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Scales of perception: public awareness of regional and neighborhood climates

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Abstract Understanding public perceptions of climate is critical for developing an effective strategy to mitigate the effects of human activity on the natural environment and reduce human vulnerability to the impacts of climate change. While recent climate assessments document change among various physical systems (e.g., increased temperature, sea level rise, shrinking glaciers), environmental perceptions are relatively under-researched despite the fact that there is growing skepticism and disconnect between climate science and public opinion. This study utilizes a socio-ecological research framework to investigate how public perceptions compared with environmental conditions in one urban center. Specifically, air temperature during an extreme heat event was examined as one characteristic of environmental conditions by relating simulations from the Weather Research and Forecast (WRF) atmospheric model with self-reported perceptions of regional and neighborhood temperatures from a social survey of Phoenix, AZ (USA) metropolitan area residents. Results indicate that: 1) human exposure to high temperatures varies substantially throughout metropolitan Phoenix; 2) public perceptions of temperature are more strongly correlated with proximate environmental conditions than with distal conditions; and 3) perceptions of temperature are related to social characteristics and situational variables. The social constructionist paradigm explains public perceptions at the regional scale, while experience governs attitude formation at the neighborhood scale.

1 Introduction

It is imperative to understand the public's perceptions of climate change in order to organize and implement effective strategies for mitigation and adaption that will reduce human vulnerability to global and local impacts. Although there is not perfect correspondence

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between environmental perceptions and behavior (Corral-Verdugo et al. 2003; Kurz 2002; Mainieri et al. 1997), individual responses to environmental problems cannot be predicted without knowing how environmental threats are perceived (Fischhoff 1985). Perceptions of environmental problems are also important because most researchers agree that, directly or indirectly, what the public thinks has a great deal of influence on policy-making (Bostrom et al. 1994; Kempton et al. 1995; Read et al. 1994). For example, Leiserowitz (2006) asserts that public perceptions of climate change risks will influence national and international support or opposition to policies, such as legislation, regulations, and treaties designed to lessen the harms of global change.

In the past two decades, perceptions of the risks of global climate change have been widely publicized and studied (Bord et al. 1998; Bostrom et al. 1994; Dunlap 1998; Krosnick et al. 2006; Ungar 1992). Although the physical evidence of changing climates is well-documented and mounting—melting polar ice gaps, rising seas, changing habitats, frequent extreme weather events (Alley et al. 2003; IPCC 2007; Karl and Trenberth 2003; Kowalok 1993)—the national US Gallup Poll in March 2010 showed that only 53% of Americans believe global warming is already happening and 48% believe the seriousness of global warming is exaggerated (Newport 2010). These figures represent increased skepticism in the American public's view of climate change since 2008, when the figures were 65% and 35%, respectively (Newport 2010).[1]

Why are the views of a substantial proportion of Americans misaligned with climate science at a time when swift and large-scale evasive action is needed to lessen the impacts of climate change? Theoretical explanations suggest that low concern about climate change is related to how people deal with the modern "risk society" (Beck 1992), in which the magnitude of global environmental problems and potential disasters are immobilizing and overwhelming. Norgaard (2011) conceptualized disinterest in climate change as the "social organization of denial," which is a way that people collectively and implicitly mute the information provided by climate science to avoid confronting the fear of an uncertain future.

Focusing on how scientific information is communicated to the public, researchers have pointed out that the US media are more likely than media in other nations to embrace climate skeptics and to question the "scientific consensus" on global warming (Dispensa and Brulle 2003). The amount and content of media coverage may help to explain why many Americans demonstrate awareness of global climate change but regard both the environment and climate change as relatively low national priorities (Bord et al. 1998; Dunlap and McCright 2008; Dunlap and Scarce 1991; Leiserowitz 2005). Within the past few years, the media has portrayed climate change as a highly politicized issue in the US. Mirroring a larger ideological division within American society, polls show that conservatives and liberals diverge sharply in their

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[1] Gallup's findings on America's increasing skepticism about climate change were challenged by a Stanford poll that asked slightly different questions and found a solid majority of the public (75%) believes that the earth has been heating up over the last 100 years and human behavior is responsible (Krosnick, Op Ed in the *New York Times*, June 9, 2010). Editor in Chief of the Gallup Poll, Frank Newport, replied that a variety of other national polls "show demonstrable drops in Americans' acknowledgement of and concern about global warming" (Newport, Letter to the Editor in the *New York Times,* June 17, 2010) Surveys conducted by the Yale Project on Climate Communication showed a shift over time toward less concern and more disbelief among the American public that climate change is happening. The percentage of the public who were alarmed or concerned in the 2008 survey was 51%, which slipped to 39% in 2010. Those who were doubtful or dismissive increased from 19% in 2008 to 31% in 2010 (Leiserowitz et al. 2010).

views on climate change (Dunlap and McCright 2008). In the 2010 Gallup Poll, 30% of conservatives believed "the effects of global warming are already occurring" (down from 50% in 2008) and 74% of liberals believed this (no change since 2008) (Jones 2010).

Another explanation for attitudes toward climate change is that most Americans have little personal experience with the impacts of global climate change, and in fact, 67% believed in 2010 that global warming will not be a "serious threat to them or their way of life in their lifetimes" (Newport 2010; Weber 2006). This sentiment may suggest that in a wealthy, industrialized, and urban society, most people who respond to telephone surveys are buffered from the immediate and severe effects of climate change by technological adaptations in the built environment (e.g., indoor heating and cooling systems, food storage capacity). Currently, and in the foreseeable future, most have employment and access to adequate fresh water, food, and energy at affordable prices. Personal experience with climate change is much more common among rural and indigenous peoples, such as native fishers in Alaska (Gregory et al. 2006; McCormick 2008), pastoralists in east Africa (Ellis and Galvin 1994), and farming peasants in the Andean highlands (Carey 2010), where changes in local climate have already threatened livelihoods and caused major changes in traditional ways of life (Galloway McLean et al. 2009).

In this study, we aim to address the question of whether urban Americans have the capacity to perceive their environment in ways that indicate sensitivity to climatic conditions. Do people have experiential knowledge about local climate that prevails over social frames of reference—ideas and attitudes absorbed from social affiliations, institutions, political ideologies, and information (or disinformation) campaigns—in shaping their views of climate change? Our study informs the global climate change field because it examines how local environmental conditions and experiences influence perceptions of climate (Bowman 2008; Krosnick et al. 2006; Ye et al. 2011).

We employed a socio-ecological research framework to investigate how environmental conditions compared with public perceptions of climate in one urban center. Socio-ecological interactions refer to the coupled feedback between natural and human systems (Gimblett 2001). Climate change represents a multi-level socio-ecological system in which human development and the modification of native landscapes are altering physical processes, as witnessed in rising global temperatures and urban heat islands (UHIs) (Brazel et al. 2000; Oke 1997). Local variability in climate has received scant attention in studies of attitudes toward global change but, as we discuss in more detail below, climate change is occurring at multiple scales and cities generate regional and neighborhood effects on climate. Previous research has shown that temperatures within urbanized regions vary substantially in direct relationship to the characteristics of neighborhoods (Harlan et al. 2006; Jenerette et al. 2007; Ruddell et al. 2010). Using the Phoenix, Arizona metropolitan area as a laboratory, we intentionally introduce spatiality into the study of public perceptions of climate change.

The four research questions we answer in this study are: *1) Is there a spatial pattern of air temperature perceptions among residents of metropolitan Phoenix? 2) Does the pattern of temperature perceptions correspond spatially with scientifically-derived measures of temperature? 3) Is the correlation between perceptions and conditions weaker or stronger at increasingly finer spatial resolutions in the current study? 4) What is the relative importance of localized temperature experience and broader social frames of reference in predicting residents' perceptions of temperature in the urbanized area?*

2 Background

2.1 Multi-scale climate changes

Climate change refers to any significant change in the state of the climate (e.g., changes in the mean and/or variability of its properties) over an extended period of time (decades or longer), whether due to natural variability or as a result of human activity (IPCC 2007). Although the media focuses the public's attention on global change, the scientific evidence strongly supports claims that changes in climate are happening at multiple scales from global to regional to local and that there are independent anthropogenic drivers of change at each scale (IPCC 2007; Oke 1997; Stedman 2004). Changes in climate at any scale affect human health and well-being (Arnfield 2003; Geller 2003; Kalkstein and Davis 1989) and may also influence the public's perceptions of risks associated with climate.

Temperature is a key variable in climate studies due to the impacts it has on ecological processes as well as its direct and indirect impacts on human comfort, health, and general well-being (McMichael et al. 2006; O'Neill and Ebi 2009). Temperature is significant in the human context since a rise of just a few degrees in core temperature can result in harmful and serious consequences (Reith et al. 1996). Although humans live in wide-ranging climate regimes, people are highly sensitive to weather and climate as a result of physical reactions, social preferences, recreation, and discussions about their local environment (IPCC 2001; List 2004).

Extremely hot weather was the leading cause of death among weather-related fatalities in the US from 1995 to 2004 (NOAA 2006) and deaths caused by heat/drought ranked highest among natural hazard fatalities in the US from 1970 to 2004 (Borden and Cutter 2008). Summer heat waves in cities such as Chicago (Semenza et al. 1996), Cincinnati (CDC 2000), Philadelphia (Mirchandani et al. 1996), and Paris, France (Vandentorren et al. 2004), among many others, claim thousands of lives each year. Temperature thresholds vary from region to region but a recent study by Meehl and Tebaldi (2004) shows that heat waves have intensified over the 20th century, and they are projected to become more frequent, more intense, and longer lasting over the next century. Illness, mortality, and displacement resulting from various environmental threats associated with climate change will pose an even greater threat to public health throughout the world (Geller 2003; IPCC 2007; McMichael et al. 2006).

Mean surface air temperature is an important measure of climate change and has been recorded and/or simulated at a variety of spatial scales. At the global level, the IPCC Fourth Assessment Report (AR4) (2007) indicated that average surface temperature increased by 0.74°C between 1906 and 2005. There is variation from region to region around the world, ranging from 2.0 to 3.5°C in higher northern latitudes, whereas regions in southern latitudes and the Antarctic show cooling trends of 0.2–1.0°C during this period (IPCC 2007). In addition to detecting variable temperature changes in different regions throughout the world, research also shows a distinct pattern of changes in surface air temperature between rural and urban environments over the past 100 years.

Studies have consistently found that temperatures are increasing at a significantly faster rate in cities compared to nearby rural areas (Lowry 1967; Oke 1997). Heat islands are, "probably both the clearest and the best documented example of inadvertent climate modification" by humans (Oke 1978). The UHI is driven by human transformations of native landscapes into dense settlements that modify the surface energy balance, which in turn produces a warmer local climate. The substitution of heat-retaining impervious surfaces and building materials for vegetation inhibits night-time cooling (Arnfield 2003; Oke 1982). Air conditioners and vehicles exhaust heat into the air near the urban surface (Grossman-Clarke et al. 2005). Surface cooling is also inhibited by reduced outgoing long-wave thermal radiation due to the vertical structure of buildings. Industry, transportation systems, and tall buildings in cities affect local meteorology in ways that increase temperature, cloud and fog formation, humidity, and rate of precipitation (Goudie 2000).

Urban climatologists agree that the UHI effect accelerates temperature changes in cities (Arnfield 2003; Lowry 1967; Taha 1997; Voogt 2002). For example, a study by Brazel et al. (2000) found that annual minimum temperatures in urban areas of Central Arizona increased by 4.2°C during the 20th century compared to an increase of 1.3°C in rural areas, representing a warming rate over three times higher in the urban area. Hedquist and Brazel (2004) measured average nighttime maximum temperature variation on a rural to urban gradient equal to 7.3°C in 2001.

An emergent theme in urban climatology is that UHIs comprise a range of microclimates (small scale variations in temperature created by “turbulence moving across rough and uneven surfaces of the earth”) (Oke 1978). Recent studies have identified significant variability in microclimates within the same city that are associated with heterogeneity of vegetation, soil, and engineered surfaces (Arnfield 2003; Jenerette et al. 2007; Sheridan and Kalkstein 2004; Souch and Grimmond 2006). Monitoring weather stations in and around metropolitan Phoenix for the period 1990 to 2004, Brazel et al. (2007) found within the urbanized area an overall spatial variability in June mean minimum temperature on the order of 2 to 4°C. Temperatures vary significantly within the cities that comprise this region (Jenerette et al. 2007; Stefanov et al. 2001).

Neighborhood microclimates were implicated in uneven levels of human exposure to heat and health outcomes among residents of the Phoenix metropolitan area during the summers of 2003 and 2005 (Harlan et al. 2006; Ruddell et al. 2010). In Harlan et al.’s study, heat stress measured by the Human Thermal Comfort Index (HTCI) in eight city neighborhoods varied significantly in late afternoon from place to place. Similarly, Ruddell et al. (2010) investigated the spatial distribution of extreme heat in 2005 among 40 diverse Phoenix metropolitan neighborhoods and found: 1) significant differences in outdoor exposure to extreme heat (temperature ≥113°F); 2) more self-reported heat-related illnesses among survey respondents in warmer neighborhoods; and 3) strong correlations between land use/land cover and neighborhood temperature. Neighborhood-specific death rates during heat waves have been documented in cities, such as Chicago (Klinenberg 2002) and Philadelphia (Johnson et al. 2009). These findings have enormous implications for social and environmental justice within cities because higher temperatures are found predominantly in low-income and minority neighborhoods (Harlan et al. 2008).

Each scale of climate and climate processes—global, regional, and micro—is important for understanding the biophysical and social contexts that influence how people perceive climate change. The scale-specific drivers of climate complicate efforts to understand what people react to when asked about their perceptions of change. It is likely that perceptions of all sources of change are relevant. The cascading effects of scalar changes may conspire to place people who live in relatively close proximity to each other into quite distinct temperature regimes. Exposure to different temperatures could, in turn, greatly influence people’s perceptions of their environment, including the perception of how temperature is changing over time and how temperature in their own neighborhood compares to others. It is likely that analyzing public perceptions of temperature within one urban environment and comparing those perceptions to scientifically-derived temperatures will contribute to understanding what shapes the urban public's views on climate change.

2.2 Physical and social constructions of environmental perceptions

Aitken et al. (1989) observed that environmental perceptions are rooted in the local contexts of space and place, in which individuals "experience, perceive, organize, and ascribe meaning to information about the environment." Two frameworks explaining the development of environmental perception are explored in this paper. The first approach focuses on the ecological dimensions of person-environment relationships, such that an individual's perceptions are informed through experiences with and knowledge of natural Earth processes. The second approach, derived from comparative research involving varied social and cultural groups, provides insight into the social and cultural relativity of perception.

2.2.1 Person-environment relationships

Slovic and Peters (2006) argue that two important components of environmental perceptions are: 1) the way in which people experience a given risk condition; and 2) proximity to an environmental threat. A direct experience with swift and fierce change (e.g., earthquakes, hurricanes, heat waves) that inflicts severe damage often precipitates heightened perceptions of risk among the general public after the event and can act as a trigger for future preventive actions. For example, San Francisco's 1989 Loma Prieta earthquake killed 63 people, injured 3,757, and left thousands homeless. This sudden and severe event resulted in seismic retrofitting of bridges, transportation systems, and buildings (Eberhart-Phillips et al., 1994). Similarly, large numbers of deaths caused by heat waves have helped to elevate awareness and perceptions of human risks associated with extreme heat. Subsequently, many cities have adopted heat/health-watch warning systems designed to reduce human mortality and exposure to extreme heat (Sheridan and Kalkstein 2004). Thus, the public is more likely to perceive risks from environmental conditions after a catastrophic event than from the remote and slowly evolving underlying causes.

Proximity is also important in how people perceive the seriousness of environmental risks. One line of reasoning is that people only conceptualize the natural environment and environmental concerns in terms of locality and immediacy (Dunlap and Catton 1979). The counter hypothesis argues that humans have a tendency to perceive environmental problems as increasingly severe risks the farther they are (geographically and temporally) from an individual (Stedman 2004); a phenomenon described as the "environmental hyperopia" effect (Garcia-Mira et al. 2005; Uzzell 2000). Uzzell (2000) found that subjects in four countries perceived nearby environmental problems as less serious than similar environmental problems in places farther away, unless the problem poses an immediate and dangerous threat. Uzzell's belief is that increasing media coverage of global environmental problems and events, in addition to increased activity of international environmental organizations, are becoming more influential in framing how people view environmental risks in a socio-spatial context.

2.2.2 Social frames of reference

Social (and cultural) frames of reference are external influences on individuals that shape how they construct beliefs and ways of behaving that are socially acceptable within their own social group or culture (Ogbu 1993). Sherif (1936) originally defined social frames of reference as the way people internalize social norms (e.g., values, customs, or conventions) from their interactions with the broader social collectivities and societies to which they belong. Frames of reference influence individual attitudes, decisions, aspirations, and interpretations of information. For example, the viewpoints proffered by institutions that frame environmental problems can affect the way individuals construct their perceptions of environmental risks (Brody et al. 2008).

Gender and ethnicity divide people into groups that are highly salient social frames of reference and strongly correlated with individuals' perceptions of climate change. Studies consistently show that women and racial minorities are more fearful of the risks of climate change (e.g., Bord et al. 1998; O'Connor et al. 1999), which corresponds to literature demonstrating that these groups are also more concerned about other environmental threats (Kellstedt et al. 2008; Tuan 1990). Race and ethnicity, for example, have been linked to perception studies because the inequities and injustices perpetrated on non-white minorities have deprived them of resources to cope with environmental problems, and therefore, they are more vulnerable to associated risks (Brody et al. 2004).

Environmental perceptions are influenced by political affiliation because public opinion on climate change has become a partisan issue. Democrats are significantly more likely to favor actions in response to impacts of climate change whereas Republicans are much less inclined to support government policies or even to be concerned about climate change (Hardisty et al. 2010; Jones 2010; Lorenzoni et al. 2005). Zahran et al. (2006) found that liberals were more likely to regard climate change as risky, and were more likely to support costly risk mitigation public policies. There are a large number of studies that are consistent in finding that social and cultural frames of reference help to explain individuals' constructions of environmental perception.

2.2.3 Hypotheses

In this study, we tested hypotheses regarding how people process experiential information about local climatic conditions. Our first hypotheses, consistent with the person-environment framework, are that spatial patterns of temperature perceptions exist among Phoenix metropolitan residents and these patterns correspond with observed temperature differences over time and across neighborhoods. Our next hypothesis is that social and cultural frames of reference will predict heightened differences in awareness of regional climate change over time and relative neighborhood temperatures. Specifically, gender and ethnic groups that traditionally face greater risks from environmental hazards, as well as groups that hold more liberal political ideologies, will have perceptions that are more consistent with scientific assessments of local climate. Our final hypothesis is that direct experience with local weather will be a better predictor of temperature perceptions than social frames of reference at finer scales of analysis (neighborhood rather than region).

3 Research methods

We employed an integrated methodology that combines, at regional and neighborhood scales, output from the Weather Research and Forecast (WRF) atmospheric model and household survey data on perceptions of temperature in metropolitan Phoenix. Although this is one of the earliest attempts to synthesize these types of data (to our knowledge), we believe the socio-ecological research framework is an innovative and promising approach despite the technical challenges, methodological complexities, and data uncertainty inherent in this process. Current techniques to quantify air temperatures include measurements from weather stations or atmospheric models that simulate air temperature. Surface meteorological stations offer precise information on air temperature at discrete sites in the urban area, but usually lack dense spatial coverage and neighborhood representativeness. On the other hand, regional atmospheric models provide spatially continuous gridded fields of simulated air temperature. The most recent regional atmospheric models (Brown 2000; Martilli 2007; Masson 2006) are capable of simulating air temperatures within urban areas at a resolution of ~1 km, which is comparable to a social unit in US Census geography (block group)[2] that represents a neighborhood. The accuracy of urban air temperature simulations have greatly improved over the past 10 years, and today regional models are widely employed to enhance scientific understanding of processes related to neighborhood-scale weather, climate, and air quality (Grossman-Clarke et al. 2010a).

This study examines historical temperature data as a measure of regional climate change and simulated neighborhood temperature data for a 2005 Phoenix heat wave. Heat waves are discrete episodes of sustained elevated temperatures that have particularly severe consequences in cities because they are amplified by the UHI. In urban environments, minimum night-time temperature remains elevated for a period of days, causing increased morbidity and mortality (Kalkstein and Green 1997; Wilhelmi et al. 2004). We selected a heat wave because, although WRF is well suited to simulate fine scale temperatures (e.g., neighborhood microclimates), the temporal period of investigation was limited due to computer processing demands. WRF was shown to capture near-surface air temperatures in the Phoenix metropolitan region during extreme heat events of the past decade with relatively high accuracy (Grossman-Clarke et al. 2010b).

3.1 Study area

Located in the Sonoran Desert of the southwestern United States, the Phoenix metropolitan area encompasses 1,800 square miles in central Arizona and is home to over 65% of the state's 6.4 million residents (Census Bureau 2010). Metropolitan Phoenix is an ideal setting for studying temperature awareness because the region has a naturally warm climate, mortality due to extreme heat is substantial, and projections indicate the region's future vulnerability to high temperatures will increase (Meehl and Tebaldi 2004). The Centers for Disease Control (CDC) (2005) reported that Arizona led the nation in heat-related deaths from 1993 to 2002. The Maricopa County Department of Public Health (county in which Phoenix is located), examined death certificates for the years 2005–2007 and concluded that heat or heat exposure was a direct or contributing cause of 215 deaths (MCDPH 2008).

Recent studies have observed warming temperatures throughout central Arizona. Brazel et al. (2000) found that average annual temperatures have increased 1.7°C (or 3.1°F) in Maricopa and Pinal counties over the 20th century (see also Section 2.1). The National Weather Service (NWS) reports that the average annual number of misery days is also on the rise. Misery days in Phoenix are defined as local temperatures ≥43.3°C (or 110°F). Phoenix reported an average of 16 misery days per summer from 1971 to 2000 (minimum

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[2] The average size of the Census Block Groups sampled in this study was 0.45 square miles (or 1.2 square kilometers); the average population count was 2,085 people per CBG.

of 4 in 1999; maximum of 28 in 1979). In 2005 (summer that matches the perceptions of our survey respondents, see Section 3.3), there were 24 misery days. This number was surpassed in 2007 with a record-setting 33 misery days.

Historical conditions of temperature in metropolitan Phoenix, therefore, indicate that local temperature is changing much faster than global trends alone would indicate. Although metropolitan Phoenix already records some of the warmest temperatures in the world, global climate models agree that the desert southwest will become increasingly warmer and drier (Diffenbaugh et al. 2005; Seager et al. 2006).

3.2 Simulated weather conditions

To investigate spatial temperature variability within the urban area, we used the Weather Research and Forecast (WRF) model (Skamarock et al. 2005) to simulate local weather conditions. WRF was developed by the National Center of Atmospheric Research (NCAR) and the National Center for Environmental Prediction (NCEP). The regional atmospheric model works by quantifying air temperatures via a complex computer code that numerically solves the physical equations governing the spatial and temporal state of the atmosphere (e.g., air temperature, pressure, specific humidity and wind speed) as well as physical processes such as energy and momentum exchange between land surface and the atmosphere, microphysics and radiation transfer.

WRF version 3.0.1.1 together with the Noah Urban Canopy Model (Noah UCM) by Kusaka and Kimura (2004) was employed to simulate spatial and temporal distribution of air temperature at 2 meters above ground level (AGL), T_{2m}, at a spatial resolution of 1 square kilometer throughout metropolitan Phoenix (Arizona, USA). The Noah UCM accounts for important urban physical characteristics influencing the energy and momentum exchange of urban surfaces with the atmosphere and subsequently T_{2m}. These are the sky view factor for roads and walls in its radiation balance; heat storage in roofs, roads and walls; anthropogenic heating through electricity consumption and combustion; and an increased momentum flux by urban roughness (Chen et al. 2011). In WRF, an anthropogenic heat flux, Q_F, can be activated which is added to the sensible heat fluxes of road, roof, and wall surfaces to form the total sensible heat flux between the urban canopy and the atmosphere.

A global land use/cover data base classified according to the 33-category USGS Land Use/Land Cover System (Anderson et al. 1976) is provided with WRF. In this dataset, the extent of the Phoenix metropolitan area is under-represented. Following the procedure developed by Stefanov et al. (2001), Landsat Multispectral Scanner System, Thematic Mapper, and Enhanced Thematic Mapper 2005 LULC data for Phoenix at 30 meter pixels were derived (Ruddell et al. 2010). According to this classification three urban land use classes were distinguished in WRF: commercial/industrial, urban mesic residential, and urban xeric residential, which are distinguished by the fractional cover of built, vegetation and soil surfaces, and urban geometry. As described in detail in Grossman-Clarke et al. (2005), vegetative cover measurements were obtained from an extensive field survey carried out in 30 m×30 m field plots at 200 randomly selected sites across the entire urban area (SURVEY-200; Hope et al. 2003).

Simulations were conducted for July 15–19 2005, which corresponds to a local extreme heat event that occurred throughout metropolitan Phoenix during the summer of 2005. The extreme heat event was identified using the definition developed by Meehl and Tebaldi (2004) which considers historical temperatures to determine periods of extreme heat in a local context. Using temperature readings from Sky Harbor International Airport, we compared historical normal temperatures (1961–1990) to present day (2005) conditions. Analyses indicated that the local threshold temperature for an extreme event was a maximum daily temperature of 45°C (or 113°F).

The WRF results used in this study were evaluated against observations from 6 rural and 12 urban surface weather stations with a good overall agreement in T_{2m} for both urban and rural land use (Grossman-Clarke et al. 2010b). See Appendix 1 for a detailed description of the model simulations. The simulation results allowed us to examine the spatial variability of local conditions throughout the study area during a time of elevated risk to extreme heat for the entire region.

3.3 Sample survey of neighborhoods

This study focused on 40 diverse neighborhoods that are part of the 2006 Phoenix Area Social Survey (PASS). The household survey asked residents' about their perceptions of regional temperature change over time and temperature in their own neighborhoods compared to others during the summer of 2005. To our knowledge, analyses of people's climate perceptions have not been joined to local weather modeling, probably due to a lack of social survey data that spatially corresponds to the model output. Recent advances in the accuracy, resolution, and sensitivity of weather simulation models, as well as a geo-referenced survey, provided the opportunity for us to compare environmental perceptions with physical conditions, neighborhood by neighborhood.

PASS employed a two-stage research design (Harlan et al. 2007). First, a systematic sample of 40 neighborhoods was selected from the 94 urban sites that are monitored by the Central Arizona-Project Long-Term Ecological Research CAP LTER project (Grimm and Redman 2004). Population data from the 2000 US Census at the block group level were assembled for all 94 sites and classified by location (urban core, suburban, and fringe), median income, ethnic composition, and average age of residents. All types of neighborhoods in several municipalities of the metropolitan area were represented among the sample of 40. Second, in each neighborhood, 40 randomly selected households were recruited for participation in PASS and repeated contacts were made until a minimum 50% response rate was achieved in each neighborhood (at least 20 responses in each). Overall survey response rate was 51% (n=808). Data were collected using a multi-modal approach (online, telephone, or personal interview). By current industry standards, PASS is a rigorously designed survey with a high response rate (Keeter et al. 2006). The survey was administered by the Institute for Social Science Research (ISSR) at Arizona State University from April 29 through September 27, 2006.

3.4 Measures used in the analysis

Our survey diverged from the line of questioning in national polls in order to reduce the effects of media filtering and politicization on environmental perceptions. We directed our questions to respondent's perceptions of local climate in our study site. In metropolitan Phoenix, personal experience with extremely high temperatures is very salient for approximately 5 months a year. By asking about local climate, we focus on experiential information processing (Marx et al. 2007) to avoid having study participants view the issues as distant or irrelevant to themselves.

Two PASS questions that elicited people's experience and judgment of an environmental issue (Fernandez-Ballesteros 2003) were used as dependent variables in this study. The first question measured respondents' awareness of how the climate in the metropolitan region is changing over time and this is analogous to Gallup questions about whether global climate change is occurring now.: "In your opinion, do you think that over time the Valley is getting a lot hotter (3), a little hotter (2) or is it not getting hotter at all (1)?" ("Valley" is a local colloquial term that means the Phoenix region.) In each case, higher scores indicate perceptions of warmer temperatures and lower scores indicate perceptions of cooler temperatures. Respondents had lived in Phoenix for variable lengths of time and, therefore, had different time frames for recalling regional changes in temperature. A length of residence variable was included in the statistical models.

The second question shifts from a temporal to spatial scale, and measures how respondents perceived their neighborhood thermal environment relative to others in the same urban area during the summer of 2005. "During the summer of 2005, do you think your neighborhood was a lot cooler (1), a little cooler (2), a little hotter (4), or a lot hotter (5) than most other neighborhoods in the Valley or do you think it was about the same temperature (3) as other neighborhoods?" The question assumed that each respondent had a unique accumulation of interactions with other neighborhoods on which they judged relative temperatures. Respondents were asked in 2006 to recall their perceptions of relative neighborhood temperatures in 2005 and this time lag could introduce a source of memory error into the responses.

Independent variables that measured social frames of reference were used in the final stage of analyzing the individual-level survey data to predict temperature perceptions: gender (male = 0; female = 1), ethnicity (Anglo = 0; minority = 1), and self-identified political ideology (liberal, moderate, conservative). Household income (log transformed) and time spent away from the Phoenix area in the summer of 2005 (1 = not at all; 2 = 1 month or less; 3 = 2 to 3 months; 4 = entire summer) measured coping resources that could enable residents to voluntarily reduce their exposure to hot summer weather. Household income was determined by self-reports for 718 respondents, and we imputed household income for 83 respondents based on their marital status, educational attainment, and the neighborhood in which they lived. Experiences with living in Phoenix and in specific neighborhood environments were measured by three variables. Household experience with heat-related illnesses in summer 2005 (no = 0; yes = 1) was used as a measure of personal experience with hot weather. Age of respondent, also included as an experience variable, was coded as years and years^2. Length of residency, signifying acclimation to the Phoenix climate, was based on how long each respondent had lived in the Valley (years). The local temperature for each neighborhood during an extreme heat event in summer 2005 derived from WRF was used as the scientifically-derived neighborhood condition. Finally, as a control variable, we included the maximum temperature (recorded at Sky Harbor International Airport) corresponding to the date on which a respondent completed the survey.

3.5 Procedures

Data analyses were organized in three primary steps. First, GIS was used to map the distribution of WRF-predicted average, high, and low daily temperatures for each of the 40 neighborhoods during the study period. We used US census block groups to define neighborhood boundaries. Moran's I was used to investigate whether neighborhood temperature is spatially autocorrelated. Spatial autocorrelation investigates spatial configuration and contiguity by measuring the presence of an attribute in space (Burt and Barber 1996). Moran's I is calculated with the following equation (Fotheringham et al. 2000; Moran 1950):

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \, z_i \, z_j}{\left[\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \right] \left[\sum_{k=1}^{n} z_k^2 \right]} \tag{1}$$

where n is the number of neighborhoods (n=40), i and j are different neighborhoods, z_i is the difference between the temperature in neighborhood i and the overall mean temperature across neighborhoods, z_j is the difference between the temperature in neighborhood j and the overall mean temperature, and k is a neighborhood index. The weights w_{ij} are given by the inverse distance: $w_{ij} = f(d_{ij},) = (d_{ij})^{-1}$ where d_{ij} is the Euclidean distance between neighborhood i and j, where $i \neq j$.

The second step in the analysis aggregated the individual survey responses on perception of regional and neighborhood temperatures by neighborhood (census block group) and GIS was used to map the means of those variables onto the WRF-predicted temperatures. We used Spearman's rank correlation (Spearman's rho) to test the strength of empirical relationships between simulated and perceived temperatures.

The final step of the analysis predicted individual responses to the questions on perceived temperatures using WRF-derived local temperature and a suite of individual-level variables as described above. We used multinomial logistic and ordinal regressions to investigate respondents' awareness of temperature change in the region and relative temperature in their neighborhood. Analysis of variance (ANOVA) (Neter & Wasserman 1974) was used to assess variability of predictor variables within each neighborhood by testing whether variability was due to true neighborhood-specific differences rather than random errors.

4 Results

4.1 Spatial variability in WRF-predicted neighborhood temperatures

Regional temperature readings and WRF-simulated neighborhood temperatures for the July 2005 4-day heat wave are presented in Table 1. Analyses show mean daily average, high, and low temperatures from the NWS regional weather station (Sky Harbor International Airport) in addition to statistics summarizing the temperature variability among the 40 neighborhoods examined in this study. During the 4-day heat wave, Sky Harbor reported mean daily temperatures of: 39.0°C (or 102.2°F) for the average, a daily high of 45.4°C (113.7°F), and a daily low of 32.5°C (90.5°F). At the neighborhood scale, however, temperatures varied considerably for all three measures of mean daily temperature. For example, the mean daily average temperature was 34.6°C (94.3°F) in the coolest neighborhood while the warmest neighborhood was 39.6°C (103.3°F). The range of mean daily temperatures varied significantly among the 40 neighborhoods: 5.0°C (or 9.0°F) for mean daily average, 4.6°C (or 8.3°F) for mean daily high, and 5.2°C (or 9.4°F) for mean daily low. Mean daily low temperatures exhibited the largest range, indicating significant differences in exposure to environmental conditions within metropolitan Phoenix. The

Table 1 Mean daily average, low, and high temperatures (C) recorded at Sky Harbor weather station and simulated by WRF for PASS neighborhoods 15–19 July 2005

Simulated Temperature (C)	Sky Harbor[a]	Summary Statistics on WRF Simulations[b]				
		Mean	SD	Min	Max	Range
Mean Daily Temperature	39.0	38.3	1.08	34.6	39.6	5.0
Mean Daily High	45.4	45.7	0.98	42.2	46.8	4.6
Mean Daily Low	32.5	30.9	1.17	27.2	32.4	5.2

[a] Official temperature readings from the National Weather Service's regional weather station, Sky Harbor International Airport

[b] Simulated temperatures from the Weather Research and Forecast atmospheric model for 40 PASS neighborhoods

variability among mean low neighborhood temperatures is particularly interesting because Karl et al. (1993) found that minimum neighborhood temperatures often increase in cities faster than maximum temperatures.

A comparison of WRF-simulated mean daily neighborhood temperatures with Sky Harbor regional temperatures showed some differences. Mean daily low temperature, for instance, was much warmer at Sky Harbor compared to the neighborhood mean for the 40 study sites. Alternatively, mean daily high temperature was comparable between Sky Harbor and the neighborhood mean while the mean daily average is slightly warmer at Sky Harbor compared to the neighborhood mean. Sky Harbor's location in the urban corridor of central Phoenix (Fig. 1), in addition to the high concentration of impervious surface surrounding the airport, explains its higher temperatures.

A snapshot of temperature variability throughout the Phoenix metropolitan area is represented in Fig. 1 as the surface air temperature at 2 meters (m) above the ground for 17 July 2005, at 5 pm, which is the hottest part of the diurnal temperature cycle (Dai and Trenberth 2004). The map illustrates spatial temperature variability as well as the simulated temperature for each of the 40 neighborhood locations in the study. Notice the warmest temperatures during the late afternoon were concentrated west of downtown (in Glendale) and in central Phoenix. Warm daytime temperatures were particularly significant in the central Phoenix area where the high concentration of buildings and impervious surfaces also correlated with the warmest minimum temperatures.

The test of spatial autocorrelation shows the degree of dependency between neighborhood temperature and geographic location within the study area. Results indicated mixed levels of statistical significance for the daily mean average, mean high, and mean low temperature readings for 15–19 July 2005 (Table 2). Daily mean average and mean low were statistically significant only at the 90% confidence level, and the mean high temperature was randomly distributed across the 40 neighborhoods. In general, mean daily temperatures varied spatially among study sites. Although results exhibit modest positive spatial autocorrelation, analyses demonstrate that temperature is more complex than an urban to fringe gradient, suggesting that temperature within the metropolitan area is variably distributed across places and at different times of day. Combined with the knowledge that temperature is rising over time in metropolitan Phoenix (see Section 3.1), these results are important because they indicate that residents are exposed to a common stimulus (increasing regional temperature over time) at varying levels of intensity. Intensity of exposure depends upon where they live within the metropolitan area.

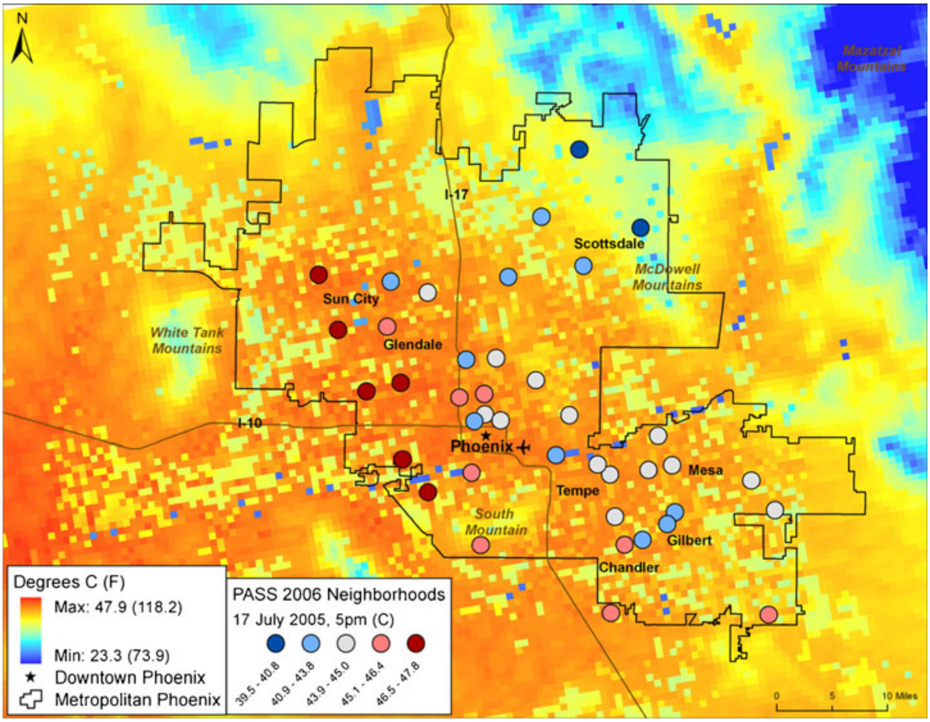

Fig. 1 Simulated air temperature for metropolitan phoenix and PASS neighborhoods for 17 July 2005, at 5pm

4.2 Temperature perceptions among phoenix-area residents

There was wide agreement among survey respondents that the region is getting warmer over time. Table 3 (Regional Temp Change) shows that 82.1% of respondents reported that it was getting a little hotter or a lot hotter. Only 17.8% of respondents reported that temperature in the region was staying the same. When considering relative neighborhood temperature (Relative N'hood Temp), about half (51%) thought their neighborhood was

Table 2 Global spatial autocorrelation results of simulated temperatures for PASS neighborhoods 15–19 July 2005

Simulated temperature	Global spatial autocorrelation		
	Moran's *I*	Z-Score	Significance
Mean Daily Temperature	0.03	1.73	0.10
Mean Daily High	0.03	1.62	Random
Mean Daily Low	0.03	1.82	0.10

Interpreting Global Spatial Autocorrelation results is as follows: a Moran's *I* value >0 indicates a clustered pattern (similar values are found together); $I=0$ indicates a random pattern; and $I<0$ indicates a dispersed pattern (high and low values are interspersed). A calculation of the variance, Z-scores represent levels of confidence that a given pattern is not random

Table 3 Descriptive statistics and frequency of survey respondents for regional and local measures of perceived temperature during summer 2005

Respondent Perceptions	Percent					N	Mean	SD
	Lot Cooler	Little Cooler	Same	Little Hotter	Lot Hotter			
Regional Temp Change	–	–	17.8	46.6	35.5	774	2.18	0.71
Relative N'hood Temp	2.3	22.3	51.2	17.5	6.6	767	3.04	0.87

Responses to regional temperature question was measured on a 3-point; responses to local temperature question was measured on a 5-point scale

about the same temperature as other neighborhoods in the summer of 2005. Of the remaining respondents, however, 24.6% perceived their neighborhood was cooler than others and 24.1% believed their neighborhood was warmer.

Figure 2 illustrates the variable spatial distribution of mean perceived temperatures for the 40 neighborhoods. In both maps, the circles represent aggregated responses for each neighborhood where the color of the circle reflects perceptions of temperature (dark blue = coolest, light blue = cooler, grey = average, light red = warmer, dark red = warmest). The spatial distribution of perceived changes in regional temperature (map on left) generally followed a structured pattern in which residents of neighborhoods near downtown centers perceived temperatures to be getting warmer, whereas residents of neighborhoods located near the urban fringe perceived temperatures to be the same over time.

Alternatively, perceptions of relative neighborhood temperatures (map on right) exhibited a more random spatial distribution. For instance, respondents in some downtown

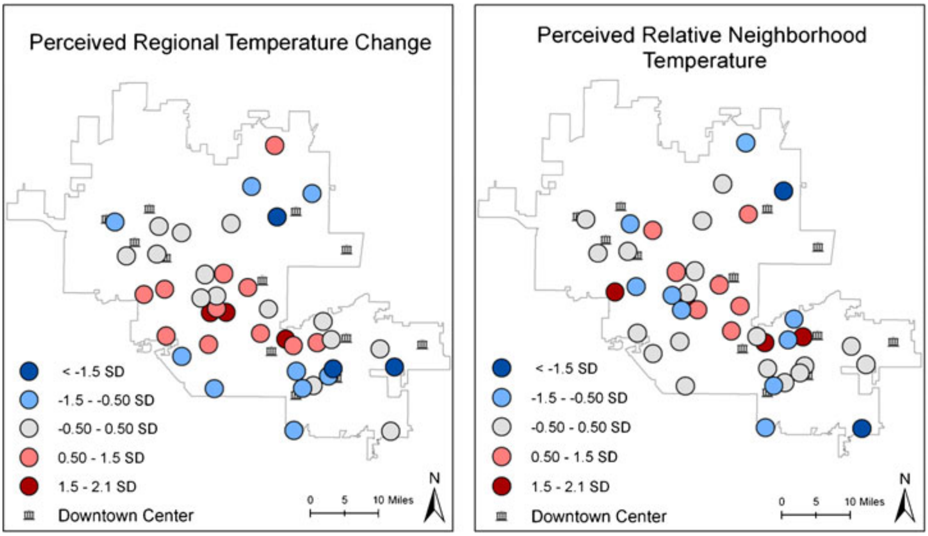

Fig. 2 Survey Responses for Perceived Temperature in Phoenix, AZ Aggregated to the Neighborhood Scale during Summer 2005. Note: The maps show standardized scores for Perceived Regional Temperature Change and Perceived Relative Neighborhood Temperature. Scores were standardized by calculating 1 standard deviation from the mean of each survey question. See Table 3 for summary statistics

urban neighborhoods perceived their neighborhood as cooler environments compared to the rest of the area, whereas respondents in fringe communities reported that their neighborhood was warmer than others. Confirming the visual patterns in the maps, global Moran's *I* tests of spatial autocorrelation indicated that the response distribution of perceived regional change exhibited a spatially significant pattern, whereas the distribution of perceptions of relative neighborhood temperatures was spatially random (Table 4).

4.3 Correlation of WRF-predicted temperatures with temperature perceptions

Spearman's rank correlation was used to compare WRF-simulated temperatures during the 2005 heat wave with perceptions of summer 2005 temperatures in the 40 neighborhoods (Table 5). Tests indicated a modest positive association between daily average, high, and low neighborhood temperatures and respondents' aggregated perceptions of change in regional temperatures over time (r=0.26 to 0.33). Neighborhood temperatures had stronger, positive and statistically significant correlations with respondents' aggregated perceptions of temperature in their neighborhood relative to others (r=0.47 to 0.50). Thus, strong relationships were evident for mean average, mean high, and mean low WRF-simulated temperatures with perceived relative neighborhood temperatures. In support of our hypothesis, these results showed that people exhibited greater sensitivity to environmental conditions (temperature) at the proximate neighborhood scale than at the more distal regional scale.

In support of our first hypotheses, there was a pattern of perceived relative temperatures that was consistent with the heterogeneous pattern of neighborhood exposure to temperatures within metropolitan Phoenix. Perceptions of rising regional temperature change were significantly more common in the urban core and weakest on the fringe, which, in general, is consistent with the UHI effect. Respondents living in the center of the UHI perceived the region as getting warmer than respondents in relatively cooler neighborhoods on the urban fringe.

4.4 Social characteristics associated with perception of temperature

The final part of the analysis utilized multinomial logistic and ordinal regression to investigate how social frames of reference, experience, and coping resources were associated with individuals' perceptions of temperature. Descriptive statistics for the ten independent variables used in the equations are presented in Table 6. In the logistic regression model examining perceptions of regional temperature over time, the dependent variable was categorized as respondents reporting "a little hotter" and "a lot hotter" with "not hotter" serving as the reference category (Table 7). Respondents who were significantly more likely to say it is getting a little hotter in the region were more likely to be women, to have spent more summer time away from the Valley, and to live in

Table 4 Global spatial autocorrelation results of perceived regional temperature change and relative neighborhood temperature

Respondent perceptions	Global spatial autocorrelation		
	Moran's *I*	Z-Score	Significance
Regional Temp Change	0.1	3.79	0.01
Relative N'hood Temp	−0.04	−0.48	Random

Table 5 Spearman correlation comparing perceived temperature with WRF-simulated temperatures for survey neighborhoods

Bivariate Correlation	N	Spearman's rho	Sig (1-tailed)
Perceived Regional Temp Change			
Mean Average Temp	40	0.33*	0.020
Mean High	40	0.33*	0.018
Mean Low	40	0.26	0.051
Perceived Relative N'hood Temp			
Mean Average Temp	40	0.47**	0.001
Mean High	40	0.48**	0.001
Mean Low	40	0.50**	0.000

*Correlation is significant at the 0.05 level (1-tailed)

**Correlation is significant at the 0.01 level (1-tailed)

neighborhoods with higher temperatures during the 2005 heat wave. Respondents who reported that it is getting a lot hotter tended to be women, minorities, politically moderate or liberal, experienced a heat-related illness in the household, and to be older and long-time residents. In support of our social and cultural frame hypothesis, ethnicity, gender, and political affiliation were statistically significant predictors of perceived regional temperature change in the Valley. Minorities and women were more likely to believe it is getting a lot hotter, whereas political conservatives were less likely to believe it is getting hotter. Coping resources (e.g., time away), and experience (e.g., illness, length of residency, age, and mean low neighborhood temperature) also affected perceptions of regional change.

Ordinal regression results on perceived temperature in one's own neighborhood relative to other neighborhoods in 2005 are presented in Table 8. In contrast to perceived regional

Table 6 Descriptive statistics for independent variables

Independent Variable	Descriptive Statistics				
	N	Mean/Proportion	SD	Min	Max
Gender (♀)	801	0.56	0.49	0	1
Ethnicity (minority)	791	0.27	0.45	0	1
Political Affiliation[a]	756	2.16	0.796	0	2
Household Income[b]	801	4.16	2.72	1	11
Time Away Summer 2005[c]	786	1.80	0.635	1	4
Heat-Related Illness (yes)	763	0.27	0.442	0	1
Age (years)	797	48.2	16.42	19	93
Residency (years)	808	20.57	16.28	0.5	83
Mean Low N'hood Temp (C)	40	30.87	1.17	27.2	32.36

[a] Political Affiliation (1) Liberal; (2) Moderate; (3) Conservative

[b] Household Income (1) $20,000 and under; (2) $20,001–40,000; (3) $40,001–60,000; (4) $60,001–80,000; (5) $80,001–100,000; (6) $100,001–120,000; (7) $120,001–140,000; (8) $140,001–160,000; (9) $160,001–180,000; (10) $180,001–200,000; (11) more than $200,000

[c] Time Away Summer 2005 (1) did not leave; (2) 1 month or less; (3) 2 to 3 months; (4) entire summer. We found significant spatial heterogeneity across neighborhoods in most of the predictor variables including Age (ANOVA, $P<0$), Ethnicity ($P<0.0001$), Income ($P<0.0001$), Time away ($P<0.001$), Residency ($P<0.001$), Temperature ($P<0.0001$), Illness ($P=0.0351$). However, there was not significant heterogeneity in terms of Gender and moderate position

Table 7 Multinomial logistic regression results for perceived temperature change in the region

Variables	Parameter Estimates				
	B	Std Error	Wald	Sig	Exp(β)
Nagelkerke Pseudo $R^2=0.172$					
A little hotter					
Social Frames of Reference					
Gender (♀)	0.682	0.229	8.007	**0.002**	1.913
Ethnicity (minority)	−0.129	0.304	0.845	0.666	0.756
Politically Moderate	−0.115	0.311	0.234	0.702	0.860
Politically Conservative	−0.412	0.294	2.710	0.149	0.616
Resources					
Imputed Income (log)	0.136	0.439	0.000	0.752	1.003
Time Away Summer 2005	0.390	0.221	2.730	**0.070**	1.440
Experience					
Illness (yes)	−0.110	0.269	0.293	0.680	0.864
Age	0.018	0.039	0.477	0.640	1.027
Age^2	0.000	0.000	0.482	0.682	1.000
Residency	−0.002	0.007	0.024	0.823	0.999
Mean Low N'hood Temp	−0.212	0.101	2.892	**0.033**	0.843
Max Temp of Survey Date	0.000	0.016	0.000	0.990	1.000
A lot hotter					
Social Frames of Reference					
Gender (♀)	0.869	0.246	10.297	**0.000**	2.203
Ethnicity (minority)	0.774	0.303	4.605	**0.010**	1.915
Politically Moderate	−0.263	0.327	0.883	0.408	0.736
Politically Conservative	−0.617	0.313	4.917	**0.043**	0.500
Resources					
Income (log)	−0.734	0.467	2.476	0.152	0.480
Time Away Summer 2005	0.138	0.232	0.059	0.545	1.058
Experience					
Illness (yes)	0.667	0.271	6.006	**0.013**	1.943
Age	0.081	0.043	4.936	**0.051**	1.099
Age^2	−0.001	0.000	5.168	**0.050**	0.999
Residency	0.013	0.008	3.206	**0.081**	1.014
Mean Low N'hood Temp	−0.067	0.117	0.002	0.556	0.995
Max Temp of Survey Date	0.017	0.017	1.019	0.313	1.017

Reference category: Not hotter

N=676

We also analyzed mean average and mean high WRF-simulated temperatures and found similar results

temperature change, the only statistically significant predictor variables were time away in summer 2005, mean low neighborhood temperature during the 2005 heat wave, and maximum temperature of survey date. Specifically, the more time respondents spent away from the Valley during the summer of 2005, the more likely they were to report that their

Table 8 Ordinal regression results for perceived temperature relative to other neighborhoods

Variables	Parameter Estimates			
	Est	Std Error	Wald	Sig
Nagelkerke Pseudo $R^2=0.092$				
Social Frames of Reference				
Gender (♀)	0.029	0.158	0.317	0.848
Ethnicity (minority)	−0.250	0.198	1.970	0.194
Politically Moderate	0.249	0.200	1.122	0.200
Politically Conservative	0.091	0.194	0.022	0.627
Resources				
Imputed Income (log)	−0.250	0.298	1.558	0.389
Time Away Summer 2005	0.393	0.151	6.817	**0.007**
Experience				
Illness (yes)	0.076	0.173	0.281	0.654
Age	0.022	0.027	1.007	0.412
Age^2	0.000	0.000	0.970	0.418
Residency	−0.006	0.005	2.127	0.218
Mean Low N'hood Temp	0.448	0.071	41.912	**0.000**
Max Temp of Survey Date	−0.022	0.011	4.098	**0.043**

Link function: Logit

$N=682$

Higher scores on perceived temperature indicate respondents perceived relative neighborhood temperature as hotter. We also analyzed mean average and mean high WRF-simulated temperatures and found similar results

neighborhood was warmer compared to other Valley neighborhoods (30.2% of respondents reported no time away during the summer of 2005; 62.1% spent 1 month or less away; and 7.8% spent more than 1 month away). Analyses of mean low neighborhood temperatures indicated that respondents who actually lived in relatively warmer neighborhoods were more likely to report that their neighborhood was warmer compared to other Valley neighborhoods. Controlling for the neighborhood temperature variable, respondents who completed surveys on days with higher temperature were less likely to report that their neighborhood was warmer than others. Ethnicity, gender, and political affiliation were not related to perceived relative neighborhood temperature. Results suggested that situational variables—time away in summer 2005, mean low neighborhood temperature during the heat wave, and daily maximum temperature of survey date—were very strong predictors for perceived temperatures in the neighborhood.

In summary, neighborhood temperature during the heat wave, a scientifically-derived measure of an individual's experience with the surrounding environment, was a significant predictor of climate perceptions and the effect of temperature on perception was much stronger at the neighborhood scale than at the regional scale. Social frames of reference (ethnicity, gender, political affiliation) did not have significant effects on perceptions of relative neighborhood temperature. In support of our final hypothesis, social frames were overwhelmed by the effects of resource/experience variables (i.e., time away summer 2005, mean low neighborhood temperature, and maximum temperature of survey date) at the more proximate neighborhood scale.

5 Discussion and conclusions

Many studies have examined perceptions of global climate change but few, if any, have considered how urban residents understand local climate and how their experiential knowledge might contribute to developing better risk communication strategies. Our study fills an important gap in this area by contributing to a more refined understanding of how Americans may formulate attitudes about climate change, which in turn leads to suggestions about types of adaptation and mitigation strategies that could be pursued with public support.

In answering our research questions, we made the following contributions. The first contribution is to document the spatial distribution of environmental conditions and social perceptions of temperature within an urban setting. Using the WRF atmospheric model to simulate sub-metropolitan temperatures, we identified a largely heterogeneous spatial pattern of the UHI, including the distribution of daily average, high, and low temperatures throughout the Phoenix region. Our analyses indicate that residents were exposed to varying levels of extremely high temperatures in the summer. Similarly, public perceptions of regional change and relative temperature differences among neighborhoods reflected spatial variability of responses when aggregated to the neighborhood level.

The second contribution is to confirm an association between WRF-simulated neighborhood temperature and residents' perceived temperatures. An overwhelming majority of respondents believed the region is getting warmer over time, which is an accurate assessment of local climate change when compared with historical temperature records. Belief in a changing local climate is spatially variable across the region because residents of some neighborhoods were more likely than others to believe that the climate is getting a lot hotter rather than only a little hotter. Average neighborhood belief in changing regional temperature had a modest correlation with the simulated temperature in their neighborhoods. Perceptions of own neighborhood temperature relative to others exhibited a stronger correlation to scientifically-derived temperature, which indicates that respondents accurately perceived their local environmental conditions. In other words, respondents were highly sensitive to temperatures and expressed experiential knowledge about local temperatures that corresponded closely with scientific knowledge.

The third contribution is to demonstrate the relative importance of environmental conditions and social frames of reference in explaining how people perceive temperature at different scales. Analyses of survey data indicated that women, minorities, political moderates and liberals, older people, longer-term residents, and people whose households had experienced heat-related illnesses were more likely to believe that it is getting much hotter in Phoenix over time. In this analysis, social variables were strong predictors of climate change. These findings support a social constructionist paradigm for attitude formation and are consistent with several previous studies regarding perceived temperature at broader scales of analysis. For instance, Bord et al. (1998), Hamilton (2008), Lorenzoni et al. (2005), and O'Connor et al. (1999) have noted differences among risk perceptions based on gender, ethnicity, and political affiliation, all of which have been described in social and cultural construction paradigms.

Interestingly, however, socially influenced attitudes toward climate were overwhelmed by shared environmental conditions (exposure to high temperature) when the dependent variable was perceived relative temperature at the neighborhood scale. The most significant predictor variable of perceived relative neighborhood temperature was neighborhood temperature (simulated by WRF), and there were no significant differences by social characteristics in how neighbors perceived it. This finding suggests that exposure and experience explain environmental perception at fine spatial scales.

Placing these findings within the context of current literature, we conclude that public perceptions of environmental risks become increasingly subject to social influences and less tightly coupled to experience as spatial scale broadens. Thus, risk assessments may also become attenuated as the scale of analysis increases and attitude formation progressively relies more on social frames of reference that guide interpretations of environmental conditions. We infer from our findings that effective communication strategies to the public about the risks of climate change should draw upon people's experiences and local knowledge of their environment. It is critical to ground support for climate adaptation and mitigation initiatives within local contexts of shared experiences.

Building upon these research findings, there appear to be two distinct policy fronts to improve public understanding and support for action on climate change. The first approach is to advance the narrative of global climate change through linking it with local experiences because these experiences are comprehensible and widely shared. Strategies for Phoenix, for example, might focus on initiatives designed to reduce anthropogenic sources of heat—such as vehicle emissions, heat-retaining pavement and building materials, and air conditioners that exhaust heat into the environment. These types of actions can reduce drivers of the regional UHI while simultaneously connecting local behavior to global impacts.

A focus on local action has the advantage of relying less on justifications from atmospheric science, global climate models, and the attendant uncertainties surrounding projects that are not easily communicated to the general public, and hence, are increasingly rejected as a basis for action. Local communication strategies rely more on weather, ecology, and social networks of informants who share an environment and many experiences in it. It is also important to note that expert interpretation of events is still important since warm winters or heavy rains, for example, can be misinterpreted as counter-evidence for global warming and long-term drought. Thus, there is a need for a second communication strategy in which scientific knowledge is crucial.

The second front is an educational approach that involves communicating to the public by highlighting the research of local scientists on climate, adaptation, and mitigation strategies that pertain to the local environment and speak directly to community interests. For instance, Arizona State University scientists studying the Phoenix UHI are currently involved in community outreach and education efforts, such as university seminars, public forums, in addition to collaborations with local municipalities. Similarly, scientists have formed the New York City Panel on Climate Change designed to help improve climate vulnerability science, increase climate outreach and education, as well as work with NYC task forces to take evasive actions. Improving public awareness and understanding of climate change at multiple scales could possibly replace skepticism, partisanship, and social divisions with a more productive model of blending scientific and experiential knowledge in an effort to reshape public opinion about climate change.

While most environmental perception studies on climate change focus on large spatial scales (e.g., global or national), our efforts examined social perceptions at fine scales of analysis and found significant variability within the same urban environment. A future line of research is to conduct similar studies in cities representing a range of climate regimes and facing a variety of climate challenges. Additional studies on temperature would provide a larger sample and evidence to help substantiate our findings in less extreme environments than Phoenix. A second area for future research is to investigate whether there are patterns of spatial correspondence between different climate processes and associated impacts, such as precipitation, coastal erosion, storm activity, or flooding, and residents' perceptions of climate change. Although this study examined temperature as one aspect of climate change, it would be valuable to have a wider spectrum of climate variables in order to understand associations between scientific and experiential knowledge. Finally, while most studies examine exclusively environmental conditions or social perceptions, this study blended both types of data. The socio-ecological framework provided a unique research perspective on climate change and should be used in other studies.

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Appendix 1: A technical note on the WRF simulations

This study employed WRF version 3.0.1.1 to simulate spatial and temporal distribution of T_{2m} in the Phoenix metropolitan area during the extreme heat event 15–19 July 2005. The WRF run was started at 00 UTC (1700 LST) allowing 24 overlapping hours for model spin up for 72 h simulation periods. 2-way nested WRF model runs with four domains and resolutions of 27, 9, 3 and 1 km, respectively were performed. In the simulations, 41 vertical levels were used with the first five vertical levels of ~25, 35, 45, 60 and 80 m AGL. The innermost domain included the Phoenix metropolitan area, surrounding desert and agricultural land.

WRF initial and boundary conditions were provided by NCEP ETA analysis data that are available with a 40 km resolution at a 3-h time-step. Planetary boundary layer processes were included via the Mellor-Yamada-Janjic scheme (Janjic 2002), microphysics through the WRF Single-Moment 3-class simple ice scheme (Hong et al. 2004), convection for the domains with 27 km and 9 km resolutions by the Kain-Fritsch scheme (Kain 2004) and the long and short wave radiation processes were included through the Rapid Radiative Transfer Model (Mlawer et al. 1997) and Dudhia scheme (Dudhia 1989), respectively. The Noah UCM and the Noah Land surface model (Noah LSM; Chen et al. 1997) were applied to the fraction of a model grid cell with built and natural surfaces, respectively.

An anthropogenic heat flux, Q_F, derived by the Sailor and Lu (2004) method was added to the sensible heat flux in WRF. Hourly Q_F values are based on the monthly energy consumption and average vehicle kilometers traveled per person. The average energy and fuel consumption data are spatially and temporally allocated based on the spatial distribution of the working and residential population densities (Grossman-Clarke et al. 2005). For this particular urban area, which is mostly suburban and not very densely settled, Q_F values are small in comparison to the other heat fluxes. Maximum values for the built-up urban, xeric, and mesic residential areas are ~30, 35 and 20 $\mathrm{Wm^{-2}}$ and occurred during the evening rush hour (LST 1700). Values during other day time hours are between 5 and 25 $\mathrm{Wm^{-2}}$.

The standard procedure for obtaining initial soil moisture for WRF is by interpolating the NCEP ETA model soil moisture values to the WRF spatial resolution. The initial soil moisture data reflect conditions in the native desert surrounding Phoenix but not the soil moisture content as influenced by specific local irrigation practices. Therefore the standard WRF cannot account for effects of irrigation on latent heat fluxes and subsequently air temperatures.

Irrigation occurs in the region year round to sustain agricultural productivity and non-native plant species that are predominantly used in urban landscaping. Most plants cannot survive extended periods of water stress, particularly during the hot summer months. Flood irrigation of agricultural fields is the preferred irrigation practice. For example, approximately 10–15 cm of water are applied to agricultural fields on a weekly basis via flooding during the summer months. This provides soil moisture conditions at field capacity to a depth of about 90 cm. Therefore, to account for flood irrigation in the WRF simulations, the initial soil moisture content of all soil levels was set to the reference soil moisture which corresponds to field capacity (USGS LULC category 3). The Noah LSM soil model has four layers with thicknesses of 0.05, 0.25, 0.70 and 1.50 m. The predominant soil categories in the region are “sandy loam” and “loam” with field capacities of 0.383 and 0.329 $m^3\ m^{-3}$ and wilting points of 0.047 and 0.066 $m^3\ m^{-3}$. In the course of the simulations the soil moisture content for the sandy loam dropped to 0.35, 0.36, 0.32 $m^3\ m^{-3}$ for soil layer one to three and stayed at field capacity for layer four. Plants did not experience significant water stress. In comparison the climatological soil moisture content as obtained from the NCEP ETA model initial data are 0.10, 0.11, 0.12 and 0.14 $m^3\ m^{-3}$.

Drip irrigation (the placement of drippers close to the plants’ stems to allow water to drip over an extended period of time into the soil) is the preferred irrigation practice for urban vegetation in Phoenix (Martin 2001; Martin et al. 2003). This irrigation technique ensures that there is sufficient water available in the root zone of plants to fulfill the transpiration demand, but very little water is “lost” by soil evaporation because the soil surfaces in between plants are usually dry. In WRF, the root depth of the urban and agricultural vegetation extends to 1 m (layer 3). To account for the drip irrigation practice and to avoid high evaporation rates from bare soil surfaces that are usually dry in urban landscaping in Phoenix, the initial soil moisture content was increased for the 3 sub-surface layers for the urban land use categories but not for the top soil layer. This ensured that vegetation in the model did not experience water stress and was able to transpire according to the atmospheric demand. The initial soil water content of the top soil layer was left at the value provided by the NCEP ETA model.

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