortality (Philadelphia, PA, USA) or heat distress (Phoenix, AZ, USA), using an ecologic study design. We use spatial Generalized Linear and Mixed Models to account for non-independence (spatial autocorrelation) between neighboring census block groups. Failing to account for spatial autocorrelation can provide misleading statistical results. Phoenix neighborhoods with more heat exposure, Black, Hispanic, linguistically and socially isolated residents, and vacant households made more heat distress calls. Philadelphia heat mortality neighborhoods were more likely to have low housing values and a higher proportion of Black residents. Our methodology can identify important risk factors and geographic areas to target interventions.

1. Introduction

Extreme heat accounts for more fatalities in the United States (U.S.) than any other weather hazard with approximately 600–1800 deaths per year (Centers for Disease Control and Prevention, 2006; Karl et al., 2009). The physical health effects of extreme heat (i.e., heat cramps, heat exhaustion, and heatstroke) are primarily related to the human body's ability to control its internal temperature (Centers for Disease Control and Prevention, 1996). Other important heat co-morbidities include nervous system, respiratory, cardiovascular, genitourinary, and diabetes-related conditions, which may be exacerbated by the heat stress (Schwartz et al., 2004; Semenza et al., 1999). Even with accurate heat warnings, improved recognition, and increased air conditioning adoption and usage, extreme heat continues to be an important public health concern (United States Environmental Protection Agency, 2006). A review of emergency response plans showed that half of the cities (nine cities) had plans specifically for extreme heat events and few had interventions to reach at-risk populations (Bernard and McGeehin, 2004).

Projected demographic and climatological trends suggest that extreme heat will continue to be an important health concern in the U.S. Firstly, the historically vulnerable older adult population is projected to grow from 35.0 million in 2000 to over 86.7 million by 2050 (U.S. Census Bureau, 2000a, b). This may be further compounded by a high proportion of older adults living alone (Tomassini et al., 2004). Secondly, global climate change is anticipated to make extreme heat events more frequent, longer lasting, and geographically widespread (Meehl and Tebaldi, 2004; Gershunov and Douville, 2008). Finally, for the first time in our history, more people are living in urban areas than rural locations, which exacerbates heat related health impacts due to the urban heat island effect (Golden et al., 2008).

Mapping is an increasing popular environmental health surveillance tool. Mapping can identify important health disparities and target or evaluate interventions. For example, vulnerability mapping considers extreme heat risk factors and provides an aggregate measure of risk (Reid et al., 2009; Vescovi et al., 2005). However, vulnerability mapping does not relate heat risk factors to health outcomes. Mapping can be further augmented using a spatial ecologic study design. Ecologic studies relate the geographic distribution of

* Corresponding author. Tel.: +1 303 497 2702; fax: +1 303 497 8401.
E-mail addresses: uejio@wisc.edu, ckuejio@gmail.com (C.K. Uejio), olgaw@ucar.edu (O.V. Wilhelmi), Jay.Golden@asu.edu (J.S. Golden), DMills@stratusconsulting.com (D.M. Mills), Sam.Gulino@phila.gov (S.P. Gulino), jasonsamenow@hotmail.com (J.P. Samenow).

1353-8292/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.healthplace.2010.12.005

environmental exposures to health outcomes, while controlling for important confounders. Indeed, environmental health problems are related to characteristics of an exposure, existing vulnerabilities, and the ability to adapt to the hazard.

Historic extreme heat ecologic studies were limited by spatial autocorrelation (Klinenberg, 2003). Spatial autocorrelation is the concept that adjacent neighborhoods are more related to one another than distant neighborhoods (Tobler, 1970). Spatial autocorrelation has practical implications for statistical analysis. Using traditional statistics to analyze spatial data may lead to biased statistical inferences and risk factors may be erroneously deemed significant (Kuhn, 2007). For example, Smoyer (1998) recognized this limitation and did not conduct a multiple variable statistical analysis. Extreme heat mapping studies have been previously conducted in Philadelphia, PA, U.S. and Phoenix, AZ, U.S. (Harlan et al., 2006; Johnson et al., 2009). However, the previous mapping studies either did not explicitly consider extreme heat health problems or did not control for spatial autocorrelation.

The goal of this study is to use an ecologic study design that controls spatial autocorrelation to derive the relative importance of heat exposure and the built environment, socioeconomic vulnerability, and neighborhood stability to heat distress calls (HDC) or heat mortality (HM) cases (Dormann et al., 2007). We analyze HM in Philadelphia and HDC in Phoenix. The analysis focuses on intra-urban (within a city) heat risk, since the same health outcomes are not analyzed in both cities. This ecologic study improves upon vulnerability mapping by deriving the relative importance of heat risk factors from heat health outcomes.

2. Materials and methods

2.1. Study cities

2.1.1. Philadelphia

We summarize each city's climatological conditions, developmental history, and experiences with and responses to extreme heat. Philadelphia is at the confluence of humid subtropical and humid continental climatic zones. Weather patterns are highly variable and summers are warm and humid (Chestnut et al., 1998). Philadelphia extreme heat events are often caused by maritime tropical air masses which originate in the Gulf of Mexico or Tropical Atlantic Ocean. These air masses are characterized by hot temperatures, high dew points, partly cloudy skies, and stagnant winds (Kalkstein et al., 1996). In Philadelphia, extreme heat events have been linked to deaths for hundreds of years (US EPA, 2006). Recent extreme heat events occurred in 1993, 1995, 1999, and 2010 (US EPA, 2006; Kalkstein et al., 1996; Wolfe et al., 2001).

Historically, the newest Philadelphia migrants moved into the oldest and most dilapidated housing stock in North Philadelphia (located in the central portion of Philadelphia). Old Word migrants moved to the suburbs and a large number of Black migrants took their place following World Wars I and II. Violence, discriminatory realtor, lending, and zoning practices further concentrated Blacks in North, South, and West Philadelphia until the passage of the Fair Housing Act in 1968 (Wolfinger et al., 2007). Similarly, neighborhood opposition forced public housing projects to be built in predominately Black neighborhoods. Public housing construction decreased the proportion of the Black population living in substandard housing from 45% to 35% between 1940 and 1950. Over 1960–1977, an estimated 200,000 white and 20,000 black residents left the City of Philadelphia to pursue economic opportunities in the suburbs and escape racial conflict (Adams et al., 1993). Today, Puerto Ricans tend to live between North and Northeastern Philadelphia, Mexican Americans in South Philadelphia and the suburbs, and new Asian migrants in South Philadelphia.

Groups that are historically vulnerable to extreme heat include elderly (age $>=60$) females and people with pre-existing health problems such as obesity, cardiovascular disease, and diabetes (Mirchandani et al., 1996). Victims of extreme heat tended to live upstairs, in brick row homes, without a cooling device, and extremely hot indoor temperatures (>54 °C) (Centers for Disease Control and Prevention, 1994). Substance abuse related injuries, poisoning, and liver disease, instead of extreme heat, are the most important causes of homeless mortality (Hibbs et al., 1994). Comprehensive heat watch/warning systems can reduce the burden of HM. Philadelphia's system includes home visits by health department staff, a heat hotline, and media notification. It is estimated to have saved 117 lives from 1995 through 1998 (Ebi et al., 2004).

2.1.2. Phoenix

Phoenix's climate can be classified as arid subtropical with very hot summer temperatures and warm winters. Normal summertime temperatures are hot enough to cause human health problems. Population growth and urbanization have increased urban annual surface temperatures by 4.2 °C over the 20th century (Golden et al., 2008). Arizona has the highest reported U.S. extreme heat death rates (age adjusted) in people aged 24 or older (LoVecchio et al., 2005). Early summer extreme heat events tend to be caused by dry tropical air masses with different physical attributes than the air masses that impact Philadelphia. As the name implies, dry tropical air masses are extremely hot, sunny, and dry. On average, each dry tropical air mass day corresponds to 2.7 excess Phoenix heat deaths (Sheridan, 2002). The arrival of the North American Monsoon in late summer increases the amount of atmospheric moisture. Interestingly, more heat distress calls are made during the hot and moist monsoon period than the drier but hotter early summer period (Golden et al., 2008).

Historically, multi-cultural Phoenix residents lived in segregated communities. Although Phoenix's demographic composition regularly changes, contemporary communities reflect historical development patterns and legacies of exclusion. Over the 20th century, Anglo-Americans progressively moved further away from downtown Phoenix to peripheral areas. In the aftermath of the 1891 Salt River flood, Anglo-Americans left Downtown Phoenix and relocated to safer, cooler, and higher elevation areas (Gober, 2005). Mexican American communities remained downtown and adapted to extremely hot days by sleeping outside (Dimas, 1999). Contemporary Mexican American communities reside in Downtown, Central, and Western Phoenix. De-facto lender and realtor segregation policies segregated Black residents to southern Phoenix until the 1980s. Today, Blacks live in multiple suburban communities, Asian Americans around Arizona State University and the Technology Park, and American Indians in the Gila, Salt, and Fort McDowell communities.

During the 2005 Phoenix extreme heat event, two-thirds of coroner classified heat mortality cases were homeless people (Yip et al., 2008). Extreme heat is one important cause of homeless mortality ($\sim$10–20% of total mortality) (Maricopa Association of Governments, 2007). Nonetheless, the homeless suffer other health threats and are five times as likely to die from accidents related to motor vehicles, poisoning, and fire arms than the general population (Arizona Homeless Coordination Office, 2009). More intense and prolonged heat exposure or fewer social services may account for greater homeless extreme heat mortality in Phoenix compared to Philadelphia (Bolton, 2005). The remaining heat mortality cases were either older adults, found dead inside of their homes, or people with high recreational heat exposure. Subsequently, the

Arizona Department of Health Services (2006) developed an emergency heat response plan to coordinate agency roles and responsibilities. Before an extreme heat event, educational materials outlining the medical symptoms, vulnerable groups, and the location of cooling shelters are distributed.

2.2. Data

We describe the extreme heat case definitions for heat mortality in Philadelphia and heat distress calls in Phoenix. The Philadelphia Department of Health defines extreme heat mortality by an individual's body temperature, the environment where the deceased is found, and the temporal sequence of heat exposure to mortality (Donoghue et al., 1997). The National Association of Medical Examiners endorses this more expansive case definition, where extreme heat does not have to be explicitly recorded on the death certificate (United States Environmental Protection Agency, 2006). We examine extreme heat mortality over July 8th–August 4th 1999, a period that included the 1999 extreme heat event with 63 reported deaths.

Extreme heat distress calls were obtained from the City of Phoenix Regional Fire Department Dispatch Center. The Phoenix study area refers to HDC originating from Phoenix, Tempe, Chandler, Scottsdale, Glendale, Surprise, Buckeye, Tolleson, Peoria, Paradise Valley, Guadalupe, and Goodyear. The dispatching of emergency services for heat distress is confirmed twice. The dispatcher at the 911 center or the person making the emergency phone call reports heat distress, which is verified by the emergency responders in their post-service report. Our spatial ecologic study expands upon a previous Phoenix time series analysis of weather conditions and the timing of HDC (Golden et al., 2008). This study found that more HDC are made during the hottest periods of the day with the most sunlight. We analyze HDC reported over June–September 2005 (637 HDC), which included the 2005 extreme heat event. This research was approved by the Institutional Review Board.

Table 1 categorizes neighborhood level heat risk factors into heat exposure and the built environment, socioeconomic vulnerability, and neighborhood stability. Smoyer (1998) presented this conceptual framework and noted that interdependent risk factors could be placed into multiple categories. It is important to recognize that risk factors may represent place-specific processes. We attempt to interpret each risk factor in the context of each city's development history and experiences with extreme heat.

Table 2 summarizes the average heat risk factor characteristics of the census block groups (CBG). Please note that the averaging of heat risk factors across CBG is not equivalent to the average of heat risk factors for the entire city. Heat exposure is clearly higher in Phoenix with elevated surface temperatures, housing densities, and less vegetation cover. Philadelphia is nonetheless more highly urbanized than Phoenix as reflected by impervious surface cover. Both cities have socioeconomic vulnerability characteristics which may increase extreme heat related distress or mortality. The percentage of households with incomes below the poverty level is almost twice as high in Philadelphia than Phoenix. Phoenix residents tend to be more Hispanic, linguistically isolated, and change households more frequently compared to Philadelphia. People living in Philadelphia are more likely to be older, Black or Asian American, and live alone. Philadelphia's housing stock is older, costs less to purchase, and tends to have more vacant units.

2.2.1. Heat exposure and the built environment

Heat exposure varies according to the heat generation, storage, and transport characteristics of urban materials and vegetation. Heat exposure may be directly measured using surface temperature or indirectly quantified by three measurements; the health and density of vegetation, the amount of man-made impervious surfaces, and the structure of the built environment. Remotely sensed satellite imagery

Table 1
The following extreme heat risk factors are considered in this study. We followed the framework of Smoyer (1998). The analysis units are a U.S. Census Block Group which contains ~800–1400 residents.

Category	Independent variable	Data source
Heat exposure and the built environment	Vegetation health and density[a]	Advanced spaceborne thermal emission and reflection radiometer
	Nighttime surface temperature—^{o}C (average, maximum)[b]	Advanced spaceborne thermal emission and reflection radiometer
	% Impervious surface	National land cover database (2001)
	Housing density—houses/km^2	U.S. Census (2000)
	% Single family detached homes	U.S. Census (2000)
Socioeconomic Vulnerability	% Residents below the poverty line	U.S. Census (2000)
	% Households renting	U.S. Census (2000)
	Population age 65 or older	U.S. Census (2000)
	% Population age 65 or older	U.S. Census (2000)
	% People living alone	U.S. Census (2000)
	% People with disabilities[c]	U.S. Census (2000)
	% Linguistically isolated households[d]	U.S. Census (2000)
	% Households with seven or more residents	U.S. Census (2000)
	% Residents in race categories (Black, Hispanic, American Indian, and Asian American)	U.S. Census (2000)
Neighborhood Stability	% Residents changed households past 5 years	U.S. Census (2000)
	% Vacant households	U.S. Census (2000)
	Year house built (median)	U.S. Census (2000)
	Housing value (median)—U.S. dollars	U.S. Census (2000)

[a] Inferred from the unit less Normalized Difference Vegetation Index.
[b] Average or maximum refers to the surface temperature aggregation process. We take either the average or maximum of surface temperature measurements in each census block group.
[c] Category includes sensory, physical, mental, self-care, go-outside, and employment disabilities.
[d] Residents "sometimes or always" speak a language other than English at home. Most households speak some English.

Table 2
Census block group summary statistics (mean, standard deviation, and range) for Phoenix, AZ and Philadelphia, PA.

	Phoenix			Philadelphia		
	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range
Outcome						
Mortality	–	–	–	0.04	0.2	(0.0:1.0)
Heat distress call	0.37	1.2	(0.0:30.0)	–	–	–
Risk factor						
Vegetation health and density	0.0	0.1	(−0.1:0.3)	0.0	0.1	(−0.1:0.4)
Surface temperature (average)	30.5	1.5	(25.3:35.4)	51.0	3.2	(6.7:58.1)
Surface temperature (maximum)	34.6	1.8	(29.8:41.7)	54.3	2.8	(44.0:71.2)
Impervious surface (%)	45.2	15.2	(0.3:79.8)	67.0	18.9	(0.8:98.3)
Housing density (houses/km^2)	883.5	728.7	(1.2:8443.3)	3297.0	2243.8	(3.1:19,189.3)
Single family detached homes (%)	63.3	34.4	(0:100.0)	9.2	13.2	(0:100.0)
Residents below the poverty line (%)	13.1	13.7	(0:84.4)	23.9	17.3	(0:90.4)
Households renting (%)	33.8	29.5	(0:100.0)	38.7	22.0	(0:99.5)
Population age 65 or older (%)	10.9	12.4	(0:97.1)	13.6	7.6	(0:71.0)
Population age 65 or older	136.4	209.1	(0:4454)	120.7	124.7	(0:1499)
People living alone (%)	10.3	9.1	(0:75.0)	13.8	10.4	(0:94.6)
People with disabilities (%)	33.0	19.5	(0:100.0)	47.5	19.6	(0:100.0)
Linguistically isolated households (%)	7.5	10.7	(0:78.3)	4.9	7.7	(0:100.0)
Households with 7+ residents (%)	3.4	4.2	(0:25.9)	2.5	4.0	(0:41.8)
Black (%)	3.9	5.1	(0:78.1)	48.3	39.5	(0:100.0)
Hispanic (%)	27.0	24.7	(0:96.8)	9.1	16.8	(0:93.5)
American Indian (%)	1.5	2.2	(0:39.5)	0.3	0.4	(0:3.4)
Asian American (%)	2.3	2.6	(0:33.3)	3.8	7.4	(0:94.3)
Residents changed households (%)	56.2	18.1	(6.9:100.0)	36.6	15.7	(0:100.0)
Vacant households (%)	6.2	6.7	(0:67.2)	11.9	8.9	(0:75.0)
Year house built	1973.9	68.9	(1939:1999)	1945.3	9.3	(1939:1998)
Housing value ($1000)	125.3	95.8	(10:1000)	66.1	63.0	(9.99:1000)

provides multiple affordable and accurate metrics of heat exposure. Heat exposure measurements were previously limited to a patchy network of weather stations. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) observes both surface temperature and vegetation health and density (Golden et al., 2009). ASTER currently provides the highest thermal data resolution (90 M) available from an orbiting platform. ASTER can measure the urban heat island during the nighttime, which may be particularly important for heat distress or mortality (Chestnut et al., 1998). Satellite based temperature measurements nonetheless contain error resulting from atmospheric conditions, the satellite sensor, and land cover emissivity (Gillespie et al., 1998). Similarly, ASTER's surface temperature measure is limited and may underestimate indoor heat exposure and only measures heat exposure at one point in time. The ASTER image was acquired from NASA through an existing agreement with the Arizona State University.

Impervious surfaces alter local hydrologic and energetic conditions. Transportation infrastructure and building rooftops are common impervious surfaces. Surface temperature is strongly associated with the fraction of impervious surface cover across all seasons (Yuan and Bauer, 2007). Impervious surface is a heat exposure proxy that may be less sensitive to changing weather conditions than the surface temperature measured at one point in time. We used impervious surface from the National Land Cover Database 2001 with 91% accuracy in Philadelphia and 93% in Phoenix (Homer et al., 2004). The Normalized Difference Vegetation Index measures vegetation health and density and captures temperature reducing vegetation shading and cooling (Rouse et al., 1974). The Normalized Difference Vegetation Index was calculated as a ratio of ASTER's land surface reflectance in the near infrared (NIR) and the red visible wavelengths (Eq. (1)).

$$\text{The normalized difference vegetation index} = \frac{NIR-RED}{NIR+RED} \quad (1)$$

Heat exposure may also be indirectly inferred from the structure of the built environment and air conditioning/cooling. More detached households, and by extension, open space in a neighborhood generally produces cooler conditions (Smoyer, 1998). Housing density may also crudely measure neighborhood stability. In St. Louis, MO, U.S., low density housing had higher elderly extreme heat mortality rates, but this relationship was not always consistent (Smoyer, 1998). Air conditioning decreases household humidity, temperature, and heat mortality risk (Braga et al., 2001; Curriero et al., 2002; Kaiser et al., 2001; Naughton et al., 2002; Semenza et al., 1996). Waste heat generated by air conditioning and other household appliances contributes to the urban heat island effect and may modestly increase heat exposure for households without air conditioning. This analysis does not consider air conditioning, because nationwide data sets are too old (1980 U.S. Census) for this analysis.

Our study design relates the geographic distribution of heat exposure to heat distress calls or heat mortality. In essence, the study tests if relatively hotter neighborhoods tend to have more extreme heat health problems. Even if there is no geographic relationship, extreme heat is still likely related to heat distress calls or mortality. Heat exposure may be sufficiently high across the city, so that the geographic distribution of heat is inconsequential.

2.2.2. *Socioeconomic vulnerability*

Societal vulnerability needs to be considered with the same degree of importance as heat exposure and the built environment. The U.S. Census Bureau conducts household surveys that provide aggregate information on resident age, race, poverty, and some information on social exclusion and mental health (Curriero et al., 2002; Medina-Ramón et al., 2006; O'Neill et al., 2003, 2005;). A CBG is analogous to a neighborhood that encompasses ~800–1400 residents with similar socioeconomic characteristics. Total neighborhood population is considered in the analysis to control for differences in the number of people at-risk.

Older adults are less efficient at dispersing heat and noticing when they are thirsty (Phillips et al., 1991). This population is also more likely to have co-morbidities and take medications that affect thermoregulation (Centers for Disease Control and Prevention, 1996). Finally, older adult mobility may be more limited and impede seeking a cooler environment or obtaining assistance. Older adults are one of the most important extreme heat risk groups and have higher mortality and hospital admission rates than the general population (Semenza et al., 1999; Stafoggia et al., 2008; Whitman et al., 1997). Both the total number and the percentage of older residents (age 65 or older) are important heat risk factors recorded by the U.S. Census. The percentage of older people may reflect a concentration of older adults (e.g. assisted living) who are more likely to have health problems or disabilities that exacerbate vulnerability. Neighborhood level risk factors are also commonly used as a proxy for individual risk (Krieger, 1992; Wilkins, 1993).

Some U.S. studies suggest a disparity in extreme heat mortality by racial categories. Evidence from the Midwestern and Southern U.S. suggests that Black/African American people have disproportionately higher heat mortality (e.g. O'Neill et al., 2003; Whitman et al., 1997). This disparity may be linked to the household characteristics such as fewer minority households with central air conditioning (Medina-Ramón et al., 2006; O'Neill et al., 2005). Starting with the 2000 U.S. Census, individuals could self identify into multiple racial categories. We calculated the proportion of Black, Hispanic, American Indian, and Asian American residents in each neighborhood, using only the first reported racial category in each CBG. Poverty, a lack of entitlements, and an inability to pay for heat mitigation or to live in a cooler section of the city are also important heat risk factors (Harlan et al., 2006). Renting is another income metric that may provide complimentary information on household amenities, maintenance, and/or neighborhood stability.

A large proportion of extreme heat victims is found living alone and social isolation can be an important risk factor (e.g. Klinenberg, 2003). Recent Western Europe research using marriage status as proxy of social isolation provided conflicting results. Living alone did not increase heat mortality in portions of England or Italy, but marriage was protective against mortality in France (Fouillet et al., 2006; Stafoggia et al., 2008; Foroni et al., 2007). We use the U.S. Census estimate of the proportion of households with people living alone and anticipate that the effect may be most pronounced in older individuals. Linguistically isolated households "sometimes or always" speak a language other than English at home. Most of these households do, however, speak some English. Linguistic isolation may hinder protective behaviors during extreme heat events by impeding an understanding of heat warnings. We grouped all linguistically isolated households reported by the U.S. Census together.

Some of the mentally ill have little control over their environments, decreased access to cooling systems, and limited mobility (Centers for Disease Control and Prevention, 1993; Schuman, 1972). Heat mortality risk generally increases with higher levels of disability, although the amount of medical care can modify this relationship (Belmin et al., 2007; Holstein et al., 2005). We grouped together all reported disabilities (sensory, physical, mental, self-care, go-outside, and employment disabilities) for the residents over the age of 5 in the analysis.

Co-morbidities such as diabetes, cardiovascular, renal, and pulmonary diseases as well as obesity, alcohol usage, and some medications increase, or are associated with behaviors that increase, extreme heat vulnerability (e.g. Semenza et al., 1999; Stafoggia et al., 2008; Oechsli and Buechley, 1970). Overweight and obese individuals generate more heat and have more difficulty dissipating heat (Barrow and Clark, 1998). Privacy considerations restrict the reporting of medical information to political units too coarse for the analysis (e.g. Behavioral Risk Factor Surveillance System). Therefore, this information is not included.

2.2.3. Neighborhood stability

High violent crime rates and the fear of being attacked may further perpetuate social isolation and may discourage protective heat behaviors like leaving a window open overnight (Palecki et al., 2001). Older adults commonly found heat relief and assistance by visiting nearby public spaces and air conditioned stores (Klinenberg, 2003). Population density and vacancy rates approximate levels of urban decline and/or a lack of protective heat amenities (Smoyer, 1998). Assisted housing developments are more likely to be placed in areas with lower housing values (Rohe and Freeman, 2001). By extension, higher crime rates tend to occur closer to public housing (e.g. McNulty and Holloway, 2000). In summary, lower neighborhood stability should increase heat distress and mortality risk.

2.3. Data preparation

The statistical analysis of heat risk factors was conducted at the CBG level. Both HDC, HM, and satellite heat exposure information was aggregated up to the CBG level, using ArcGIS's 9.3 (ESRI, Inc.) Zonal Statistics function. We summed the total number of HDC in each CBG in Phoenix and dichotomized Philadelphia CBG into either hosting or not hosting a heat mortality case.

2.4. Statistical techniques

Generalized Linear and Mixed Models (GLMM) commonly control temporal autocorrelation and this approach has been extended to control spatial autocorrelation (Orme et al., 2005). We modeled autocorrelation between all CBG in a study region with a fixed random effect. Autocorrelation is modeled with a function (Gaussian, spherical, exponential) that considers the distance between CBG centroids and the range over which unexplained spatial autocorrelation exists (Venables and Ripley, 2002). Spatial GLMM analysis was conducted in R (version 2.8.1), using the MASS package (version 7.2). This technique does not produce a true log-likelihood, so model selection procedures such as Akaike's Information Criterion cannot be used. Instead, we screened individual risk factors exhibiting relatively strong associations ($p < 0.25$) to heat distress or heat mortality for inclusion in the multiple variable analysis (Hosmer and Lemeshow, 2004). Next, backwards stepwise selection with a removal probability of $p > 0.05$ removed risk factors from the multiple variable analysis. Finally, intuitive interaction terms were retained at the $p < 0.05$ level.

We report the GLMM odds or incidence rate ratios, interpret the results, and map the geography of fitted heat risk. The GLMM risk factor coefficients are commonly expressed as odds ratios (Philadelphia) or incidence ratios (Phoenix) in public health. The odds ratio is the probability heat mortality, occurs compared to the probability it does not for a one unit risk factor change. Analogously, the incidence ratio compares the change in expected heat distress calls for a unit risk factor change. For example, a degree temperature increases correspondingly increases the probability of heat mortality by 20% for an odds ratio of 1.2. We assessed accuracy using the mean square error difference between fitted and observed heat distress calls (Phoenix) and area under the Receiver Operating Characteristic (ROC) curve for heat mortality (Philadelphia) (Sing et al., 2005). The area under the ROC curve is the probability that a CBG hosting heat mortality will be correctly fitted with a higher mortality probability than a non-case CBG.

3. Results

We present the final GLMM results and map the fitted heat mortality in Philadelphia and heat distress calls in Phoenix. We report the adjusted odds ratios and confidence intervals of significant risk factors from the multiple variable analyses.

3.1. Philadelphia

The geographic distribution of outdoor heat exposure was not related to Philadelphia heat mortality cases (Table 3). During an extreme heat event, locally hotter neighborhoods were not more likely to report heat mortality cases. The GLMM with a spherical correlation structure (range 200 m) provided the best heat mortality fit (Area under ROC: 0.71). Neighborhoods with more Black/African American residents (1.01, 95% CI: 1.00–1.02) tended to host mortality cases more disproportionately. The probability of hosting heat mortality was strongly influenced by neighborhood stability characteristics. Neighborhoods with a newer housing stock were protective against heat mortality (0.93, 95% CI: 0.89–0.98). Conversely, a higher proportion of vacant housing increased the heat mortality risk. Fig. 1 displays the observed and fitted heat mortality probabilities. The GLMM fits high heat risk to North Philadelphia (south central region), but does not capture high risk in South and West Philadelphia.

3.2. Phoenix

Heat exposure and the built environment, socioeconomic vulnerability, and neighborhood stability all exhibited important relationships to Phoenix HDC (Table 4). The best fitting GLMM with a Gaussian correlation structure (range 78.2 m) had a mean squared prediction error of 0.76 HDC per census block group. The urban heat island as measured by impervious surface (1.01, 95% CI: 1.01–1.02) and maximum nighttime surface temperature (1.17, 95% CI: 1.09–1.25) increased HDC. The impervious surface and housing density interaction term likely controlled for commercial areas with large amounts of built materials and fewer households. Housing density is inversely related to HDC. Housing density appears to capture both suburban growth and the loss of housing in downtown Phoenix.

Neighborhoods with a higher proportion of residents living alone tended to report more HDC (1.03, 95% CI: 1.02–1.04). More HDC were made from the neighborhoods with higher proportions of Black, Hispanic, linguistically isolated, and renting residents. Conversely, neighborhoods with a higher proportion of Asian American residents made fewer HDC. Interestingly, neighborhoods with a larger number of older residents were protective against making HDC (0.86, 95% CI: 0.78–0.95). Consistent with other studies (e.g. Klinenberg, 2003), a higher proportion of vacant households (1.03, 95% CI: 1.02–1.04) increased the HDC risk. Fig. 2 maps the observed and fitted HDC from the analysis. The GLMM highlights the greatest HDC risk neighborhoods in Downtown Phoenix, Tolleson, Goodyear, and Tempe. The GLMM also correctly fits the low HDC risk to most of the municipalities surrounding Phoenix. However, the GLMM notably understates HDC risk in Northern Phoenix.

Table 3
Generalized Linear and Mixed Effect Model results for the 1999 summer season in Philadelphia, Pennsylvania, U.S. ($N=1741$).

Risk factor	Odds ratio	Std. error	95% CI	*p*-Value
Black (%)	1.01	0.004	1.00–1.02	0.014
Year house built	0.93	0.023	0.89–0.98	0.005
Vacant households (%)	1.04	0.016	1.01–1.07	0.010
Total population (per 1000 people)	1.09	0.034	1.00–1.16	0.005

4. Discussion

The areas of Philadelphia and Phoenix with the most extreme heat health problems share similar development histories. North, South, and West Philadelphia and Downtown Phoenix experienced economic stagnation and Anglo-American migration to the suburbs. Discriminatory economic practices further prevented people of color from living in cooler, safer, and newer housing in each city. In Phoenix, the Downtown area hosts homeless people with minimal entitlements or options to adapt to extremely hot outdoor temperatures. In Philadelphia, people living in neighborhoods with the oldest and most dilapidated housing cannot cope with extremely hot indoor temperatures.

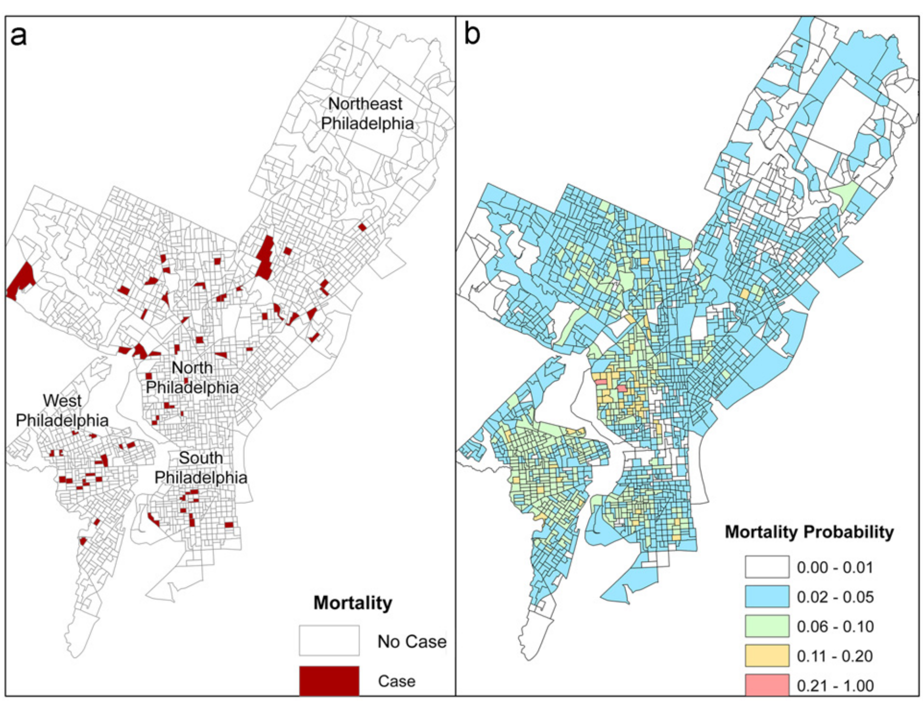

Fig. 1. Observed (a) and fitted Generalized Linear and Mixed Model (b) heat mortality in Philadelphia, PA, U.S. Heat mortality was recorded during the summer of 1999.

Table 4
Generalized Linear and Mixed Effect Model results for the 2005 summer season in Phoenix, Arizona, U.S. ($N=1704$).

Risk factor	Odds ratio	Std. error	95% CI	p-Value
Nighttime Surface Temperature (maximum)	1.17	0.042	1.09–1.25	< 0.001
Impervious surface (%)	1.01	0.004	1.01–1.02	0.001
Housing density (100 houses/km^2)	0.82	0.033	0.76–0.89	< 0.001
Households renting (%)	1.01	0.002	1.00–1.01	0.003
Population age 65 or older (per 100 people)	0.86	0.045	0.78–0.95	0.003
People living alone (%)	1.03	0.005	1.02–1.04	< 0.001
Linguistically isolated households (%)	1.01	0.004	1.00–1.02	0.010
Black (%)	1.03	0.007	1.01–1.04	< 0.001
Hispanic (%)	1.01	0.003	1.01–1.02	< 0.001
Asian(%)	0.93	0.030	0.87–0.99	0.015
Vacant households (%)	1.03	0.005	1.02–1.04	< 0.001
Imperviousness surface X housing density	1.002	0.001	1.001–1.003	< 0.001
Total population (per 1000 people)	1.36	0.077	1.21–1.51	< 0.001

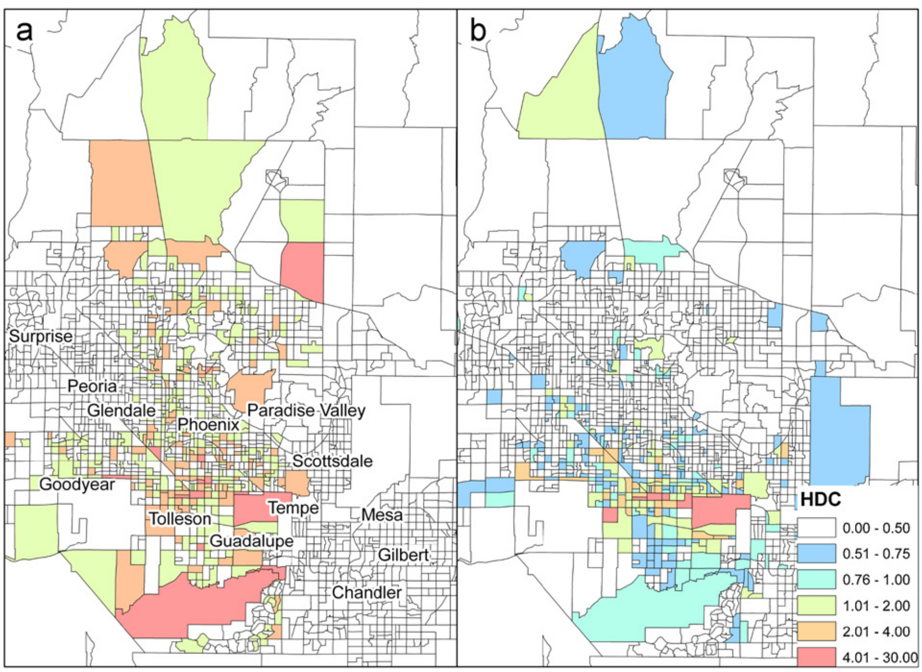

Fig. 2. Observed (a) and fitted Generalized Linear and Mixed Model (b) heat distress calls in Phoenix, AZ, U.S. The heat distress calls were reported during the summer of 2005.

Older housing units may represent multiple processes such as substandard housing or the legacy of discriminatory housing practices. In Philadelphia, the percentage of households reporting substandard housing problems is much higher than the rest of the United States. As of 1999, ~60,000 households face plumbing, heating, and building maintenance problems that may increase heat exposure and limit heat mitigation strategies (Hillier and Culhane, 2003). More than half of Philadelphia residents live in housing built before 1934 and older housing was historically more likely to be substandard (Wolfinger, 2007).

Housing density, instead of housing age, better approximates the geography of development and migration in Phoenix. In Phoenix, it appears that housing density captures the related processes of urban decline and suburban growth. Phoenix's population grew rapidly from 1 million in 1970 to 4.28 million in 2008. Contrary to city-wide trends, housing stock and populations decreased in the Downtown Phoenix over the same period. Affluent suburban regions such as Scottsdale, Tempe, and Glendale host the highest housing densities. In short, housing density may also reflect intra-urban development patterns as well as neighborhood stability (Smoyer, 1998).

Smoyer (1998) observed the persistence of high heat mortality in the same regions of St. Louis, MO between 1966 and 1988. Likewise, North, South, and West Philadelphia suffered high heat mortality during both the 1993 and 1999 extreme heat events. Examining areas which chronically suffer from extreme heat may point to underlying disparities and processes that perpetuate heat risk. Qualitatively, Philadelphia heat mortality tends to be concentrated in the portions of the city that historically suffer from lead poisoning (Robinson, L., personal communication). Further research should examine the inter-linkages between multiple environmentally sensitive health outcomes.

The case studies suggest that the most important heat risk factors are place-specific. Risk factors common to both cities are neighborhoods with a higher proportion of vacant housing units and Black/African American residents. Racial categories which are sometimes significant individual risk factors in case-control studies appear to be very important neighborhood level risk factors. Lower income Hispanic Phoenix neighborhoods tend to lack centralized air conditioning and this probably accounts for some of the increased HDC risk (Harlan et al., 2006). Similarly, air conditioning prevalence in white households was twice as high as black households in four United States Midwestern cities (O'Neill et al., 2005). At-risk, people are often unaware of electricity subsidies. Further research is needed to determine how the cost of electricity may translate into an increased heat risk.

Phoenix hosts a large number of retirement communities, so it is not entirely surprising that the number of older adults is protective against heat distress. Some communities enforced age restriction zoning, where every household must contain an older person (Gober, 2005). This policy fosters homogenous retirement communities. These areas likely have higher incomes, protective behaviors, and/or access to medical care to manage extreme heat. O'Neill et al. (2003) did not find an association between older adults and heat mortality, which further suggests that risk factors are place-specific.

Outdoor surface temperature was strongly related to Philadelphia heat mortality in 1993 (Johnson et al., 2009). However, outdoor heat exposure was not related to heat mortality in 1999. This discrepancy may be related to different study designs or changing vulnerabilities over time. It may also suggest that outdoor and indoor temperatures of heat mortality cases are not always related. In other words, personal behaviors such as closing windows and household-specific building materials may be more relevant heat exposure metrics.

Philadelphia public agencies, not-for profit organizations, and volunteers target support services to hard to reach, at-risk, and homeless risk groups. People in need of emergency services can contact an extreme heat hotline and receive follow up medical care. Some volunteer Block Captains identify at-risk populations and "check in" with them during extreme heat events. However, large portions of Philadelphia are not served by Block Captains. Mapping may help target resources such as educational materials, reverse 911 measures, cold water distribution, and the provision of transportation to cooling centers.

4.1. Limitations and future directions

This study is limited by the quality of the heat distress information, a lack of air pollution data, interpretation of extreme heat risk factors, and fundamental limitations of ecologic studies. Homeless people are an important Phoenix risk group and their heat distress is likely under-represented in this analysis. This population probably has less access to telephone service and may make fewer HDC. A transient homeless population may also introduce risk factor misclassification bias: the locations of HDC may not align with the neighborhood, where homeless people were originally censused. Existing air pollution measurements are either too sparse (pollution monitors) or too coarse (satellite) to be considered in this neighborhood study. Yip et al. (2008) found that ozone and PM_{10} were not related to 2005 Phoenix heat mortality. Neighborhood level extreme heat risk factors may serve as crude proxies for relatively complex processes. We attempted to interpret risk factors in the context of each city's development and history with extreme heat events. Further, qualitative research is required to more thoroughly interpret the meaning of neighborhood level risk factors.

Ecologic studies which analyze aggregate human health and risk factor information are limited by three problems: (1) ecologic fallacy, (2) modifiable area unit problem, and (3) lack of human behavior information (Beale et al., 2008; Wilhelmi et al., 2004). The ecologic fallacy states that inferences from the neighborhood level may not necessarily describe individual risk factors. Future multilevel studies considering individuals nested within neighborhoods would limit false ecological inferences (e.g. Robert and Reither, 2004). The modifiable area unit problem refers to the process of aggregating individual level information to CBG or census tracts. Repeating the study at a different analysis level may produce divergent results (Openshaw and Taylor, 1981). Finally, neighborhood level socioeconomic vulnerability information cannot account for individual adaptations and protective behaviors that can modify heat distress or mortality (United States Environmental Protection Agency, 2006). For example, most people know when heat warnings are issued, but fewer than half of the respondents changed their behavior to adapt to extreme heat (Sheridan, 2007). Future research will attempt to limit information bias by incorporating individual knowledge, attitudes, and practices.

5. Conclusion

Evidence based, neighborhood level studies determine the most important extreme heat risk factors from heat distress or mortality cases. This procedure improves upon previous vulnerability mapping procedures which do not determine the relative importance of heat risk factors. By contrast, our procedure derives the relative importance of heat exposure, socioeconomic vulnerability, and neighborhood stability from locations, where people suffer from heat distress or mortality. There is a need to expand heat emergency plans that identify at-risk populations domestically and abroad. This cost-effective analysis may be particularly beneficial to cities without a comprehensive heat watch/warning system. Mapping heat distress or mortality risk highlights important health inequalities and can be used to target educational or public health interventions.

Acknowledgments

The authors thank Helen Lamont, Jonathan Patz, Lawrence Robinson, Richard Keller, Annemarie Schneider, Stephen Vavrus, Sharon Long, Megan Christenson, Tanja Fransen, and the Original Weather and Society*Integrated Studies Workshop participants for comments on earlier versions of the paper. The authors also thank anonymous reviewers whose comments improved the manuscript. This research was unfunded.

References

Adams, C., Bartelt, D., Elesh, D., Goldstein, I., Yancey, W., 1993. Philadelphia: Neighborhoods, Division, and Conflict in a Post-industrial City. Temple University Press, Philadelphia.

Arizona Department of Health Services, 2006. Heat Emergency Response Plan. Arizona Department of Health Services, Phoenix, AZ.

Arizona Homeless Coordination Office, 2009. Current Status of Homelessness in Arizona. Arizona Homeless Coordination Office and Department of Economic Security, Phoenix.

Barrow, M.W., Clark, K.A., 1998. Heat-related illnesses. American Family Physician 58, 749–756.

Beale, L., Abellan, J.J., Hodgson, S., Jarup, L., 2008. Methodologic issues and approaches to spatial epidemiology. Environmental Health Perspectives 116, 1105–1110.

Belmin, J., Auffray, J.C., Berbezier, C., Boirin, P., Mercier, S., de Reviers, B., Golmard, J.L., 2007. Level of dependency: a simple marker associated with mortality during the 2003 heatwave among French dependent elderly people living in the community or in institutions. Age and Ageing 36, 298–303.

Bernard, S.M., McGeehin, M.A., 2004. Municipal heat wave response plans. American Journal of Public Health 94, 1520–1522.

Bolton, C.J.H., 2005. Helping the Homeless: Program Evaluation of Philadelphia's Supportive Housing Program. Drexel University.

Braga, A.L.F., Zanobetti, A., Schwartz, J., 2001. The time course of weather-related deaths. Epidemiology 12, 662–667.

Centers for Disease Control and Prevention (CDC), 1996. Extreme Heat: a Prevention Guide to Promote your Personal Health and Safety. U.S. Dept. of Health & Human Services, Washington, DC.

Centers for Disease Control and Prevention (CDC), 2006. Heat-related deaths—United States, 1999–2003. Morbidity and Mortality Weekly Report 55, 796–798.

Centers for Disease Control and Prevention (CDC), 1994. Heat-related deaths—Philadelphia and United States, 1993–1994. Morbidity and Mortality Weekly Report 43, 453–455.

Centers for Disease Control and Prevention (CDC), 1993. Heat-related deaths—United States, 1993. Morbidity and Mortality Weekly Report 42, 558–560.

Chestnut, L.G., Breffle, W.S., Smith, J.B., Kalkstein, L.S., 1998. Analysis of differences in hot-weather-related mortality across 44 US metropolitan areas. Environmental Science and Policy 1, 59–70.
Curriero, F.C., Heiner, K.S., Samet, J.M., Zeger, S.L., Strug, L., Patz, J.A., 2002. Temperature and mortality in 11 cities of the Eastern United States. American Journal of Epidemiology 155, 80–87.
Dimas, P.R., 1999. Progress and a Mexican American Community's Struggle for Existence: Phoenix's Golden Gate Barrio. Peter Lang Publishing, New York.
Donoghue, E.R., Graham, M.A., Jentzen, J.M., Lifschultz, B.D., Luke, J.L., Mirchandani, H.G., 1997. Criteria for the diagnosis of heat-related deaths: National Association of Medical Examiners. Position paper. National Association of Medical Examiners Ad Hoc Committee on the definition of heat-related fatalities. The American Journal of Forensic Medicine and Pathology 18, 11–14.
Dormann, C.F., McPherson, J.M., Araújo, M.B., Bivand, R., Bolliger, J., Carl, G., Davies, R.G., Hirzel, A., Jetz, W., Kissling, W.D., 2007. Methods to account for spatial autocorrelation in the analysis of species distributional data: a review. Ecography 30, 609–628.
Ebi, K.L., Teisberg, T.J., Kalkstein, L.S., Robinson, L., Weiher, R.F., 2004. Heat watch/warning systems save lives: estimated costs and benefits for Philadelphia 1995–98. Bulletin of the American Meteorological Society 85, 1067–1073.
Foroni, M., Salvioli, G., Rielli, R., Goldoni, C.A., Orlandi, G., Zauli Sajani, S., Guerzoni, A., Maccaferri, C., Daya, G., Mussi, C., 2007. A retrospective study on heat-related mortality in an elderly population during the 2003 heat wave in Modena, Italy: the Argento Project. The Journals of Gerontology Series A, Biological Sciences and Medical Sciences 62, 647–651.
Fouillet, A., Rey, G., Laurent, F., Pavillon, G., Bellec, S., Guihenneuc-Jouyaux, C., Clavel, J., Jougla, E., Hemon, D., 2006. Excess mortality related to the August 2003 heat wave in France. International Archives of Occupational and Environmental Health 80, 16–24.
Gershunov, A., Douville, H., 2008. Extensive summer hot and cold extremes under current and possible future climatic conditions: Europe and North America. In: Diaz, H.F., Murnane, R.J. (Eds.), Climate Extremes and Society. Cambridge University Press, New York, pp. 74–98.
Gillespie, A., Rokugawa, S., Matsunaga, T., Cothern, J.S., Hook, S., Kahle, A.B., 1998. A temperature and emissivity separation algorithm for advanced spaceborne thermal emission and reflection radiometer (ASTER) images. IEEE Transactions on Geoscience and Remote Sensing 36, 1113–1126.
Gober, P., 2005. Metropolitan Phoenix. Place making and community building in the desert University of Pennsylvania Press, Philadelphia.
Golden, J.S., Hartz, D., Brazel, A., Luber, G., Phelan, P., 2008. A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006. International Journal of Biometeorology 52, 471–480.
Golden, J., Chuang, W.C., Stefanov, W.L., 2009. Enhanced classifications of engineered paved surfaces for urban systems modeling. Earth Interactions 13, 1–18.
Harlan, S.L., Brazel, A.J., Prashad, L., Stefanov, W.L., Larsen, L., 2006. Neighborhood microclimates and vulnerability to heat stress. Social Science and Medicine 63, 2847–2863.
Hibbs, J.R., Benner, L., Klugman, L., Spencer, R., Macchia, I., Mellinger, A.K., Fife, D., 1994. Mortality in a cohort of homeless adults in Philadelphia. New England Journal of Medicine 331, 304–309.
Hillier, A.E.,Culhane, D.P., 2003. Closing the gap: housing (un) affordability in Philadelphia. Departmental Papers (Philadelphia City and Regional Planning).
Holstein, J., Canoui-Poitrine, F., Neumann, A., Lepage, E., Spira, A., 2005. Were less disabled patients the most affected by 2003 heat wave in nursing homes in Paris France? Journal of Public Health 27, 359–365.
Homer, C., Huang, C., Yang, L., Wylie, B., Coan, M., 2004. Development of a 2001 national landcover database for the United States. Photogrammetric Engineering and Remote Sensing 70, 829–840.
Hosmer, D.W., Lemeshow, S., 2004. Applied Logistic Regression. Wiley-Interscience, New York.
Johnson, D.P., Wilson, J.S., Luber, G.C., 2009. Socioeconomic indicators of heat-related health risk supplemented with remotely sensed data. International Journal of Health Geographics 8, 57.
Kaiser, R., Rubin, C.H., Henderson, A.K., Wolfe, M.I., Kieszak, S., Parrott, C.L., Adcock, M., 2001. Heat-related death and mental illness during the 1999 Cincinnati heat wave. The American Journal of Forensic Medicine and Pathology 22, 303–307.
Kalkstein, L.S., Jamason, P.F., Greene, J.S., Libby, J., Robinson, L., 1996. The Philadelphia hot weather-health watch/warning system: development and application, summer 1995. Bulletin of the American Meteorological Society 77, 1519–1528.
Karl, T.R., Melillo, J.M., Peterson, T.C. (Eds.), 2009. Global Climate Change Impacts in the United States. Cambridge University Press, New York.
Klinenberg, E., 2003. Heat Wave: A Social Autopsy of Disaster in Chicago. University of Chicago Press, Chicago.
Krieger, N., 1992. Overcoming the absence of socioeconomic data in medical records: validation and application of a census-based methodology. American Journal of Public Health 82, 703–710.
Kuhn, I., 2007. Incorporating spatial autocorrelation may invert observed patterns. Diversity and Distributions 13, 66–69.
LoVecchio, F., Stapczynski, J.S., Hill, J., Haffer, A.F., Skindlov, J.A., Engelthaler, D., Mrela, C., Luber, G.E., Straetemans, M., Duprey, Z., 2005. Heat-related mortality—Arizona, 1993–2002, and United States, 1979–2002. Morbidity and Mortality Weekly Report 54, 628–630.
Maricopa Association of Governments, 2007, Continuum of Care Planning Subcommittee Meeting Minutes.
McNulty, T.L., Holloway, S.R., 2000. Race, crime, and public housing in Atlanta: testing a conditional effect hypothesis. Social Forces 79, 707–729.
Medina-Ramón, M., Zanobetti, A., Cavanagh, D.P., Schwartz, J., 2006. Extreme temperatures and mortality: assessing effect modification by personal characteristics and specific cause of death in a multi-city case-only analysis. Environmental Health Perspectives 114, 1331.
Meehl, G.A., Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305, 994–997.
Mirchandani, H.G., McDonald, G., Hood, I.C., Fonseca, C., 1996. Heat-related deaths in Philadelphia-1993. The American Journal of Forensic Medicine and Pathology 17, 106–108.
Naughton, M.P., Henderson, A., Mirabelli, M.C., Kaiser, R., Wilhelm, J.L., Kieszak, S.M., Rubin, C.H., McGeehin, M.A., 2002. Heat-related mortality during a 1999 heat wave in Chicago. American Journal of Preventive Medicine 22, 221–227.
Oechsli, F.W., Buechley, R.W., 1970. Excess mortality associated with three Los Angeles September hot spells. Environmental Research 3, 277–284.
O'Neill, M.S., Zanobetti, A., Schwartz, J., 2003. Modifiers of the temperature and mortality association in seven US cities. American Journal of Epidemiology 157, 1074–1082.
O'Neill, M.S., Zanobetti, A., Schwartz, J., 2005. Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. Journal of Urban Health 82, 191–197.
Openshaw, S., Taylor, P.J., 1981. The modifiable areal unit problem. In: Wrigley, N., Bennett, R.J. (Eds.), Quantitative Geography: a British View. Routledge, Boston, pp. 60–69.
Orme, C.D.L., Davies, R.G., Burgess, M., Eigenbrod, F., Pickup, N., Olson, V.A., Webster, A.J., Ding, T.S., Rasmussen, P.C., Ridgely, R.S., 2005. Global hotspots of species richness are not congruent with endemism or threat. Nature 436, 1016–1019.
Palecki, M.A., Changnon, S.A., Kunkel, K.E., 2001. The nature and impacts of the July 1999 heat wave in the Midwestern United States: learning from the lessons of 1995. Bulletin of the American Meteorological Society 82, 1353–1367.
Phillips, P.A., Bretherton, M., Johnston, C.I., Gray, L., 1991. Reduced osmotic thirst in healthy elderly men. American Journal of Physiology—Regulatory, Integrative and Comparative Physiology 261, 166–171.
Reid, C.E., O'Neill, M.S., Gronlund, C., Brines, S., Brown, D., Diez-Roux, A., Schwartz, J., 2009. Mapping community determinants of heat vulnerability. Environmental Health Perspectives 117, 1730–1736.
Robert, S.A., Reither, E.N., 2004. A multilevel analysis of race, community disadvantage, and body mass index among adults in the US. Social Science and Medicine 59 (12), 2421–2434.
Rohe, W.M., Freeman, L., 2001. Assisted housing and residential segregation: the role of race and ethnicity in the siting of assisted housing developments. Journal of the American Planning Association 67, 279–292.
Rouse, J.W., Haas, R.H., Shell, J.A., Deering, D.W., Harlan, J.C., 1974. Monitoring the vernal advancement of retrogradation of natural vegetation. NASA/Goddard Space Flight Center, Type III, Final Report, Greenbett, MD.
Sheridan, S.C., 2002. The redevelopment of a weather-type classification scheme for North America. International Journal of Climatology 22, 51–68.
Schuman, S.H., 1972. Patterns of urban heat-wave deaths and implications for prevention: data from New York and St. Louis during July, 1966. Environmental Research 5, 59–75.
Schwartz, J., Samet, J.M., Patz, J.A., 2004. Hospital admissions for heart disease: the effects of temperature and humidity. Epidemiology 15, 755–761.
Semenza, J.C., McCullough, J.E., Flanders, W.D., McGeehin, M.A., Lumpkin, J.R., 1999. Excess hospital admissions during the July 1995 heat wave in Chicago. American Journal of Preventive Medicine 16, 269–277.
Semenza, J.C., Rubin, C.H., Falter, K.H., Selanikio, J.D., Flanders, W.D., Howe, H.L., Wilhelm, J.L., 1996. Heat-related deaths during the July 1995 heat wave in Chicago. The New England Journal of Medicine 335, 84–90.
Sheridan, S.C., 2007. A survey of public perception and response to heat warnings across four North American cities: an evaluation of municipal effectiveness. International Journal of Biometeorology 52, 3–15.
Sing, T., Sander, O., Beerenwinkel, N., Lengauer, T., 2005. ROCR: visualizing classifier performance in R. Bioinformatics 21, 3940–3941.
Smoyer, K.E., 1998. Putting risk in its place: methodological considerations for investigating extreme event health risk. Social Science and Medicine 47, 1809–1824.
Stafoggia, M., Schwartz, J., Forastiere, F., Perucci, C.A., Group, S.I.S.T.I., 2008. Does temperature modify the association between air pollution and mortality? A multicity case-crossover analysis in Italy. American Journal of Epidemiology 167, 1476–1485.
Tobler, W.R., 1970. A computer movie simulating urban growth in the Detroit region. Economic Geography 46, 234–240.
Tomassini, C., Glaser, K., Wolf, D.A., Broese van Groenou, M.I., Grundy, E., 2004. Living arrangements among older people: an overview of trends in Europe and the USA. Population Trends 115, 24–34.
U.S. Census Bureau, 2000a. U.S. population projections homepage [online]. Available at: 〈http://www.census.gov/population/www/projections/popproj.html〉 (accessed 16.08.07.).
U.S. Census Bureau, 2000b. U.S. census 2000 [online].Available at: 〈http://factfinder.census.gov〉 (accessed 06.11.07.).
United States Environmental Protection Agency (US EPA), 2006. Excessive Heat Events Guidebook U.S.. Environmental Protection Agency, Washington, DC.
Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S 4th. Springer verlag, New York.
Vescovi, L., Rebetez, M., Rong, F., 2005. Assessing public health risk due to extremely high temperature events: climate and social parameters. Climate Research 30, 71–78.

Whitman, S., Good, G., Donoghue, E.R., Benbow, N., Shou, W., Mou, S., 1997. Mortality in Chicago attributed to the July 1995 heat wave. American Journal of Public Health 87, 1515–1518.
Wilhelmi, O.V., Purvis, K.L., Harriss, R.C., 2004. Designing a geospatial information infrastructure for mitigation of heat wave hazards in urban areas. Natural Hazards Review 5, 147–158.
Wilkins, R., 1993. Use of postal codes and addresses in the analysis of health data. Health Reports 5, 157–177.
Wolfe, M.I., Kaiser, R., Naughton, M.P., Mirabelli, M.C., Yoon, S.S., Hanzlick, R., Henderson, A.K., 2001. Heat-related mortality in selected United States cities, summer 1999. The American Journal of Forensic Medicine and Pathology 22, 352–357.
Wolfinger, J., 2007. Philadelphia Divided: Race and Politics in the City of Brotherly Love. The University of North Carolina Press, Chapel Hill.
Yip, F.Y., Flanders, W.D., Wolkin, A., Engelthaler, D., Humble, W., Neri, A., Lewis, L., Backer, L., Rubin, C., 2008. The impact of excess heat events in Maricopa County, Arizona: 2000–2005. International Journal of Biometeorology 52, 765–772.
Yuan, F., Bauer, M.E., 2007. Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery. Remote Sensing of Environment 106, 375–386.