# SCALE AND SCIENTIFIC INQUIRY: AN INVESTIGATION OF THEORETICAL, METHODOLOGICAL, AND PRACTICAL APPLICATIONS

by

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A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

ARIZONA STATE UNIVERSITY

May 2009

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has been approved

March 2009

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ABSTRACT

For centuries scholars from wide-ranging disciplines have been challenged by physical, social, and methodological implications of scale. Wide-ranging spatial scales, for instance, present challenges to researchers examining physical or social processes operating on scales of analysis from the molecular to the planetary. Temporal scales represent a different concern such that the appropriate scale of analysis varies along the continuum of the instantaneous to the geological. Scale also presents methodological challenges as witnessed in the variability of results associated with discrete spatial and/or temporal scales of analysis. The various permutations of scale-related issues therefore underscore the complexity and breadth of research on scale within the scientific community.

This study aimed to contribute to scale research in four ways. The first effort focused on synthesizing existing literature on scale among five dominant research themes in geography. The second way is through the introduction and evaluation of a new framework to analyze physical and social constructions of scale. The third component of this study investigated methodological frameworks for analyzing processes at individual or multiple scales of analysis, and introduced and tested the viability of a new mixed method multi-scale framework. The fourth contribution of this dissertation was a case study which investigated physical and social dimensions of temperature at multiple scales of analysis. Research findings indicate that investigating complex socio-ecological processes via a mixed theoretical framework at multiple scales of analysis provides a new and innovative research perspective. In this study, social perceptions of environmental conditions become increasingly distorted as spatial scale increased.

ACKNOWLEDGMENTS

I would like to take this opportunity to express my appreciation to the many people that helped make this study possible. I would like to begin by recognizing my advisory committee, chaired by Elizabeth Wentz, Ph.D. Dr. Wentz has been an excellent mentor and her guidance, patience, and dedication helped me overcome numerous challenges throughout my doctoral studies. Equally inspiring is Sharon Harlan, Ph.D. whose expertise and insight has been invaluable not only on this dissertation, but throughout my graduate studies at Arizona State University. I would also like to recognize the sound advice of committee members Christopher Boone, Ph.D. and Robert Edsall, Ph.D. I appreciate the time, effort, and feedback you put into serving on my doctoral committee.

I would also like to recognize various scientists and colleagues whose contributions helped me complete this dissertation. Susanne Grossman-Clarke and Alexander Buyanteyev provided output from an advanced climate model, and Gerardo Chowell offered expertise on statistical analyses. Comments from peer-reviewers also helped enhance the dissertation. This dissertation is based upon work supported by the National Science Foundation (NSF) under Grant Nos. GEO-0816168 and SES-0216281. Any opinions, findings, and conclusions or recommendation expressed in this material are those of the author(s) and do not reflect the views of the NSF.

In addition to collaborating with the scientific community, I would also like to acknowledge my parents, family members, and friends who have supported me throughout my life. I appreciate your continued help and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

Table Page

LIST OF FIGURES

# CHAPTER ONE: INTRODUCTION

## Problem Statement

For centuries scholars from an array of disciplines have been challenged by physical, social, and methodological implications of scale. Wide-ranging spatial scales, for instance, present challenges to researchers examining physical or social processes operating on scales of analysis from the molecular to the planetary (Hobbs, 1998; Wu, 2004). Temporal scales represent a different concern such that the appropriate scale of analysis varies along the continuum of the instantaneous to the geological (McMaster and Sheppard, 2004; Meentemeyer, 1989). Scale also presents methodological challenges as witnessed in the variability of results associated with discrete spatial and/or temporal scales of analysis (Fotheringham, 1998; Openshaw, 1984; Robinson, 1950). The various permutations of scalar issues therefore underscore the complexity and breadth of research on scale within the scientific community.

Even within a single discipline, such as geography, questions about scale are an integral component of research. These questions, however, are being posed quite differently. Physical geographers, for example, investigate scale linkage (e.g., hierarchical organization) governing natural processes (Bendix, 1994; Phillips, 2004; Wu, 2004), while human geographers theorize on the social constructions of scale (Lefebvre, 1991; Smith, 1984; Taylor, 1982). Scale also challenges GIScientists in the form of data modification or the (mis)representation of features in models of human and/or physical processes (Aspinall, 2001; Tate and Atkinson, 2001). Geographers studying issues of nature and society (e.g., climate change, biodiversity) recognize the need to identify the appropriate operational scale of human and physical interactions (Sheppard and McMaster, 2004).

Increased attention to scale by geographers over the last thirty years has helped disentangle some of the complexities of scalar issues. Discussions on the various definitions of scale have served to clarify the ways in which different sub-disciplines approach scalar issues (Lam et al., 2005; Marston, 2000). For instance, while scientists utilizing remote sensing are primarily concerned with spectral scale, human geographers typically concentrate on geographic scale. A second area of progress is understanding how a given process works at multiple scales of analysis. While processes were traditionally couched in a linear context, studies have found that both physical and social phenomena often exhibit non-linear patterns at different scales of analysis. Robinson (1950), for example, found that the results of voting preferences varied based on different spatial scales. Similarly, Wu (2004) found that landscape pattern is dependent upon spatial scales of analysis. Studying multiple scales of analysis therefore helps to better understand a given process while broadly contributing to our knowledge of scale in general.

Although clarifying definitions of scale and conducting multi-scale analysis represents advances in scale research, many issues remain. Two particular challenges are theoretical conceptions of scale and methodological techniques to examine a given process. Despite the various ways in which scale is analyzed, there are currently two theoretical frameworks for constructing scale, downscaling and upscaling. While downscaling is commonly used to examine physical systems and the upscaling model is usually applied to social systems, both theoretical frameworks possess limitations and are inadequate for conceptualizing scale among complex systems (e.g., processes comprised of physical and social systems). A second research challenge is the methodological approach employed to examine a given process at multiple scales of analysis. Studies of physical systems, for example, typically employ quantitative techniques while social processes may be investigated by quantitative or qualitative methods (Grossman-Clarke et al., 2005; Uzzell, 2000; Wiens, 1989). Utilizing a single methodological framework, however, often presents a limited perspective of a given process. The integration of mixed method analyses enhances the general understanding of a given process while reducing weaknesses and/or biases of studies employing a single methodological approach (Jick, 1979; Shih, 1998). Although the mixed method framework offers valuable insight into a given process, studies have been limited to examining a single scale of analysis. There is every indication that a mixed method multi-scale analysis would yield new and interesting research findings.

**Research Context**

To investigate the theoretical and methodological challenges related to scale as outlined above, this study focuses on the Phoenix, AZ metropolitan area. Metropolitan Phoenix is a particularly interesting and dynamic environment to study multi-scalar issues due to the rapid physical and social changes that have been taking place throughout the urban area over the last fifty years (Baker et al., 2003; Gober and Burns, 2002; Grimm and Redman, 2004; Keys et al., 2007). The human modification of native landscapes into built environments has resulted in significant ecological changes, as witnessed in the urban heat island (UHI) effect (Oke, 1987). Understanding the influence of scale is particularly relevant when studying physical, social, and/or socio-ecological processes throughout the urban area. For instance, recent research indicates that urban climate is more complex than an urban to fringe temperature gradient. Instead, the urban environment in comprised of heterogeneous microclimates (Grossman-Clarke et al., 2008; Jenerette et al., 2007; Hedquist and Brazel, 2004). Similarly, social processes exhibit scale dependencies, such as variable ethnic composition, household income, environmental perception, crime rates, among other topics when analyzing various scales of analysis (e.g., Census block groups) within metropolitan Phoenix (Bolin et al., 2002; Grineski et al., 2007).

Two reasons underscore the importance of studying urban growth. First, global population and human settlement patterns show a distinct and increasing trend towards urbanization. Although the majority of global residents already live in urban areas, this figure is expected to rise to 66 percent of world inhabitants by 2030 as urban areas expand to encompass fringe communities (WRI, 1998). In addition, rural migrants are resettling in urban centers in search of employment, and higher education, among other reasons. The second reason urban growth is an increasingly important research topic is the coupled socio-ecological processes associated with the transformation of native landscapes into urban environments. The coupled socio-ecological feedback refers to the human modification of native landscapes and ecosystems, which results in changes in the natural environment that affect people (Gimblett, 2001). Climate change and urban heat islands are examples of these human-driven changes, which consequently pose a variety of challenges to numerous physical and social systems, such as water supply and human health and comfort. Scale provides a critical link in studying and understanding the way in which various physical, social, and socio-ecological processes are connected. Whereas this dissertation focuses on the Phoenix metropolitan area as a case study, the implications of this research represents a much broader scientific context.

**Project Overview**

This dissertation focuses on the implications of scale when studying complex socio-ecological systems at multiple scales of analysis. Organized into six chapters, the dissertation examines four distinct perspectives of scale which are presented in chapters two through five of this manuscript. A summary of each paper is described below. Although each of the four chapters is a self-contained peer-reviewed research paper, the focus on scale serves as a unifying research theme. In the spirit of most contemporary scholarship, the research papers reflect a collaborative effort among scientists from multiple fields of study (i.e., geography, sociology, physics). Although I am the lead author of each research paper, the names of coauthors and grant numbers are acknowledged where appropriate.

The following briefly describes the four data sets that were used in this dissertation and the specific contributions of each researcher. The Phoenix Area Social Survey (PASS) 2006 investigated the behaviors, attitudes, and perceptions of 808 local residents across 40 neighborhoods on four environmental research themes (air quality, climate change, land use, and water supply). My contributions to this study as a research assistant (2005-2007) to the Project Director, Sharon Harlan, included: conducting field research, organizing Census data, developing survey questions, digitizing aerial photos, creating maps, organizing and analyzing survey responses, as well as coauthoring the final report. This dissertation also utilized output from the Weather Research and Forecast (WRF) climate model, which simulated fine-scale air temperature throughout the study area for a critical heat wave period in the summer of 2005. Susanne Grossman-Clarke ran the model simulations and Alexander Buyantuyev applied advanced remote sensing techniques to help inform model input variables. I identified the temporal period to run the model by comparing present conditions (summer 2005) to historical temperatures (1961-1990). The author also organized two ancillary data sources. I examined data from the National Oceanic and Atmospheric Administration (NOAA) regarding historical temperature readings (1965-2006) among four regional weather stations. I also conducted a text analysis on the media coverage of extreme heat for the summer of 2005 from a Lexus-Nexus key word search.

**Chapter 2: Multi-tasking: scale in geography**

This paper serves to provide a review of literature on issues of scale by examining five major research themes in geography. Specifically, by investigating research on scale among physical geography; human geography; the modifiable areal unit problem (MAUP); GIScience; and nature and society, we aim to discuss the various ways in which scale is constructed and operationalized among five research themes. In addition to reviewing scalar issues among the five research themes, the paper pays particular attention to the theoretical and methodological approaches used to study scale. Findings indicate that geographic research on scale has largely remained isolated among subdisciplines; however, preliminary evidence indicates that the integration of theoretical and/or methodological among multiple research themes has provided new insight into scalar issues. The paper concludes by calling for greater theoretical and methodological integration to across sub-disciplines.

**Chapter 3: Advancing theory on scale in geography**

This paper aims to expand the theoretical paradigm on scale by developing and testing a new model for constructing scale. Although research within geography covers a broad spectrum of topics (e.g., physical, human, economic, among other themes), currently, there are only two theoretical frameworks to construct scale. This paper identifies limitations of existing approaches and argues for an alternative theoretical framework to investigate complex processes (e.g., systems comprised of physical and social processes) at multiple scales of analysis. Specifically, we introduce and test the hybrid framework which incorporates the downscaling and upscaling models. The research question informing this study is: *How might introducing a hybrid model improve theorization on scale in socio-ecological research?* Research findings support adopting the hybrid theoretical approach for studies examining complex socio-ecological processes.

**Chapter 4: A mixed method multi-scale analysis: a case study on extreme heat in Phoenix, AZ**

The objective of this paper is to evaluate the effectiveness of using the mixed method research framework on processes operating on multiple scales of analysis. Although mixed method analyses (the integration of quantitative and qualitative techniques) and multi-scale studies yield significant research contributions independently, there is a lack of research utilizing the mixed method research framework at multiple scales of analysis. For instance, mixed method studies have helped understand a given process via confirmation of results or comprehension of a study; however, studies have been limited to single scales of analysis. Only studying one scale of analysis is problematic because investigations of various physical or social processes often communicate different (even conflicting) findings based on spatial or temporal scale. To address this gap in research, we develop and test the mixed method multi-scale research framework by analyzing physical and social dimensions of temperature at multiple scales of analysis. This study addresses the following research question: *Does analyzing extreme heat via a mixed method multi-scale research framework lend new insight into socio-ecological issues?* Research findings indicate that the methodological framework developed in this paper is a viable approach for investigating complex systems at multiple scales of analysis.

**Chapter 5: Scales of perception: public awareness of regional and neighborhood climate change**

The final research paper is a case study on scale which compares environmental conditions and social perceptions of temperature at multiple scales of analysis. More specifically, we analyze output from the Weather Research and Forecast (WRF) climate model, and combine these data with self-reported perceptions of temperature from a social survey of Phoenix, AZ (USA) metropolitan area residents at the neighborhood and regional scales. Analyses investigate the four following research questions: *1) Is there a spatial pattern of temperature perceptions among residents throughout the Phoenix metropolitan area? 2) Does the pattern of temperature perceptions correspond spatially with scientifically-derived measures of temperature? 3) Is the correspondence 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?* Notable research findings provided a new and unique perspective on climate change, thus, validating the effectiveness of the hybrid theoretical model and the mixed method multi-scale research framework introduced in this dissertation.

**Chapter 6: Conclusions**

The dissertation concludes with a chapter summarizing the major research findings as well as directions for future research. This dissertation contributes to research on scale in four ways: 1) it summarizes current literature on scale; 2) it introduces a new theoretical approach for constructing scale; 3) it tests the viability of a mixed method multi-scale research framework; and 4) it carries out a case study on climate change by investigating physical and social dimensions of temperature at multiple scales of analysis.

# CHAPTER TWO: MULTI-TASKING: SCALE IN GEOGRAPHY

## About this Chapter

This chapter is an article that has been accepted for publication as is currently in press in *Geography Compass*. The title of the manuscript is “Multi-tasking: scale in geography” and the authors are Darren Ruddell and Elizabeth A. Wentz.

Geographers are inherently focused on the integrated processes and systems that comprise the physical and social environment; however, to date, geographic research on scale has remained relatively isolated within subdisciplines. While scale has become an increasingly important research topic in the field of geography, little effort has been made to identify commonality between research themes. This paper investigates scalar issues among five research themes within geography, which are: physical geography; human geography; the modifiable areal unit problem (MAUP); GIScience; and nature and society. The thrust of this paper is threefold: 1) to review scalar issues among the five research themes; 2) to discuss alternative theoretical frameworks to investigate scale; and 3) to call for greater theoretical and methodological integration to help resolve scalar issues.

## Introduction

Describing the world is a natural social skill. Not only have humans been describing places and processes to each other since early societies began sharing information, but other animals and insects (e.g., bees) have developed advanced techniques for communicating important geographical information such as the location to food sources (Goodchild, 2001). Oliver (2001) explains that it is not possible to describe every location on the Earth; thus, humans developed ways to generalize the Earth’s surface while communicating important details. Hunter-gatherers, explorers, and scientists, therefore, have used various means to describe their surroundings though medians such as "notebooks, film cassettes, paper maps, and most recently digital storage devices and geographical information systems," (Goodchild, 2001, p. 4). Creating an appropriate scale of information allows selected aspects of processes to be identified at different locations, making the level of detail an important characteristic of a geographical description.

The term scale, in once sense used to describe the level of detail of a description, has a vast number of distinct meanings. In a non-geographic context, scale refers to an instrument for measuring weight, a protective plate on reptiles and fish, a domain of musical notes, as well as action words to ascend or to mount. Within geography, the term scale presents semantic challenges: scale is used to describe the *level of detail*, or scale of observation; scale can also refer to the scope or spatial extent of the study area, known as the *geographic scale* (Lam, 2004). Additional meanings include *cartographic scale*, or the distance on a map in relation to the distance on the ground (Lam et al., 2005); *operational scale*, corresponds to the level or scale at which a process under examination operates (Cao and Lam, 1997); *temporal scale* which refers to the degree of detail in the recording of change through time (Meentemeyer, 1989); *spectral scale*, the degree of detail in the spectral characteristics of remotely sensed data (Lillesand and Kiefer, 2002); *support*, or the domain within which linear averages of a geographical variable may be computed (Olea, 1990); as well as *resolution*, the length measure, such that large-scale studies incorporate coarse resolution while small-scale studies are based upon fine resolution (Lam and Quattrochi, 1992).

Research on scale presents various challenges throughout the scientific community. Within geography, questions about scale are at the forefront of research; however, these questions are being posed quite differently. Physical geographers, for example, examine scale as it relates to scale linkage and hierarchical organization (Bendix, 1994; Phillips, 2004; Wu, 2004). Human geographers theorize on the social constructions of scale (Lefebvre, 1991; Smith, 1984; Taylor, 1982). Both physical and human geographers have recognized the importance of the Modifiable Area Unit Problem (MAUP), which identifies the sources of error when data are aggregated (Gehlke and Biehl, 1934; Openshaw and Taylor, 1979; Robinson, 1950). GIScientists face scale challenges when representing or modeling human and/or physical processes (Tate and Atkinson, 2001). Geographers studying nature and society recognize the need to identify the operational scale of human and physical interactions, such as climate change (Sheppard and McMaster, 2004). While there is some integration on scale among these five research themes, some issues remain disjointed. The objective of this paper therefore aims to draw together some of this disjointed literature through the following: 1) to review scalar issues among the five geographic research themes; 2) to discuss alternative theoretical frameworks to investigate scale; and 3) to call for greater theoretical and methodological integration to help resolve scalar issues.

The recent influx of research on scale in geography has helped enhance the current understanding of scale by discussing its various constructions and applications. One challenge, however, is that varying conceptions of scale employed in geography's subdisciplines makes any modern definition of scale difficult (Gibson et al., 2000; Manson, 2008). The purpose of this paper, therefore, is to present the way in which five research themes understand scale, and to use this platform to encourage integration across them. The five themes explored in this paper are: physical geography; human geography; the modifiable areal unit problem (MAUP); GIScience; and nature and society. While only a handful of scholars have attempted to synthesize scalar issues among multiple perspectives (Sayre, 2005; Sheppard and McMaster, 2004; Tate and Atkinson, 2001), recognizing various ways of understanding scale is desirable for two reasons. First, discussing theoretical frameworks and relevant research on scale for each theme should help clarify similarities and/or differences. Second, identifying commonality among research themes increases the potential for integration which we hope will help advance scholarship on scale research.

**Physical geography: data and processes**

Issues of scale among physical geographers have traditionally focused on scale linkage and the reductionist approach. Scale linkage is understood as “transferring information, relationships, models, and rules between different spatial and temporal scales” (Phillips, 2004, p. 86). Climatologists, for instance, investigate temperature records at various temporal and spatial scales, and results are often used to inform models or simulate past, present, or future conditions. The reductionist framework is an organizing principle in the physical geography subdiscipline. While geoscientists study a variety of earth systems, they have long recognized that processes and environmental controls relevant at a given spatial or temporal scale exercise at least partial control over processes operating at finer scales (Phillips, 2004). For example, the drainage area for a large-scale study exerts a measure of control over finer variables such as discharge, flow dimensions, and velocity (Leopold and Maddock, 1953; Leopold and Miller, 1956).

While research within physical geography considers wide-ranging spatial and temporal scales, such as the molecular to the planetary or the instantaneous to the geological, the concept of scale is relatively simple. For instance, most physical geographers examine one (or more) of the following conceptualizations of scale: geographic extent (operational scale); spatial/temporal resolution, or hierarchical organization (e.g. reductionist approach). Hierarchy theory represents a conceptual framework which links multiple scales of analysis (DeBoer, 1992; O'Neill et al., 1986). The underlying principle is that environmental systems are linked at successive scales, whereby higher-level systems constrain a given system while lower-level systems explain mechanistic operation (Allen and Starr, 1982; Bendix, 1994; Phillips, 2004; Urban et al., 1987). Hierarchy theory has frequently been used as a reductionist approach to estimate the properties of a given process when it is not possible or too expensive to acquire data at finer scales of analysis (Goodchild, 2001).

Research on hierarchical organization, however, indicates that relationships change as the spatial and temporal scales change when investigating certain processes. For example, Braun and Slaymaker (1981) examined snowmelt runoff at four different spatial scales and identified varying levels of snowmelt runoff based spatial scale where smaller basins report faster runoff travel times. Similarly, Imeson and Lavee's (1998) study of soil erosion and climate change found that temporal and spatial scales are not linked successively, but vary based on local properties such as slope, patch, and/or landscape. Research by Wiens (1989) found that patterns or relationships discerned at one spatial scale of observation may be invisible, or even contradicted, when examined at another spatial scale. Thus, although some physical processes are linked at successive scales, research indicates that other physical processes vary at different spatial and/or temporal scales of analysis. To help resolve some of these scalar issues, physical geographers may benefit by examining scale from different theoretical perspectives.

New research in time geography, for example, offers an alternative approach for investigating processes at multiple scales of analysis. Rather than employing hierarchical organization to study fine-scale processes, Miller (2005) argues for studying individual observations to model the behavior of the aggregate. Utilizing activity theory as the theoretical framework, Miller (2003) stresses the need for research that observes individual cases rather than place-based methods. Activity theory observes individual participation in space and time, and when aggregated, illustrates the behavior of a given process at larger scales of analysis (Ben-Akiva and Bowman, 1998). Therefore, in contrast to hierarchy theory, activity theory relies on individual data samples to scale up, which, in turn, presents large-scale patterns. Although most research in physical geography operationalizes scale via hierarchical organization, the subdiscipline may benefit by utilizing theoretical and/or methodological approaches applied in other concentrations of geography.

**Human geography: constructions of scale**

While physical geographers have observed nested hierarchies of scale among earth systems, many human geographers understand scale as the outcome of social constructions (Brown and Purcell, 2005; Cox, 1998; Manson, 2008; Marston, 2000; Smith, 1984). The treatment of scale in human geography is different from other subdisciplines in that many social theorists reject the notion of scale as an ontological category in favor of the "production of scale" (Smith, 1984). Unlike hierarchical organization governing scale in physical geography, most human geographers separate human activity from the physical environment when conceptualizing scale (Herod and Wright, 2002; Johnston et al., 2000). For instance, scale emerges out of social dynamics ranging from local scales such as the micropolitics of the household to broad scales like international economic regimes. The conceptualization of scale by most social theorists is therefore a reflection of social behavior carried out at various levels of analysis (household, neighborhood, state, nation).

Employing a hierarchical structure was the modus operandi in scale research until Taylor (1982) challenged this empiricist conception by couching social scale in a non-hierarchical theoretical framework. Taylor introduced a new arrangement whereby scale was utilized as an organizing principle to emphasize relations between scales. Smith (1984) expanded upon Taylor's work by arguing that scale is a construction of politics, and reasoned that "geographical scale defines the boundaries and bounds the identities around which control is exerted and contested." Finally, Lefebvre (1991) offered the simple yet powerful idea that space is a social product. Collectively, these works have grounded four tenets on scale in human geography. Scale is: 1) socially constructed; 2) amenable to varying constructions; 3) often contradictory and contested; and 4) not necessarily enduring (Sayre, 2005; Smith, 1984).

Despite agreement among scholars that scale is socially constructed and not necessarily part of a nested hierarchy, there has been active debate regarding the forces contributing to its construction. Two foremost perspectives are offered by Brenner (1997; 2001) and Marston (2000; Marston et al., 2005). Brenner reasons that social scale is a dynamic and malleable process, and that capital, labor, and the state mediate its construction. Thus, Brenner theorizes that social scale is constructed at the global level where it is largely influenced by the capitalist model. In contrast, Marston argues that situating scale around capitalist production (and the role of the state, capital, labor, and nonstate political actors) is insufficient, and argues for incorporating the relevance of social reproduction and consumption when constructing social scale. Marston aligns the construction of scale at the individual level, and considers socially defined roles such as gender as critical variables when constructing scale.

Research on scale among human geographers since the 1980s has resulted in a theoretical repositioning of scale as well as an active debate regarding how scale is socially constructed. While many human geographers questioned the treatment of scale in terms of Euclidean units in favor of social constructions of scale, a central concern among social theorists is the importance of geographic scales (e.g., household, neighborhood, city, nation) typically used in contemporary human geography (Sheppard and McMaster, 2004). To address this relative gap in theoretical research on scale, social theorists may consider borrowing methodological techniques from other geographic subdisciplines to better understand interactions between scales of analysis.

**Modifiable Areal Unit Problem (MAUP)**

While the research themes of physical and human geography respectively investigate scale as it relates to processes and construction, scholars have also noted statistical challenges related to scale as described in the modifiable areal unit problem (MAUP). Long regarded as a problem in spatial analysis, MAUP is composed of two distinct but interrelated issues: scale effects and zoning effects (Openshaw, 1984). MAUP is the effect on statistical properties (e.g., mean, variance) when interval/ratio data are aggregated into arbitrary units of analysis. Utilizing physical as well as social data, scholars have found that statistical properties vary when either the number of units change (scale) or the delineation of units varies (zoning), thus rendering results capricious (Blalock, 1964; Gehlke and Biehl, 1934).

The scale effect refers to how many units the geographic area is divided into prior to the calculation of statistical properties. When the number of units changes—either due to further subdivision or aggregation—the statistical properties of units in the geographical area change thereby changing the interpretation of the problem (Figure 1, images 1-3). Notice the change in the statistical results as the number of areas into which the attribute is divided changes. Robinson's (1950) classic study noted that the correlation between race and illiteracy rose with the level of geographic aggregation, suggesting that relationships established at one spatial scale may not translate to another spatial scale in a linear fashion (Gardner et al., 1989; Jantz and Goetz, 2005; Jenerette and Wu, 2001; Kok and Veldkamp, 2001).

The second part of MAUP, zoning effects, refers to the zoning scheme used at a given level of aggregation. Zoning refers to the delineation of the zone rather than the number or size of a unit. Research indicates that the configuration of areal units may affect the analysis, and that what is significant at one spatial scale may not be significant at another (Gehlke and Biehl, 1934). Images 2 and 4 in Figure 1 illustrate the effects of zoning—while the mean is constant the variance changes due to different zoning schemes. Openshaw and Taylor (1979) discovered that they could obtain almost any value when correlating voting behavior and age in Iowa merely by aggregating counties in different ways (e.g., gerrymandering). Zoning effects, therefore, is an important component when studying multiple scales of analysis

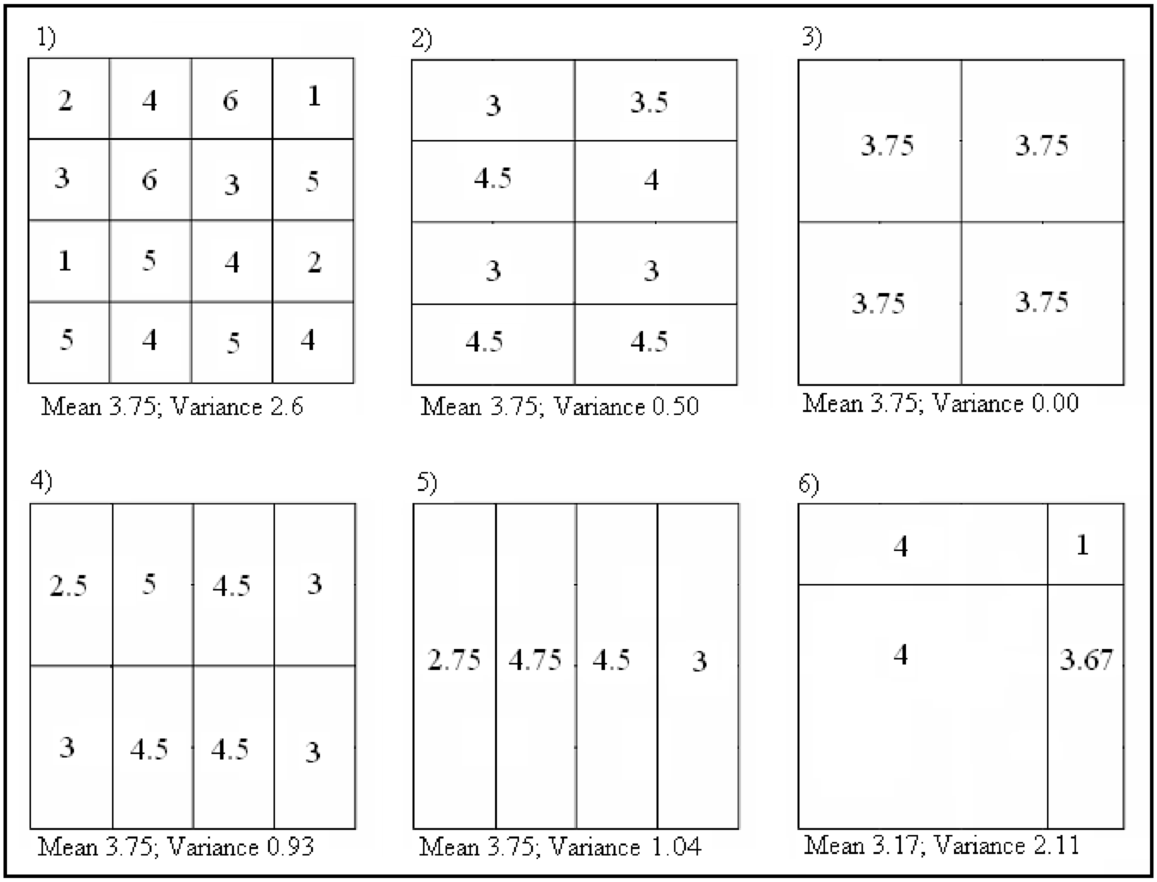


*Figure 1*: Illustration of Interrelated Aspects of MAUP (Jelenski and Wu 1996).

Scale and zoning effects arise due to the spatial analysis of areal data, often in the form of Census tracts or Enumeration districts. Goodchild et al. (1993) explains that unlike continuous phenomena (e.g., temperature, elevation) that can be sampled as point data, discrete phenomena, such as population, requires data to be aggregated (e.g., averaged) into units or zones inside a study area. The problem, however, depicted in the Figure 1, is that results from an analysis of aggregate spatial data vary based on the number of units within a study area or the arrangement of zones. For instance, an agency looking to allocate funds to a state or region would surmise varying results for distributing funds based on different levels of aggregation (e.g., county data, census tract, block group). Conclusions, therefore, are variable and the reliability of any one analysis is uncertain as a means of uncovering knowledge on spatial processes (Fotheringham 1998). Thus, it is important to conduct analyses and different spatial scales.

Although scholars have tried various techniques to minimize the influence of MAUP, such as mathematical approaches (e.g., Arbia, 1989; Wrigley, 1995; Holt et al., 1996) as well as spatial analysis (Fotheringham et al., 2001), MAUP remains a major challenge in scale research. Steel and Holt (1996), for example, constructed data aggregation ‘rules’ by investigating common statistics (e.g., means, variances, coefficients) from the analysis of geographic areas. Despite employing weighted and unweighted statistical methods to investigate aggregate data, research findings continued to be unreliable. Alternatively, Fotheringham and others (2001) developed a method, geographically weighted regression (GWR), which incorporates spatial scale when analyzing aggregate data. Although GWR helped minimize problems of MAUP by utilizing local regression models rather than classic global regression, further research on zoning and spatial data analysis is required. While scale is operationalized in terms of spatial extent in studies examining MAUP, research findings consistently show varying outcomes between correlation variables when analyzing the same data at different scales of analysis or at different aggregations (Sheppard and McMaster, 2004).

**GIScience: computational solutions**

Geographic information science (GIScience) represents another research theme in geography where scholars increasingly study challenges associated with scale via computation. GIScientists began using computer-assisted quantitative analysis of spatial data in the 1990s as a means of investigating the effects and implications of scale since geography spans human, biological, and physical arenas, including spatial scales from single points to the entire globe (Fotheringham, 1998; Meentemeyer, 1989). While scale research has traditionally investigated environmental processes with recent attention on social constructions of scale, GIScience provides a platform to examine physical and social processes at multiple scales of analysis. Thus, GIScience provides both the conceptual framework and the tools required to study empirical and theoretical constructs of scale (Goodchild, 2004).

Current literature on scale among GIScientists highlights two unique aspects of research requiring further investigation. Fisher et al. (2006), for example, call attention to the importance of understanding the influence of scale when examining relationships within or across human and physical systems. Broadly speaking, the challenge is to better understand the nature of phenomena when modeling. If a model is to successfully generalize geographical phenomena, it is necessary to know about the nature of the phenomena. More specifically, GIScientists have found two distinct but interrelated research challenges on scale: 1) modeling human and physical systems; and 2) modeling the effects of scale on description.

The first research challenge, modeling human and physical systems, is concerned with capturing sufficient detail of the properties that are critical to accurately model a given process. For instance, Goodchild (2001) explains that the choice of residential location can be affected by a person’s perception of socio-economic status. If a potential resident perceives socio-economic status averaged within 1 km of a prospective residential location, then it is essential to measure socio-economic status either at the same scale or a scale finer than it is perceived to understand and to correctly predict behavior. Likewise, it is not possible to successfully model physical processes without data obtained at an appropriate scale. If precipitation varies significantly over distances less than 100 miles, for instance, modeling outcomes dependent upon rainfall (e.g., agricultural yield or habitat type), will be unsuccessful unless the map informing the model captures significant spatial detail (Goodchild, 2001). Scale is, therefore, critically important in modeling because input data must be of sufficient detail to successfully model a process. If data are measured at scales too coarse, information vital to the process being modeled will not be captured and the model will not produce valid results.

The second research challenge on scale is modeling the effects of scale on description, and considers the implications of changing the scale of analysis on data quality and/or the representation of features. Models are often used to simulate a given process when data are unavailable at a particular scale; however, changing the scale of analysis typically results in modifications (e.g., changes in data or the misrepresentation of features) (Tate and Atkinson, 2001). Consider Arizona’s state boundary presented in Figure 2, which shows two different data sets of the same study area, but digitized at different spatial scales (1:2,500,000 and 1:500,000, respectively). Notice the outline for the 1:2,500,000 layer as more angular and less detailed than the boundary represented by the 1:500,000 layer. The reason why features represented in the 1:500,000 dataset are more accurate than the features in the 1:2,500,000 file is because the data in the 1:500,000 layer were digitized at a larger spatial scale. Thus, the scale of observation is important in modeling a given process, and as Figure 2 illustrates, can influence the representation or description of spatial features.

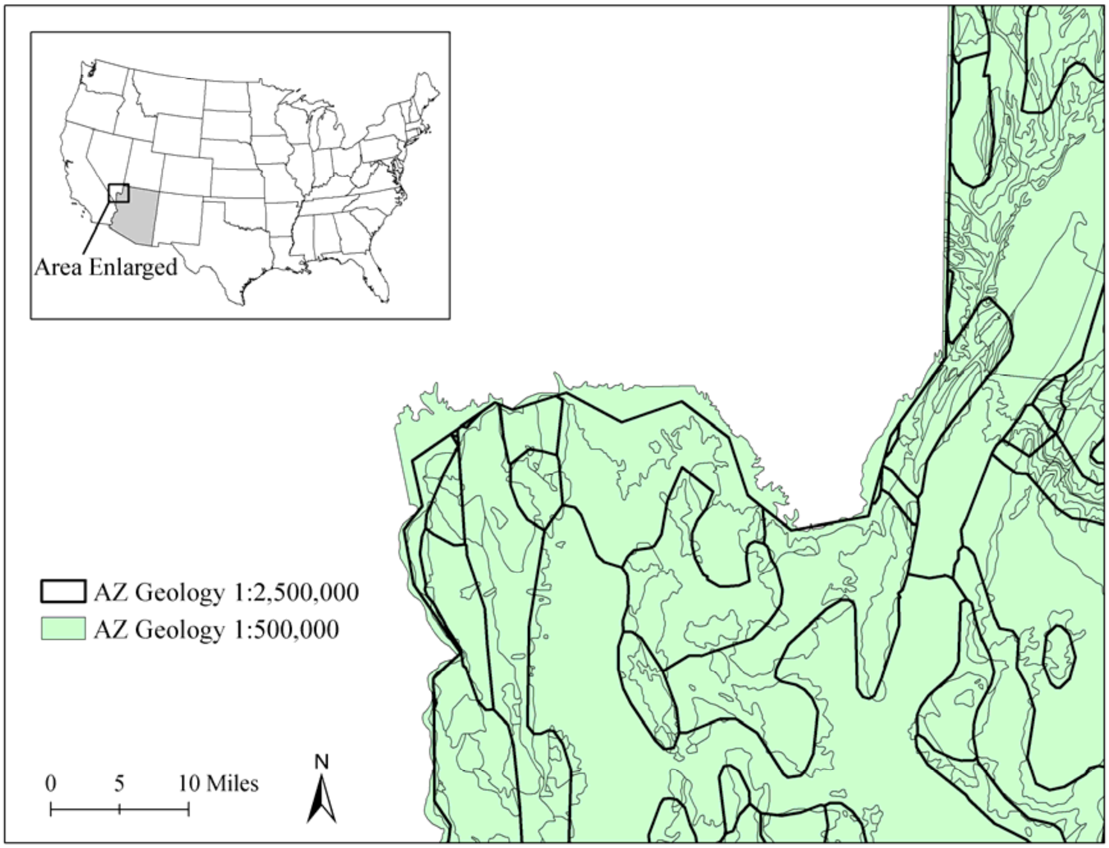


*Figure 2*: A Comparison of Arizona Geology Maps Based on Data Digitized at Different Spatial Scales.

Although computation and modeling have helped advance research on scalar issues, such as minimizing problems of MAUP, some techniques have also introduced new research challenges (i.e., error associated with changing the scale of analysis). Two particular issues related to changing the scale of analysis are generalization and multi-scale modeling (Atkinson and Tate, 2001). Generalization is the process by which geographical data are modified as a result of scale change, which produces effects (e.g.

changes in length or displacement of features) that have implications for the accuracy of the data (Joao, 2001). Cartographic generalization, for example, occurs within spatial databases when objects or features (e.g. railways, rivers) are modified or misrepresented as a result of changing the scale of analysis, as witnessed in Figure 2.

Multi-scale modeling is the use of models to simulate a phenomenon at one scale of space and/or time based on observations from another (larger or smaller) scale. Hill et al. (1997), for instance, modeled plant growth and environmental preferences by developing a laboratory experiment and applying the results at large geographical scales via input variables from the laboratory-based model into the GIS analysis. A second study by Aspinall (2001) simulated the use of model coefficients identified at one scale of analysis and compared data output at multiple scales using Bayesian modeling and found that changing the scale of analysis from 1 km to 10 km to 20 km alters the information content of the data. Changing the scale of analysis when modeling, therefore, is vulnerable to modifications in the representation of spatial features (generalization) as well as alterations in data quality (multi-level modeling).

**Nature and society: scale integration**

The fifth and final research theme on scale this paper examines is nature and society's integrative approach to scalar issues which contrasts to the relatively isolated approaches of scale research employed among the previous themes. Physical geography, for instance, traditionally examines scale as it relates to physical processes such as the spatial distribution of temperature or the temporal records in palaeogeography. The debate on scale among social theorists centers on how scale is socially constructed. Research on MAUP spans both physical and social scholarship; however, focuses exclusively on geographical scale. In GIScience, scale implications pivot on the representation of spatial features or modeling particular processes. The theme of nature and society represents an increasingly important arena of academic research as scholars investigate the dialectic relationship between physical processes and the outcomes and consequences of human behavior.

For example, early observations by Carson (1962) noted the sensitive relationship between earth systems and social systems. While American agricultural policy aimed to improve crop production through the use of pesticides such as Dichloro-Diphenyl-Trichloroethane (DDT), significant biological and ecological health hazards emerged from these efforts. Pesticides, for instance, were introduced into ecosystems and research found that contaminants not only damaged organisms directly in contact with certain pesticides, but that these synthetic chemicals also became embedded in the tissue of organisms, and thus, entered the global food chain (Marsh and Grossa, 2002). In addition to underscoring the degree to which the planet is integrated, this example illustrates how human behavior and decision-making at discrete spatial and temporal scales may influence regional or global processes, not only immediately but also well into the future. Moreover, in order to effectively investigate such research challenges, it is necessary to simultaneously draw upon multiple sources of research to synthesize varying spatial and temporal scales (Hobbs, 1998; Levin, 1992).

Recent studies, however, have attempted to investigate physical and social processes by integrating multiple research perspectives. Work by Bolin et al. (2008), for instance, juxtaposed environmental conflicts over water resources with local politics in Arizona. This study required a synthesis of socially defined political scales which represented spatial mismatches over natural watershed boundaries. A second study conducted by Easterling and Polsky (2004) discussed challenges associated with modeling human-environment interactions at multiple scales of analysis. Research findings note 1) the difficulty of modeling variable spatial and temporal scales as well as different human and natural processes; and 2) the use of complex systems theory to help unravel relationships within human-environment systems.

Although it may be appealing to think of social and natural systems as distinct, Ayres (1994) argues that the two systems are inseparable. Sayre (2005) underscores the importance of understanding the sensitivities and interrelations between physical and social processes which is imperative to successfully investigate global challenges of the 21$^{st}$ century (e.g., climate change, air and water pollution, habitat degradation). Scholars seeking to investigate the coupled human-environment system have recently turned to scale to help address processes of variable spatial and temporal scales (Easterling and Polsky, 2004). This section not only discusses the importance of integrating theoretical and/or methodological approaches to help resolve global environmental challenges, but also argues for more research collaboration which should improve our understanding of scalar issues. For example, to investigate the urban heat island, one might utilize computation and modeling coupled with social constructions of scale to examine vulnerability and risk to climate change at multiple scales of analysis.

## Discussion

This study offers three contributions to scale research in geography. As researchers continue to investigate and theorize on issues of scale, recognizing various definitions, theoretical frameworks, and methodological challenges regarding the ways in which geographers investigate scale is critically important. This paper has reviewed how scale is understood among five research themes, which are: physical geography; human geography; MAUP; GIScience; and nature and society. Results underscore two fundamental concerns: 1) scale is operationalized in a variety of ways depending upon research theme and the process being investigated; and 2) the way in which scale is defined influences the kind of research that can be conducted. Thus, the importance of scale is elevated when considering theoretical or methodological approaches for studying physical and/or social processes. Our first contribution, therefore, is to clarify the various ways in which scale is used and operationalized among the five research themes explored in this paper.

The paper’s second contribution is a discussion of alternative theoretical frameworks to investigate scale. Although Taylor (1982) challenged the hierarchical model for studying scale almost thirty years ago, his contribution has remained relatively isolated in human geography. While many social theorists debate the forces contributing to the construction of social scale, the discipline may benefit by applying Taylor’s idea to research efforts on scale outside of cultural geography. Another alternative to hierarchical organization is activity theory. Utilizing individual observations to model outcomes of the aggregate has helped advance issues of scale in computational solutions. Studying individual behavior, for example, has helped scholars studying time geography model large-scale patterns (Miller, 2005). Agent-based modeling also relies on scaling up from individuals to interpolate the aggregate (Nara and Torrens, 2007). Complex systems theory represents a third alternative framework for studying scale. Easterling and Polsky (2004) modeled linear and non-linear relationships of human-environment systems by using complex systems theory. Research in physical geography and MAUP may also yield scientific breakthroughs on scale research by reconceptualizing theoretical frameworks to study scale.

Rather than remain isolated in theoretical and/or methodological approaches for analyzing or constructing scale within geographic subdisciplines, this paper argues the need for greater integration. The third and final contribution of this paper calls for mixing and matching various theoretical/methodological approaches to help advance research on scale. In the research theme of nature and society, integrating data, theory, and/or methods have helped scholars understand the sensitivities of physical and social processes operating at various temporal and spatial scales. For instance, research on climate change and the urban heat island effect correlates urban development and population growth with rising temperatures (Brazel et al., 2000; Oke, 1987). To effectively mitigate or adapt to the changing physical environment at regional, national, or global scales of analysis, it will be imperative to understand social perceptions on climate change (Leiserowitz, 2005). Present and future research challenges, therefore, may benefit by employing mixed methods research techniques.

Scholarship should proceed with caution, however, because mixed methodological approaches may not always provide greater clarity on a research topic. Recent work by Dunning et al. (2008), for example, employed a mixed methods approach to better understand subjective and objective frameworks for assessing quality of life (QoL). Considering four measures of QoL, notable research findings included methodological challenges in operationalizing the mixed methods approach as well as a lack of confirmation between the two methods. Mixed methods approaches, therefore, may offer greater depth and/or breadth to a research problem; however, it is important to recognize potential shortcomings as well as benefits. An additional challenge of a mixed methods analysis is vulnerability to research validity. Among the four threats to validity (e.g., external, internal, construct, and conclusion), mixed methods analyses may heighten the risk to validity by blurring steps or boundaries in the scientific method.

Although issues of scale represent a long-standing challenge within geography, we note opportunities to better understand scale among the five research themes explored in this paper. While research within each of the five themes aims to advance our current understanding of scalar issues, the concentration of nature and society is unique in its focus on integrating data, theory, and/or methods to examine varying physical and social processes operating at variable spatial and temporal scales. Meeting current and future research challenges globally or locally will require creative and integrative scholarship, and understanding various conceptions of scale will be essential to solving these problems.

# CHAPTER THREE: ADVANCING THOERY ON SCALE IN GEOGRAPHY

## About this Chapter

This chapter is an article that will be submitted to the *Annals of the Association of American Geographers*. The title of the manuscript is "Advancing Theory on Scale in Geography." The authors are Darren Ruddell, Elizabeth A. Wentz, Sharon L. Harlan, and Susanne Grossman-Clarke.

Discussions of scale-related issues have proliferated in geography over the last few decades. Although geography's subfields cover a broad spectrum (e.g., physical, human, economic, GIScience, among others), and geographic literature is rich in discussing various spatial and temporal scales as well as methodological solutions to deal with scale, currently, there are only two theoretical frameworks for operationalizing the various conceptions of scale. This study examines existing theoretical frameworks used to investigate scale, and aims to contribute to literature on scale by introducing and testing a new framework to help scientists move toward greater theoretical sophistication. Our analyses focus on the complex socio-ecological issue of climate change which operates on multiple spatial scales of analysis.

## Introduction

Issues of scale permeate space and time as well as physical and social processes. Spatial scales of analysis are particularly important when examining various physical and/or social processes associated with climate change. For instance, the Intergovernmental Panel on Climate Change (IPCC) (2007) reported varying degrees of change with regards to mean surface temperature, sea level rise, and snow cover depending upon the regional scale of analysis. While studies of climate change often examine physical systems at a discrete spatial scale (Baker et al., 2003; Brazel et al., 2000), scholars are also concerned with investigating the interactions of a given process at multiple scales of analysis (IPCC, 2007). Understanding the physical and social processes associated with climate change across multiple scales of analysis is important for a variety of reasons. Urban heat islands (UHI), for example, offer a key link between human decision-making and modifying a physical environment at the regional scale of analysis (Karl et al., 1993; Oke, 1992). At the molecular level, meteorologists have found that water ($H_2O$) proficiently stores and transports heat which helps explain how heat transfer affects local to global climate (Kreith and Bohn, 1997). It is important therefore to understand the behavior of a given process at multiple scales of analysis. This study investigates scale as a unifying research thread that provides the framework to analyze and expand the current understanding of socio-ecological processes (e.g., climate change).

Scale represents a variety of complex challenges in the discipline of geography. While research efforts among the subfields encompass wide-ranging topics (e.g., modeling scale in GIScience, scale linkage in physical geography, social conceptions of scale in human geography, among other issues), studies of scale can be broadly organized into two groups. The first group can be described as research *about* scale. For instance, studies exploring the various conceptions of scale (e.g., geographic, cartographic, operational, among other forms) aim to clarify differences and/or commonality regarding the ways in which geographers utilize scale to examine a given process (Cao and Lam, 1997; Lam, 2004; Sheppard and McMaster, 2004). While some processes can be studied via a single system (e.g., physical or social), complex socio-ecological processes (e.g., human-environment interactions) require synthesizing multiple systems (e.g., physical *and* social). The second group can be understood as research *at* various scales of analysis. For example, it is important to examine a given process at multiple discrete spatial and/or temporal scales of analysis because relationships may change as the scales change. Imeson and Lavee's (1998) study of soil erosion and climate change found that temporal and spatial scales are not linked successively, but vary based on local properties such as slope, patch, and/or landscape. So while some processes are linked at successive scales, other systems exhibit non-linear relationships. In short, research on scale has advanced by examining the broader context of research *about* scale as well as analyzing processes *at* different scales of analysis.

Although there are a number of studies which investigate a given process at multiple scales of analysis, scale is currently operationalized by using one of two theoretical frameworks (Hobbs, 1998; Meentemeyer, 1989; Sayre, 2005; Uzzell, 2000). The first and most common method for analyzing scale is the downscaling framework. The traditional downscaling approach is couched by scale linkage which organizes systems hierarchically, whereby a given process exercises at least partial control over processes operating at finer spatial and/or temporal scales (Phillips, 2004). For example, the drainage area for a large-scale study exerts a measure of control over finer variables such as discharge, flow dimensions, and velocity (Leopold and Maddock, 1953; Leopold and Miller, 1956). The second theoretical framework for examining multiple scales of analysis is upscaling, which relies on individual observations to examine a given process at larger scales (Ben-Akiva and Bowman, 1998; Miller, 2005). Taylor (1982) challenged the empiricist downscaling model by arguing that not all processes operate in a linear top-down environment. The upscaling model emerged by offering an alternative theoretical framework to investigate a given process from the individual to global scales of analysis. Although the deterministic downscaling model is commonly used to examine physical processes at multiple scales of analysis, the upscaling model is often preferred for studies of social systems, which typically observe individual observations to understand the aggregate. A major limitation regarding existing theoretical frameworks, however, is the inability to operationalize scale for socio-ecological processes.

Complex socio-ecological processes (e.g., human-environment interaction issues) present new challenges to scale research by requiring scholars to simultaneously investigate human and physical systems at multiple scales of analysis (Gibson et al., 2000). Human-environment interactions refer to the coupled feedback between human behavior and the subsequent impacts on the dynamic natural environment (Gimblett, 2001). Climate change represents a human-environment interaction issue whereby human development and the modification of natural environments is altering physical processes, as witnessed in rising global temperatures and urban heat islands (IPCC, 2001; Lowry, 1967; Oke, 1997). To investigate human-environment interactions, scholars have recently turned to scale to help address processes of variable spatial and temporal scales (Easterling and Polsky, 2004). For instance, geographers studying climate change recognize the need to identify the operational scale of human and physical systems (Sheppard and McMaster, 2004). There is a need, therefore, to utilize a theoretical framework which integrates physical and social systems at multiple scales of analysis.

Although there are currently two theoretical frameworks to operationalize scale, this paper identifies limitations of both approaches and argues for an alternative theoretical framework to investigate complex processes at multiple scales of analysis. Specifically, this study examines a hybrid approach by incorporating both downscaling and upscaling techniques. The practicality of this framework is examined with a case study on temperature variability within the Phoenix, AZ metropolitan area. Although previous studies have investigated human-environment interactions via mixed method analysis (Bolin et al., 2008; Harlan et al., 2006; Ruddell et al., 2009), there is a lack of research discussing theoretical frameworks synthesizing physical and social conceptions of scale. Testing existing theoretical frameworks against the hybrid model introduced in this paper is desirable for two reasons: first, it helps recognize the strengths and limitations of current approaches while outlining the need for an alternative technique. Second, it tests whether or not the hybrid framework offers an enriching perspective that is currently unavailable when studying a particular process. The research question informing this study is: *How might introducing a hybrid model improve theorization on scale in socio-ecological research?*

**Literature**

**Constructing Scale**

Despite the "almost intimidating diversity" (Sheppard and McMaster, 2004) of conceptions of geographic scale, currently there are only two theoretical frameworks for opertionalizing scale. The downscaling model, traditionally applied to physical systems, links processes in a top-down hierarchical structure. Downscaling was the de facto method for operationalizing scale until the upscaling framework was introduced which focuses individual observations to show patterns of aggregation at broader scales (Figure 3). The two existing methods for operationalizing scale represent dueling theoretical approaches, with each framework possessing different strengths and weaknesses. Investigations of complex research challenges, such as socio-ecological processes, may benefit by utilizing alternative theoretical approaches.

| 1. Downscaling | 2. Upscaling |
|---|---|

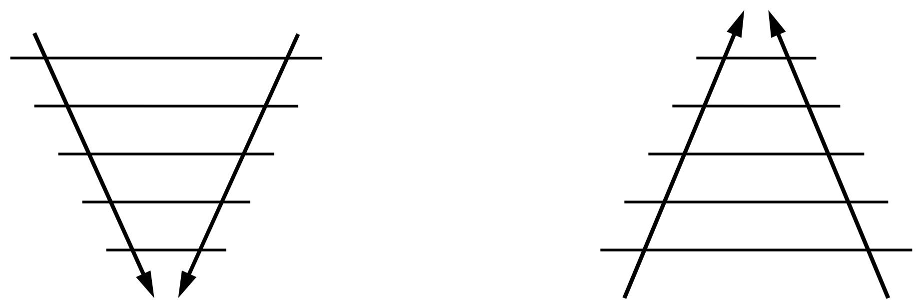

*Figure 3*: Current Theoretical Frameworks for Constructing Scale.

Note: the horizontal lines represent potential constructions of scale at various discrete spatial scales of analysis. The vertical lines represent the direction in which each theoretical framework constructs scale.

**Downscaling**

The process of downscaling is understood as observing properties at one scale and deducing information at a finer scale. Earth scientists have traditionally examined natural systems via downscaling, or scale linkage and the reductionist approach. Scale linkage is understood as “transferring information, relationships, models, and rules between different spatial and temporal scales” (Phillips, 2004, p. 86). Climatologists, for instance, investigate temperature records at various temporal and spatial scales, and results are often used to inform models or simulate past, present, or future conditions. While geoscientists study a variety of earth systems, they have found that processes and environmental controls relevant at a given spatial or temporal scale exercise at least partial control over processes operating at finer scales (Phillips, 2004). For instance, the drainage area for a large-scale study exerts a measure of control over finer variables such as discharge, flow dimensions, and velocity (Leopold and Maddock, 1953; Leopold and Miller, 1956). The reductionist framework therefore serves as an organizing principle among physical systems.

The downscaling model utilizes hierarchy theory which represents a conceptual framework linking multiple scales of analysis (DeBoer, 1992; O'Neill et al., 1986). The underlying principle is that environmental systems are linked at successive scales. Higher-level systems govern a given system while lower-level systems explain mechanistic operation (Allen and Starr, 1982; Bendix, 1994; Phillips, 2004; Urban et al., 1987). Goodchild (2001) explains that hierarchy theory has frequently been used as a reductionist approach to estimate the properties of a given process when it is not possible or too expensive to acquire data at finer scales of analysis.

Hierarchical organization, however, is subject to uncertainty and error when investigating certain processes. For example, Braun and Slaymaker (1981) examined snowmelt runoff at four different spatial scales and identified varying levels of snowmelt runoff based on spatial scale, such that smaller basins reported faster runoff travel times. Research by Wiens (1989) found that patterns or relationships among physical systems discerned at one spatial scale of observation may be invisible, or even contradicted, when examined at another spatial scale. So while some physical processes are linked at successive scales, other physical processes vary by spatial and/or temporal scales of analysis.

A second challenge to hierarchy theory is the ecological fallacy which is the inference of characteristics about lower scales (e.g., individuals) from aggregate data.

The ecological fallacy is inherent in the modifiable areal unit problem (MAUP), which observes statistical challenges related to scale (Robinson, 1950). Long regarded as a spatial analysis problem, MAUP is composed of two distinct but interrelated issues: scale effects and zoning effects (Openshaw, 1984). MAUP is the effect on statistical properties (e.g., mean, variance) when interval/ratio data are aggregated into arbitrary units of analysis. Scholars have found that statistical properties of physical as well as social data vary when either the number of units change (scale) or the delineation of units varies (zoning), thus rendering results unreliable (Blalock, 1964; Gehlke and Biehl, 1934).

To help resolve issues of downscaling, scholars investigate the interaction of variables operating within and across different scales of analysis for a given process. For instance, if the objective is to estimate temperature at fine spatial scales based on a broader global measurement, an appropriate algorithm would likely incorporate variables correlated with temperature (e.g., elevation, wind speed, precipitation, among others). The underlying principle is that lower-level systems can be used to help reduce uncertainty of broad measurements based on the correlation between variables (Allen and Starr, 1982; Bendix, 1994; Urban et al., 1987). Thus, scientists are able to model or simulate physical processes at varying spatial and/or temporal scales of analysis based on knowledge of a given system.

**Upscaling**

The second theoretical framework for operationalizing scale is known as upscaling. The upscaling framework emerged as an alternative to the deterministic downscaling approach which was commonly applied to all processes regardless of physical or social composition. While the downscaling framework may by sufficient for estimating earth systems (within an acceptable margin of error), there was a need to better represent social phenomena which the downscaling framework could not provide. One example of the ecological fallacy using social data would be to presuppose individual voting behavior based on the percent of votes within given precinct. Since many social processes exhibit non-linear relationships (e.g., voting behavior, environmental perception), the upscaling model emerged by offering an alternative framework rooted in individual observations to understand patterns operating at broader scales of analysis.

Downscaling served as the modus operandi in scale research until Taylor (1982) challenged the notion of investigating a given process via hierarchical structure. Although Taylor observed that scale organization for the international financial structure represented a non-hierarchal framework, his efforts set in motion various interpretations of understanding the ways in which scale can be operationalized. For example, while earth scientists traditionally use naturally defined boundaries to investigate a given process among nested hierarchies, most human geographers use socially defined boundaries (e.g., political territories) and theorize on broad patterns emerging from individual behavior (Brown and Purcell, 2005; Cox, 1998; Manson, 2008; Marston, 2000; Smith, 1984). In other words, unlike hierarchical organization governing scale in physical geography, human geographers typically separate human activity from the physical environment by investigating scales of analysis that emerge out of social constructions rather than natural boundaries (Herod and Wright, 2002; Johnston et al., 2000).

The alternative framework for operationalizing scale (e.g., upscaling) relies on examining individual observations to understand the behavior and patterns of the aggregate. The theoretical foundation of the upscaling framework is activity theory. Ben-Akiva and Bowman (1998) explain that activity theory relies on individual participation in space and time to illustrate the behavior of a given process at broader scales of analysis. New research in time geography, for example, employs upscaling to model large-scale human behavior. Rather than employing hierarchical organization to study fine-scale processes, Miller (2005) argues for studying individuals to observe aggregate patterns which helps improve modeling social behavior. Utilizing activity theory as the theoretical framework, Miller (2003) stresses the need for research that focuses on individual cases rather than traditional place-based approaches (e.g., central place theory). So in contrast to hierarchy theory, activity theory utilizes individual data observations to scale up, which, in turn, presents large-scale patterns.

Although the upscaling framework helps understand relationships between the individual and the aggregate, this theoretical approach is not without shortcomings. Specifically, there are two problems related to analyzing a given process via the upscaling framework. The first problem is that upscaling is vulnerable to the reductionist fallacy (i.e., making inferences about groups from individual-level data). While activity theory is useful for observing or describing certain processes (e.g., commuting patterns), it is not necessarily suitable for predicting behavior. A second challenge of upscaling is the problem of drawing conclusions across multiple scales of analysis. Similar to understanding physical systems at multiple scales of analysis, research shows that social processes communicate different findings based on spatial scale. For instance, research on environmental perception indicates that people perceive global environmental problems as more severe compared to similar local environmental problems (Garcia-Mira et al., 2005; Stedman, 2004; Uzzell, 2000). This tendency suggests that people perceive environmental problems as progressively severe as the distance from the perceiver increases. Many environmental problems (e.g., hurricanes, earthquakes, air pollution), however, are regional in nature so efforts to extrapolate broad or fine-scale social patterns is open to uncertainty and error.

**Contribution: Hybrid Framework**

Whereas the downscaling framework is commonly used to extrapolate physical properties at finer spatial and/or temporal scales, and whereas the upscaling method offers an alternative theoretical framework to observe individual behavior at various levels of aggregation, current theoretical frameworks for constructing scale remain inadequate. Socio-ecological processes, such as climate change and biodiversity, require a framework to simultaneously investigate physical and social processes operating at multiple scales of analysis. Current theoretical frameworks, however, are mutually exclusive. Figure 4 introduces the hybrid framework which accommodates an investigation of complex processes at multiple scales of analysis. Notice the hybrid model is able to construct multiple scales of analysis from a top-down perspective as well as a bottom-up approach.

| 1. Downscaling | 2. Upscaling | 3. Hybrid |
|---|---|---|

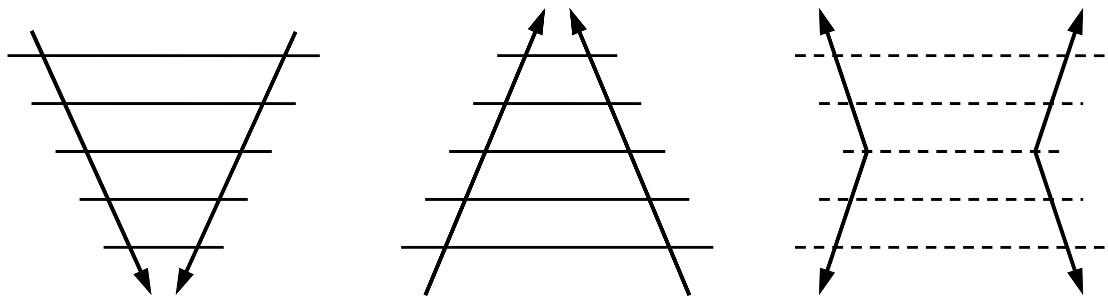

*Figure 4*: Diagram Representing Three Frameworks for Constructing Scale.

Note: horizontal lines are represented as solid and dashed lines. The solid lines represent potential constructions of scale from a single direction (down or up) while the dashed line represents potential scale constructions from multiple directions (e.g., down and up).

Research over the last few decades positions climate change as an exemplar subject to better understand socio-ecological processes. The IPCC (2007) defines climate change as 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. Although the Earth has experienced periods of warming and cooling many times during its 4.5 billion year history (naturally caused by volcanic eruptions, changes in the Earth’s orbit, among other causes), current changes in the Earth’s climate (e.g., sea level rise, increased surface temperatures, retreating polar ice caps) are well beyond normal variation (IPCC, 2001). An overwhelming majority of scientists argue that: 1) human activity is largely responsible for the changes in physical systems; and 2) the impacts of climate change (e.g., intensified weather conditions, increased heat waves, pest and disease outbreaks, among other issues) are largely unpredictable and vary from region to region (IPCC, 2007; Oke, 1997; Stedman, 2004). It is important therefore to better understand the various ways in which climate change threatens human health and well-being at global and regional scales of analysis (Arnfield, 2003; Geller, 2003; Kalkstein and Davis, 1989).

While physical dimensions of climate are routinely investigated, there is a lack of research on public perceptions of climate change (Dunlap, 1998). Understanding how people perceive climate is important because public perceptions have a significant impact on policy-making (Kempton, 1993; Morgan, 1995). For example, a study by Leiserowitz (2006) found that public perceptions of the risks and dangers of global climate change greatly influenced public support or opposition to climate policies (e.g., treaties, regulations, taxes, subsidies). Research also indicates that public perceptions of climate change vary by spatial scales of analysis. For instance, studies have found that a majority of respondents see global climate change as a significant problem that is currently occurring or will occur within their lifetime (Dunlap, 1998; Leiserowitz, 2005; Stedman, 2005). Public perceptions of climate change at the local scale of analysis, however, are perceived as less serious despite the fact that the physical impacts of environmental problems are most acute at local scales (Garcia-Mira et al., 2005; Uzzell, 2000). Thus, there is a need to investigate social perceptions of climate change at multiple scales of analysis.

While current frameworks for operationalizing scale are limited to either downscaling or upscaling, we introduce and test a hybrid approach which provides the framework to investigate complex socio-ecological processes at multiple scales of analysis. We believe comparing physical and social processes at spatially explicit scales will help enrich the current understanding of climate change by examining differences and/or similarities among data sources. Our assumption is that the hybrid model will offer a unique research perspective to compare physical and social data on temperature, which will lead to more sophisticated theorization on socio-ecological processes.

**Research Methods**

This study examined temperature variability throughout the Phoenix metropolitan area to investigate the practicality of using the hybrid framework to examine socio-ecological processes at multiple scales of analysis. Specifically, we investigated physical environmental conditions of temperature and social perceptions of temperature to evaluate the three frameworks discussed in this paper.

**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 percent of the state's 6.1 million residents (Census Bureau, 2006). An ideal setting for studying physical and social dimensions of temperature, metropolitan Phoenix has a naturally warm climate and is expected to become warmer and drier over the next century. While the IPCC (2007) reports that the average global temperature has increased by about 0.74°C (or 1.3°F) over the past century, there is significant regional variability. For instance, a study by Brazel et al. (2000) found distinct trends in average annual temperatures in Maricopa and Pinal counties over the 20$^{th}$ century. Findings indicated that average annual temperature for greater Phoenix has risen steadily (by 1.7°C) during this period; however, temperatures in urban areas have increased by 4.2°C compared to an increase of 1.3°C in rural areas. This represents a warming rate over three times higher in urban areas compared to rural areas (Brazel et al., 2000). Changes in the region's physical environment have been driven, in part, by the past 50 years of population growth (Bolin et al., 2002; Gober and Burns, 2002). Listed among the country's fastest growing urban areas in 2007, metropolitan Phoenix has experienced rapid anthropogenic transformations in the environment, such as 1) land use change (Keys et al., 2007); 2) the urban heat island (UHI) effect (Brazel et al., 2000); and 3) water resource management (Stromberg et al., 1996), among other issues. The various regional trends, therefore, provide a rich environment to study scale effects and investigate details underlying physical and social dimensions of climate change.

**Historical Temperature Trends**

Annual minimum and maximum temperatures were analyzed among four weather stations to examine historical temperature trends throughout the Phoenix metropolitan area. Data were obtained from the National Oceanic and Atmospheric Administration (NOAA), and examined temperature readings from 1965-2006. The 41-year temporal period offers insight into regional and local temperature patterns at four discrete locations throughout the greater Phoenix area. In addition to examining temperature readings from Sky Harbor International Airport (the commonly used regional weather station), we also analyzed historical temperatures from three local weather stations (Carefree, Tempe, and Youngtown). Although all of the weather stations are located within the Phoenix metropolitan area, the Sky Harbor, Tempe, and Youngtown weather stations have similar elevation (~350 m) and landuse (urban) profiles while the Carefree weather station has a relatively higher elevation (771 m) and is a predominately rural area located on the fringe (Table 1). Analyses provide a baseline for comparing physical temperature variability throughout the study area in addition to couching social perceptions on temperature.

Table 1

*Characteristics of Carefree, Sky Harbor, Tempe, and Youngtown, AZ Weather Stations*.

| Weather Station | Latitude | Longitude | Elevation (m) | Landuse |
|---|---|---|---|---|
| Carefree | 33°49'N | 111°54'W | 771 | Rural |
| Sky Harbor | 33°26'N | 112°00'W | 337 | Urban |
| Tempe | 33°25'N | 111°56'W | 356 | Urban |
| Youngtown | 33°36'N | 112°18'W | 345 | Urban |

**Simulated Weather Conditions**

To examine the spatial distribution of temperatures currently experienced throughout the Phoenix metropolitan area, we utilized the meso-scale Weather Research and Forecast (WRF) climate model developed by the National Center for Atmospheric Research (NCAR) (Shamrock et al., 2005). WRF represents a highly sophisticated atmospheric model that quantifies air temperature at fine spatial scales by considering various complex relationships governing the spatial and temporal state of the atmosphere (e.g., air temperature, pressure, specific humidity and wind speed). In the current study, we analyzed temperature variability via the WRF climate model which reported surface air temperature at 2m above the ground with a spatial resolution of 1km (see Ruddell et al., 2009 for a full description of methodology). Research by Grossman-Clarke et al. (2005; 2008) demonstrated that a well-tested mesoscale model is suited to simulate air temperature variability throughout the Phoenix metropolitan region. We examined a four-day heat event (July 15-19, 2005) to measure temperature variability throughout the Phoenix metropolitan area for the summer of 2005 (Meehl and Tebaldi, 2004).

**Survey Respondents**

Offering a comparison to the scientifically-derived output of the WRF climate model is the 2006 Phoenix Area Social Survey (PASS) which reflects the perceptions of

808 local residents. Focusing on 40 diverse metropolitan neighborhoods, PASS provides insight into residents' perceptions of regional temperature change over time and neighborhood temperature relative to others for the summer of 2005. We are unaware of previous studies integrating model output with survey data at discrete spatial scales, but recent advances in climate models in addition to geo-referenced survey data provides the framework to compare social perceptions with physical conditions at multiple scales of analysis. PASS employed a two-stage research design which is described in detail in Harlan et al. (2007). One respondent from 40 randomly selected households in each of the 40 neighborhoods was invited to participate in the study. Within each household, the target survey respondent was the member who was 18 years or older with the most recent birthday. Surveys were collected using a multi-modal approach (online, telephone, or personal interview). The survey was administered by the Institute for Social Science Research (ISSR) at Arizona State University from April 29 through September 27, 2006 and had a response rate of 51%.

We analyzed the two following PASS questions to investigate perceived temperature at the regional and neighborhood scales of analysis: "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)?" "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 term "Valley" is a local colloquial expression that refers to the Phoenix metropolitan area.

## Procedures

Data analyses were organized into four primary steps. The first step in the analysis examined historical (1965-2006) minimum and maximum annual temperature trends among four weather stations located throughout the Phoenix metropolitan area. The second phase of the analysis utilized output from the downscaling WRF climate model. Using GIS, we mapped the spatial distribution of predicted temperature readings by examining the spatial average, high, and low daily temperatures for each of the 40 neighborhoods during the study period. US census block groups defined neighborhood boundaries. The third step in the analysis examined social perceptions of temperature via upscaling survey data. Responses from PASS questions regarding perceived regional and neighborhood temperature were examined at regional and neighborhood scales of analysis. GIS was used to map social variables at a neighborhood (block group) scale congruent with the WRF-predicted temperatures. The final step of the analysis examined the potential for a hybrid theoretical framework to analyze physical and social data at multiple scales of analysis. We used the Pearson product-moment correlation to statistically test the strength of the relationship between environmental conditions and perception of temperature in the Phoenix region.

## Results

### Historical Temperature Trends

Historical temperature readings report warming trends between 1965-2006 for both minimum and maximum mean annual temperatures among the four weather stations examined in this study (Figure 5). Analyses confirm asymmetric temperature trends that include significantly higher increases in mean annual minimum temperatures compared to mean annual maximum temperatures in urban areas (Baker et al., 2003; Karl et al., 1993). The Sky Harbor, Tempe, and Youngtown weather stations reported relatively similar mean annual maximum temperatures between 1965-2006 while Carefree was considerably cooler. Among mean annual minimum temperatures, Sky Harbor reported the warmest temperature readings (by 2.34$^{o}$C or 4.21$^{o}$F) while Youngtown, Carefree, and Tempe had relatively similar temperatures. Situated in the desert landscape on the urban fringe, the Carefree weather station reported the smallest increase in mean annual minimum temperature in contrast to Tempe which experienced the greatest increase in temperature. Although exposure to minimum and maximum temperature depends upon location within the Phoenix metropolitan area, these results clearly show that temperatures have been increasing at varying degrees between 1965-2006, and that temperatures for the year 2005 were among the warmest during this period.

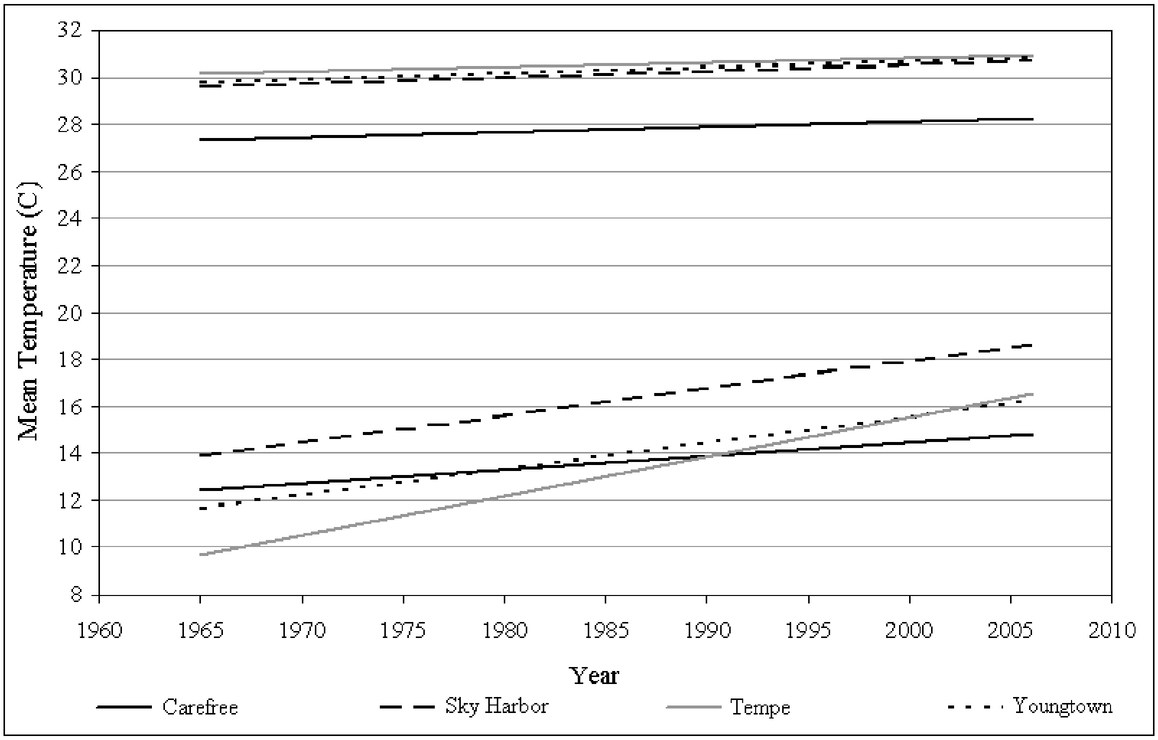


*Figure 5*: Historical Mean Maximum and Minimum Temperatures for Four Phoenix Metropolitan Weather Stations.

**Downscaling Physical Temperature**

The WRF climate model simulated mean average, mean high, and mean low 2 m air temperatures among 40 neighborhoods throughout the Phoenix metropolitan area for the four-day heat wave occurring from July 15-19, 2005 (Table 2). Regional temperatures ranged from an average of 38.28°C (101°F) to an average high of 45.67°C (114°F) with an average low of 30.87°C (88°F), respectively. The three measures of mean temperature represent the daily averages for each of the forty metropolitan neighborhoods in the study. The simulated temperatures, however, indicate significant variability in mean average, mean high, and mean low temperatures among individual neighborhoods. For instance, the range of mean averaged temperatures was 4.97$^{o}$C (or

8.9°F) between the warmest and coolest neighborhood. Mean low temperatures reported the greatest neighborhood range (5.16°C or 9.3°F), indicating significant differences in exposure among the coolest temperatures within the metropolitan area.

Figure 6 represents a temporal snapshot of temperature variability throughout the Phoenix metropolitan area for July 17, 2005, at 5pm. The spatial resolution is 1 km with the predicted surface air temperature at a height of 2 m above the ground. Representing the warmest part of the diurnal cycle, temperature readings at 5pm are often the hottest time of day (Dai and Trenberth, 2004). Notice temperatures are coolest in the eastern part of metropolitan Phoenix, warmest in the west, and strongly heterogeneous surrounding Downtown Phoenix. Although the average temperature among the forty neighborhoods was 44.62°C (112.3°F), temperatures ranged from a minimum of 39.52°C (103.1°F) to a maximum of 47.78°C (118.0°F). While this map illustrates fine-scale temperature variability for a discrete temporal period, simulated temperatures were consistent with historical temperature readings from the four local weather stations. For example, Tempe and Youngtown reported high simulated and historical temperatures while maximum temperatures in Carefree were relatively cooler.

Table 2

*Simulated Mean Average, High, and Low Temperature (C) for July 15-19 2005.*

| Simulated Temperature (C) | Descriptive Statistics | | | | |
|---|---|---|---|---|---|
| | Mean | SD | Min | Max | Range |
| Mean Average | 38.28 | 1.08 | 34.65 | 39.62 | 4.97 |
| Mean High | 45.67 | 0.98 | 42.16 | 46.78 | 4.62 |
| Mean Low | 30.87 | 1.17 | 27.2 | 32.36 | 5.16 |

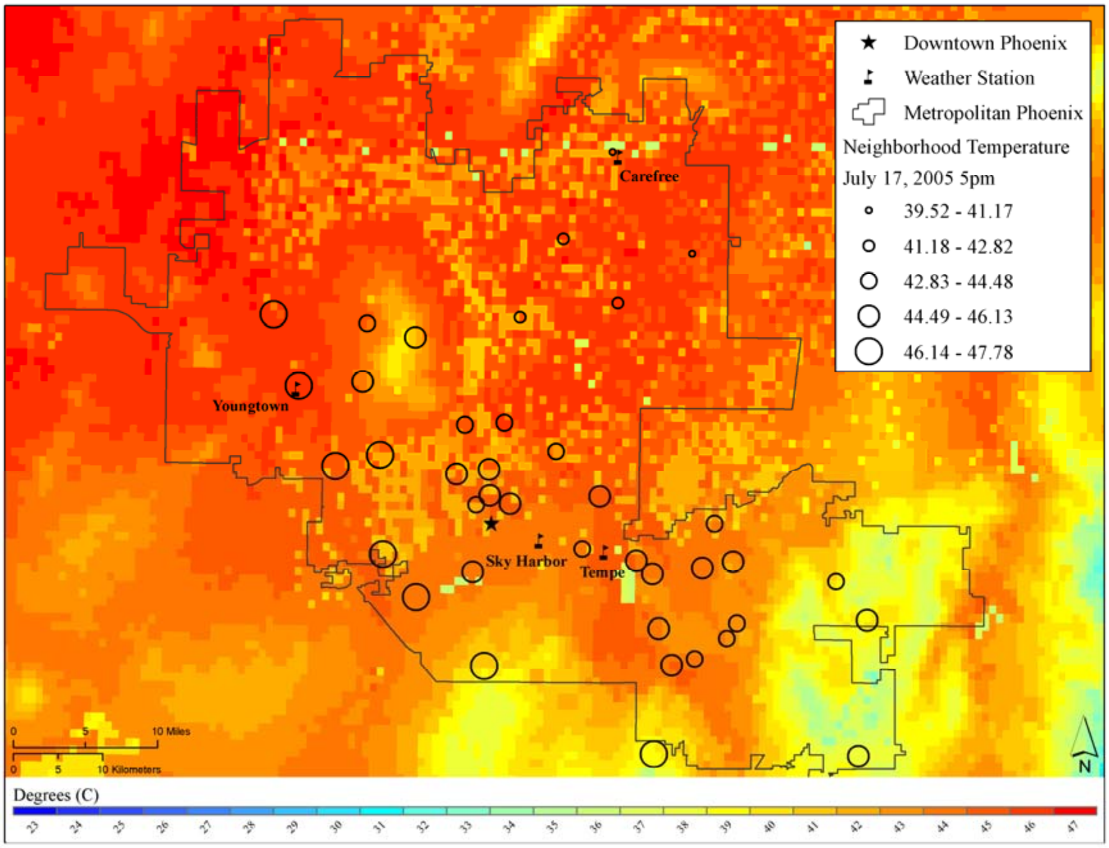


*Figure 6*: WRF-Simulated Air Temperature for the Phoenix, AZ Metropolitan Area for July 17 2005, at 5pm.

**Upscaling Perceived Temperature**

Among PASS survey respondents, an overwhelming majority believed the region to be getting warmer over time, whereas about half of respondents (51 percent) perceived temperature in their neighborhood was about the same as other metropolitan neighborhoods for the summer of 2005 (Table 3). Although respondents were not asked whether they thought the region was getting cooler over time, only 17.8 percent of respondents reported that temperature in the region was staying the same compared to over eighty-two percent who believe the temperature is getting warmer.

An analysis of survey responses aggregated at the neighborhood level indicates varying degrees of perception that the region is getting warming over time (perceived regional temperature) as well as how respondents perceived temperatures in their neighborhood compared to the temperature of other Phoenix area neighborhoods for the summer of 2005 (perceived neighborhood temperature). For example, Table 4 shows that the average neighborhood score for perceived regional temperature ranged from 1.71 to 2.61 on a 3-point scale, indicating varying perceptions that regional temperature is increasing over time. Similarly, while the majority of respondents indicated that they perceived temperature in their neighborhood to be about the same as other neighborhoods for the summer of 2005, respondents in some neighborhoods perceived their local environment as either cooler or warmer than others.

Figure 7 illustrates the spatial distribution of average perceived temperatures throughout the 40 neighborhoods. Representing aggregated responses for each neighborhood, the circles reflect varying perceptions such that the smaller circles reflect perceived cooler/lower temperatures while the larger circles signify perceived warmer/higher temperatures. The spatial distribution of perceived regional temperature shows a spatial pattern whereby neighborhoods near downtown centers perceived temperatures to be getting warmer while neighborhoods located near the urban fringe perceived temperatures to be the same over time. Alternatively, perceived neighborhood temperature exhibits a more random spatial distribution. For instance, respondents in some downtown urban neighborhoods perceived their neighborhood as cooler environments compared to other metropolitan neighborhoods, whereas respondents in fringe communities reported that their neighborhood is warmer than others.

A comparison of social perceptions to historical temperatures reveals interesting findings. For instance, respondents in Carefree perceived regional temperatures to be increasing over time, yet they also reported that their neighborhood was relatively cooler compared to other Valley neighborhoods for the summer of 2005. In contrast, Youngtown respondents reported an average score that regional temperatures were increasing, and indicated that temperatures in their neighborhood were about the same as other metropolitan neighborhoods for the summer of 2005. While perceived temperatures parallel historical trends in Carefree, social perceptions are inconsistent with historical trends in Youngtown (Youngtown was among the warmest neighborhoods in the study although temperatures were perceived to be about the same as other Valley neighborhoods).

Table 3

*Descriptive Statistics and Frequency of Survey Respondents on Perceived Regional and Neighborhood Temperature for Summer 2005*.

| Dependent Variable | Descriptive Statistics | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | N | Mean | SD | Lot Cooler | Little Cooler | Same | Little Hotter | Lot Hotter |
| Perceived Regional Temp | 774 | 2.18 | 0.709 | --- | --- | 17.8 | 46.6 | 35.5 |
| Perceived Neighborhood Temp | 767 | 3.04 | 0.870 | 2.3 | 22.3 | 51.2 | 17.5 | 6.6 |

Note: Perceived regional temperature was measured on a 3-point; perceived neighborhood temperature was measured on a 5-point scale.

Table 4

*Descriptive Statistics on Perceived Regional and Neighborhood Temperature for Summer 2005 Aggregated to the Neighborhood Scale*.

| Respondent Perceptions | Descriptive Statistics | | | | |
|---|---|---|---|---|---|
| | Mean | SD | Min | Max | Range |
| Perceived Regional Temp | 2.17 | 0.21 | 1.71 | 2.61 | 0.9 |
| Perceived Neighborhood Temp | 3.04 | 0.31 | 2.35 | 3.70 | 1.35 |

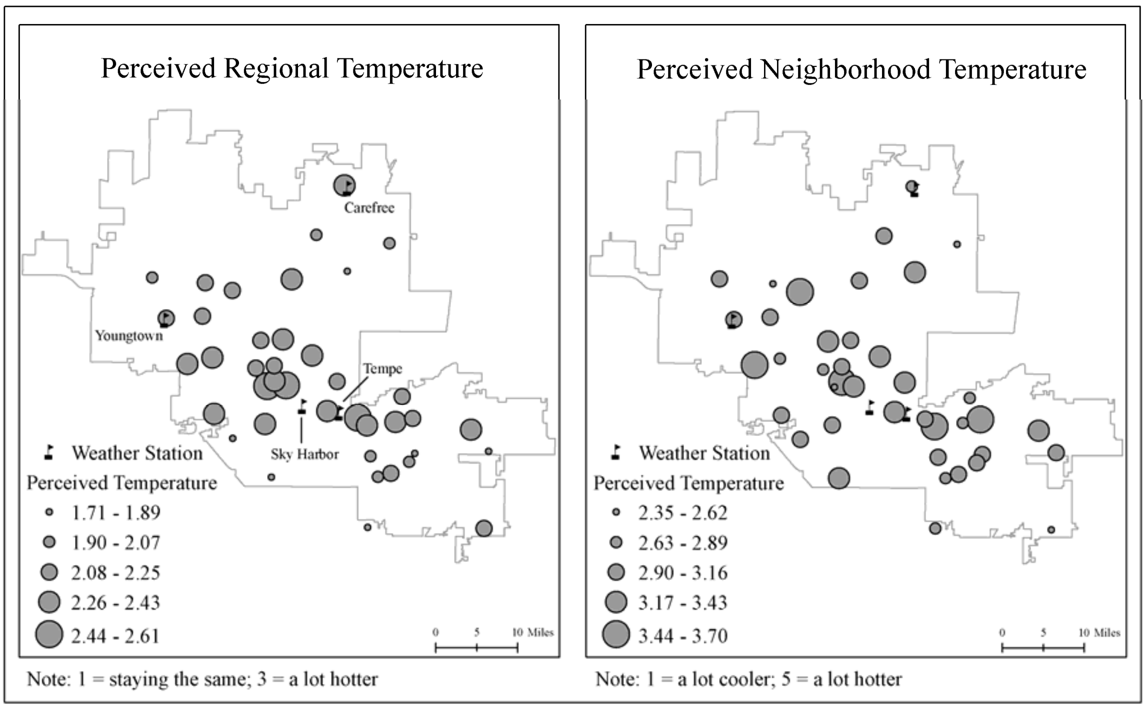


*Figure 7*: Perceived Regional and Neighborhood Temperatures in Phoenix, AZ Aggregated to the Neighborhood Scale.

**Hybrid Framework**

The integration of downscaling and upscaling techniques into a hybrid framework provides the capacity to downscale temperature variability throughout the study area, analyze the distribution of PASS survey respondents via an upscaling approach, as well as the ability to synchronize data sets and conduct statistical tests.  For instance, a Pearson's correlation comparing environmental conditions (WRF output) to social perceptions (PASS responses) aggregated at the neighborhood level indicated that social perceptions reported a weak association with environmental conditions regarding regional temperature change over time. Alternatively, perceived temperatures were significantly correlated with environmental conditions when analyzing neighborhood temperature relative to others (Table 5). Strong relationships were evident for mean average, mean high and mean low WRF predicted temperatures for the 2005 heat wave. The results suggest that people exhibit greater sensitivity to nearby temperatures (e.g., the neighborhood scale) compared to the more distant regional scale.

Table 5

*Results of Pearson's Correlation Comparing Perceived Temperature with WRF-Predicted Temperatures Aggregated to the Neighborhood Scale*.

| Bivariate Correlation | N | Pearson's *r* | Sig (2-tailed) |
|---|---|---|---|
| *Perceived Regional Temp* | | | |
| Mean Average | 40 | 0.206 | 0.202 |
| Mean High | 40 | 0.204 | 0.207 |
| Mean Low | 40 | 0.188 | 0.245 |
| *Perceived Neighborhood Temp* | | | |
| Mean Average | 40 | 0.585** | 0.000 |
| Mean High | 40 | 0.589** | 0.000 |
| Mean Low | 40 | 0.606** | 0.000 |

**Correlation is significant at the 0.01 level (2-tailed)

**Discussion**

The objective of this paper was twofold: 1) to examine existing theoretical frameworks for studying scale, and to determine if there is a need for a new theoretical approach; and 2) to evaluate the effectiveness of the proposed hybrid framework to analyze complex socio-ecological processes (such as climate change) at multiple scales of analysis. As a baseline, we analyzed historical minimum and maximum temperatures throughout the Phoenix metropolitan area, and observed increased temperatures over time. Then we employed the meso-scale WRF climate model as a downscaling framework to simulate temperature variability throughout the study area for a heat wave occurring July 15-19, 2005. Analyses reported on mean average, high, and low regional and neighborhood temperatures, and observed significant differences among neighborhoods in the study.

We also examined social perceptions of regional and neighborhood temperature via the upscaling framework. Analyses indicated that perceived temperature varies by spatial scale such that an overwhelming majority of respondents believe regional temperatures are rising over time; however, at the neighborhood scale, respondents indicated temperatures are staying the same. Similarly, perceived neighborhood temperature reports different findings by the level of aggregation. While the majority of respondents perceived temperature in their neighborhood to be comparable to other metropolitan neighborhoods for the summer of 2005, there was considerable variability when aggregated to the neighborhood scale. Analyses therefore identified variable patterns regarding perceived regional and neighborhood temperature throughout the study area via the upscaling framework.

While the downscaling model was used to predict temperature from a broad scale down to fine scales of analysis, and the upscaling model provided an understanding of perceived temperatures by scaling up from individual to neighborhood scales of analysis, the hybrid approach integrates downscaling and upscaling techniques by examining data at a common spatial resolution. Advantages of integrating theoretical approaches include the capacity to conduct statistical tests between data sets. For instance, the Pearson’s test of correlation reported that the relationship between environmental conditions and social perceptions of temperature were relatively weak at the regional scale, but very strong at the neighborhood scale. This finding is significant because it allows us to further theorize on environmental perception research. For instance, people are likely to perceive nearby environmental conditions with greater accuracy compared to environmental conditions at broader scales of analysis. A hypothesis for future research is that social perceptions of environmental conditions become increasingly distorted as spatial scale broadens. This research finding, however, would not have been possible to identify without integrating downscaling and upscaling approaches via the hybrid framework.

For studies examining single systems (e.g., physical or social processes) at discrete or multiple scales of analysis, either one of the current theoretical frameworks (e.g., downscaling, upscaling) is sufficient. Studies investigating complex socio-ecological processes (e.g., problems comprised of physical and social systems); however, might be better served by investigating a given research problem via an integrated approach. For example, this study found that social perceptions of temperature are more closely aligned with environmental conditions at the neighborhood scale compared to the broader regional scale of analysis. Comparing social perceptions with physical conditions is critical to developing an effective strategy to address climate change (Dunlap, 1998; Leiserowitz, 2005). Investigating a given process in this fashion will provide scientists with new insights into different research challenges which will likely help unravel complex processes while leading to more sophisticated theorization.

**Conclusions**

The influx of research on scale over the last thirty years precipitates the need to examine existing methods for operationalizing scale. Although the downscaling framework was the traditional method for analyzing processes at multiple scales of analysis, the upscaling model emerged as an alternative approach to better represent social systems ranging from individual to global scales. As scientists focus greater attention on complex processes (e.g., socio-ecological issues), there is a need to concurrently examine multiple systems (e.g., physical and social) at multiple scales of analysis. Existing theoretical frameworks for operationalizing scale, however, are unable to analyze complex processes at multiple scales of analysis.

A summary of research findings indicates that: 1) there is a need for theoretical integration to examine current research challenges (e.g., processes comprised of both physical and human systems); and 2) the hybrid framework is an effective model to address this gap in research. The case study on temperature demonstrated the limitations of existing theoretical frameworks while illustrating the viability of an integrated hybrid model which is able to synthesize downscaling and upscaling approaches, in addition to providing the platform better understand a given process via statistical tests.

## CHAPTER FOUR: A MIXED METHOD MULTI-SCALE ANALYSIS: A CASE STUDY ON EXTREME HEAT IN PHOENIX, AZ

### About this Chapter

This chapter is a paper that will be submitted to the *Professional Geographer*. The manuscript is entitled "A Mixed Method Multi-scale Analysis: A Case Study on Extreme Heat in Phoenix, AZ." The author of this paper is Darren Ruddell.

Mixed method multi-scale analysis presents two distinct challenges: 1) investigations of various physical or social processes at multiple scales of analysis typically employ either a quantitative or qualitative framework; and 2) mixed method analyses (the integration of quantitative and qualitative techniques) often examines a single scale of analysis. A pressing challenge among studies of socio-ecological issues, however, is to examine a given process via the mixed method framework at multiple scales of analysis. This study aimed to address this gap in research by examining extreme heat in the Phoenix, AZ (USA) metropolitan area as a case study. Specifically, we employed the Weather Research and Forecast (WRF) climate model to simulate local environmental conditions while using self-reported perceptions on temperature from a social survey of local residents. Data were synthesized into a mixed method framework and analyzed at multiple scales of analysis (e.g., regional and neighborhood), which compared biophysical conditions (e.g., local temperature) with social perceptions of temperature at two spatial scales of analysis. We also analyzed local media reports to determine if media coverage on extreme heat may have influenced local and/or regional perceptions. Results support using the mixed method multi-scale research framework.

**Introduction**

Within the framework of hypothesis testing and developing theories and laws designed to procure truth, knowledge, and enhanced understanding are various methods for investigating biophysical and social processes. While biophysical scientists traditionally employ quantitative approaches (e.g., mathematical techniques, theorems, and proofs) to examine form and/or causal relations of a given system, social scientists often utilize qualitative methods (e.g., personal interviews, surveys, text analysis, among other techniques) to investigate how people experience and/or view the world (Johnston et al., 2000). Recently, however, scholars have integrated quantitative and qualitative approaches into a mixed method framework which has become an increasingly popular research technique in the scientific community (Boyd, 2000; Thurmond, 2001). For instance, scholars have utilized the mixed method framework to investigate a variety of complex research topics such as water resource management, quality of life (QoL), climate change, among other issues (Bolin et al., 2008; Costanza et al., 2007; Harlan et al., 2006). The argument for mixed methods is that studies employing exclusively quantitative or qualitative methods often present a limited picture of a given process; however, mixed method analyses provide a multidimensional perspective into various phenomena, and thereby, increases the ability to present truth, knowledge, and enhanced understanding (Dunning et al., 2008; Mitchell, 1986; Shih, 1998).

Mixed method analysis was initially used to validate a study’s findings by using both quantitative and qualitative research methods (Shih, 1998). Over time, the mixed method approach moved beyond a validation system (confirming research findings) to a framework that utilizes multiple methods to enhance the current understanding of a given process (comprehension) (Reichardt and Cook, 1979; Tashakkori and Teddlie, 1998). Confirmation is defined as the convergence of findings from two or more data sets which have been generated via general accepted approaches. Comprehension blends quantitative and qualitative research techniques to help provide a more inclusive understanding of a phenomenon. The assumption is that each research method is vulnerable to different weaknesses and/or biases, but the use of multiple methods seeks to counterbalance the shortcoming of any single strategy (Jick, 1979; Thurmond, 2001). While a quantitative analysis aims to provide hard, replicable, and reliable data, qualitative measures focus on richness, depth, and data validity (Shih, 1998). Recent work by Dunning et al. (2008) examined issues of quality of life (QoL) via the *confirmation* and *comprehension* framework, and notable research findings included: 1) a lack of confirmation between quantitative and qualitative methods; 2) methodological challenges in operationalizing the mixed method framework; and 3) enriched comprehension (analyses identified two variables contributing to perceived QoL).

The confirmation/comprehension framework lends itself to examining socio-ecological issues since such studies require an investigation of both social and biophysical dimensions of a given problem. Socio-ecological issues refer to the coupled feedback between human decision-making (or behavioral patterns) and the associated impacts on the dynamic natural environment (Gimblett, 2001). Climate change represents a social-ecological issue whereby human development and the modification of the natural environment has resulted in increased anthropogenic heat into the environment contributing to rising global temperatures and urban heat islands (UHI) (IPCC, 2001; Lowry, 1967; Oke, 1997). The modification of native landscapes into urban centers has transformed natural systems, which in turn, have resulted in warming temperatures, regionally and globally. While scholars routinely examine physical dimensions of climate change, public perceptions of climate change are relatively under-researched yet equally important for developing effective policy to adapt to or mitigate the impacts of climate change (Brazel et al., 2000; IPCC, 2007; Leiserowitz, 2005; Oke, 1987).

Another mechanism to provide depth to an investigation is through multi-scale analysis. Scholars investigating socio-ecological issues, for instance, have recently focused on processes of variable spatial and temporal scales (Easterling and Polsky, 2004). Current literature on scale-related issues highlights two distinct themes: first, research findings may communicate different (even conflicting) results when analyzing data at multiple scales of analysis. For instance, Imeson and Lavee's (1998) study of soil erosion and climate change found that spatial and temporal scales do not exhibit a linear relationship, but vary based on local properties such as slope, patch, and/or landscape. The second theme on scale research is that studies utilizing mixed theoretical or methodological approaches have helped advance research on scale. Work by Bolin et al. (2008), for instance, juxtaposed environmental conflicts over water resources with local politics in Arizona. This study required a synthesis of socially defined political boundaries that were spatially mismatched with natural watershed boundaries. Scientists therefore are making new and valuable research contributions to research on scale by utilizing the mixed method framework.

Although research has benefited from mixed method analysis by confirming results and/or enhancing the comprehension of a given process, one limitation of mixed method research is the tendency to examine one scale of analysis. For instance, while Dunning et al. (2008) enhanced comprehension on QoL via the mixed method framework, the spatial scale of analysis (the city of Saskatoon, Saskatchewan) was constant. Employing mixed methods to a single scale of analysis (temporal or spatial) presents similar limitations to investigating a given process using a single methodology (e.g., quantitative or qualitative). Since studies examining processes at multiple scales of analysis via a single methodology have identified patterns of non-linearity, and investigations using the mixed method framework at a single scale have added richness to a study, it is likely that a mixed method multi-scale analysis will further enhance the present knowledge and understanding of a given process.

New research challenges (e.g., socio-ecological issues) often require new or alternative methods to better understand a given process. While quantitative or qualitative methodologies offer insight into various physical or social processes, this study aimed to evaluate the potential of enhancing the mixed method framework to analyze a multi-process issue (e.g., climate change) at multiple scales of analysis. Specifically, we test the confirmation/comprehension framework by analyzing biophysical and social measurements of temperature as one dimension of climate change at multiple scales of analysis (regional and neighborhood) among forty diverse Phoenix, AZ metropolitan neighborhoods. Analyses offer a comparison on the physical distribution of temperatures to public perceptions of temperature throughout selected neighborhoods. We also incorporate a text analysis to determine if public perceptions were influenced by local media sources. Confirmation and comprehension were assessed by comparing results of environmental conditions with public perceptions of temperature throughout the study area. The research question informing this study is: *1) Does analyzing extreme heat via a mixed method multi-scale research framework lend new insight into socio-ecological issues?*

**Literature**

Literature highlights advances in both mixed method and multi-scale research. For instance, the mixed method framework described above recognizes the value of integrating quantitative and qualitative research methods to help confirm research findings and/or enhance the comprehension of a given process. Similarly, studies examining physical or social processes at multiple scales of analysis contribute to the current understanding of a particular system as well as lend insight into research on scale (Horner, 2007). Research is limited, however, on studies investigating a given process using mixed methods at multiple scales of analysis (Table 6). For instance, a variety of studies have examined either biophysical or social processes at multiple scales of analysis (e.g., surface temperature, environmental perception), or studies have utilized the mixed method framework to examine a given process at one discrete scale of analysis (e.g., Brazel et al., 2000; Dunning et al., 2008; Harlan et al., 2006; Uzzell, 2000). There is a need, however, to examine complex socio-ecological processes (e.g., climate change) via the mixed method framework at multiple scales of analysis.

Table 6

*Review of Research Frameworks for Investigating Scale.*

| Scale of Analysis | Research Framework | | |
|---|---|---|---|
| | Biophysical | Social | Mixed Method |
| Single Scale | X | X | X |
| Multi Scale | X | X | |

**Mixed Method Analysis**

One way to increase the validity, strength, and interpretative potential of a study while decreasing investigator biases is to use mixed method analysis (Denzin, 1970; Punch, 1998). Although the mixed method research framework originally emerged out of the "triangulation of methods" movement (Dunning et al., 2008), it has become an established methodological approach by moving beyond a validation system (e.g., confirmation of findings from divergent methods) by offering greater insight into a study (e.g., comprehension of research findings) (Tashakkori and Teddlie, 1998). So while triangulation initially aimed to confirm results from two or more analytical methods to help increase the ability to interpret the findings of a study, mixed method analysis also incorporates comprehension (Campbell and Fiske, 1959; Denzin, 1970; Kimchi et al., 1991). Thus, the goal of mixed method analysis is twofold: confirmation of analytical techniques and comprehension of results (Creswell, 2003; Thurmond, 2001).

There are two different forms of methodological confirmation: within-method and across-method. Within-method involves comparing the results of two or more methodological types of the same method, such as personal interviews, surveys, text analysis are types of qualitative methods. The second and more complex form of methodological confirmation is across-method. Across-method analysis aims to utilize divergent methods to measure the same phenomenon from varying perspectives, as the conceptual framework presents in Figure 8 (Mitchell, 1986). Notice the two large circles each represent the domain of method bound techniques for a given phenomenon. This combination creates the potential for counterbalancing the flaws or weaknesses of one method with the strengths of another, and thus, increasing comprehension of a study while providing a platform to validate research findings.

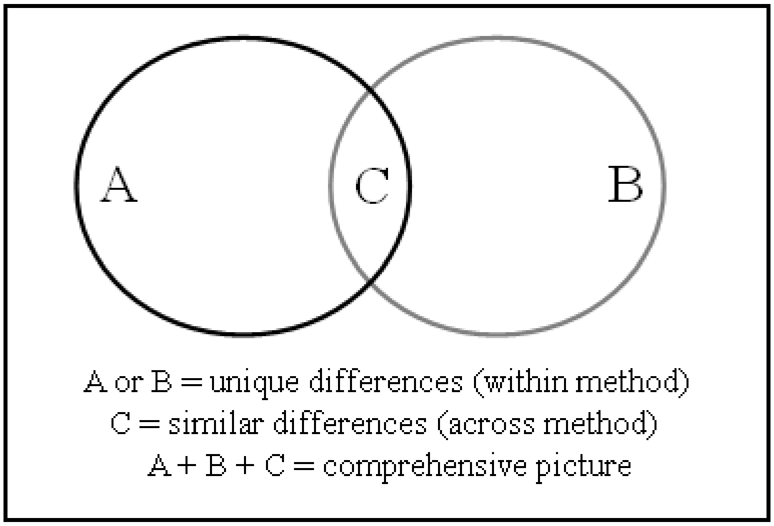


*Figure 8*: Methodological Integration Framework [Adapted from Mitchell 1986].

Although a variety of studies in geography utilize mixed method approaches, discussions of the use of these approaches are sparse and often couched by overcoming the quantitative/qualitative divide (Dunning et al., 2008). Graham (1999) suggests that mixed method approaches can assist in moving the focus of investigation away from data-rich questions toward issues that require subjective interpretation which includes the socio-cultural context where lived experiences are situated. Madsen and Adriansen (2004) argue that mixed method approaches offer unique perspectives on geographic issues, such as investigating rural environments (the focus on their study) or processes unique to urban areas, such as physical and social dimensions of urban climate change. While some disciplines consider social survey data as quantitative, geographers largely view rankings of people’s attitudes and behavior as qualitative data. This study therefore employs output from a global climate model as a quantitative framework while using survey responses as qualitative data.

**Scale**

Scale has become an important and complex research topic in geography, particularly over the last thirty years. Although scalar issues represent a major challenge within geography's various subdisciplines, the objectives and research questions being posed are quite different. Physical geographers, for example, are concerned with scale as it relates to scale linkage and hierarchical organization (Bendix, 1994; Phillips, 2004; Wu, 2004). Alternatively, research among human geographers has largely theorized on social constructions of scale (Lefebvre, 1991; Smith, 1984; Taylor, 1982). GIScientists face scale challenges when representing or modeling human and/or physical processes (Tate and Atkinson, 2001). Geographers studying socio-ecological issues, such as climate change, recognize the need to identify the operational scale of human and physical systems (Sheppard and McMaster, 2004).

Although geographers approach scale from a variety of perspectives, there is some common ground linking these research efforts. For instance, operationalizing temporal scale is an important consideration whereby the appropriate scale of analysis varies along the continuum of the instantaneous to the geological (Meentemeyer, 1989). Various subfields also have strong interests in the concept of spatial scale such that physical and/or social processes operate on a range of scales from the molecular to the planetary (McMaster and Sheppard, 2004). For example, some scientists investigate scaled relations between neutrons and atoms while others conceptualize space in terms of light-years or other alternative geometries (Sheppard and McMaster, 2004). A third commonality is the way in which a given process operates. For instance, physical geographers typically rely on mathematics and view scale as part of a nested hierarchy in contrast to social processes which are not necessarily constructed in terms of Euclidean units, but rather emerge out of social behavior.

Issues of scale among physical geographers have traditionally employed the quantitative research framework to investigate processes via scale linkage and the reductionist approach. Scale linkage is understood as “transferring information, relationships, models, and rules between different spatial and temporal scales” (Phillips, 2004, p. 86). For instance, climatologists investigate temperature records at various temporal and spatial scales, and results are often used to simulate past, present, or future conditions. The reductionist framework is an organizing principle in the physical geography subdiscipline. While geoscientists study a variety of earth systems, they have long recognized that processes and environmental controls relevant at a given spatial or temporal scale exercise at least partial control over processes operating at finer scales (Phillips, 2004). For example, the drainage area for a large-scale study exerts a measure of control over finer variables such as discharge, flow dimensions, and velocity (Leopold and Maddock, 1953; Leopold and Miller, 1956).

Hierarchy theory is the conceptual framework commonly used to link multiple scales of analysis (DeBoer, 1992; O’Neill et al., 1986). The underlying principle is that environmental systems are linked at successive scales, whereby higher-level systems constrain a given system while lower-level systems explain mechanistic operation (Allen and Starr, 1982; Bendix, 1994; Phillips, 2004; Urban et al., 1987). Research indicates, however, that not all physical systems exhibit linearity. Studies of physical systems show that processes often communicate different patterns at different spatial scales of analysis. The IPCC Fourth Assessment Report (AR4), for example, indicates that average global surface temperature increased by 0.74°C between 1906-2005; however, there was significant variability from region to region. Average surface temperature changes in higher northern latitudes reported a rise from 2-3.5°C, while regions in southern latitudes and the Antarctic showed cooling trends of 0.2-1°C during this period (IPCC, 2007). It is important therefore to investigate processes at multiple spatial and temporal scales of analysis.

While physical geographers typically employ quantitative techniques to analyze earth systems, most human geographers use qualitative methods to study varying social processes at discrete or multiple scales of analysis (Herod and Wright, 2002; Johnston et al., 2000). In contrast to viewing scale as a nested hierarchy, human geographers largely conceive scale boundaries as the outcome of social constructions (Brown and Purcell, 2005; Cox, 1998; Manson, 2008; Marston, 2000; Smith, 1984). Social theorists often reject the notion of scale as an ontological category in favor of the "production of scale" (Smith, 1984). Scale, human geographers argue, emerges out of social dynamics ranging from local scales (e.g., the micropolitics of the household) to broad scales like international economic regimes. Thus, the conception of scale by most social theorists is a reflection of social behavior carried out at various levels of analysis (e.g., household, neighborhood, state, nation).

A central concern among social theorists is the importance of geographic scales typically used in contemporary human geography (Sheppard and McMaster, 2004). While a given scale of analysis may result from social constructions rather than naturally defined boundaries (e.g., watersheds, geology), investigating processes at multiple spatial scales is also important in human geography. For instance, an analysis of literacy at the census block level will likely yield different results when compared to the block-group, tract, or county levels. Similarly, research on environmental perception indicates that people perceive environmental problems differently based on the spatial scale of analysis. Murch (1971) and Ingold (1993) found that people expressed greater concern over global environmental problems compared to similar local problems despite the fact that individuals have significantly less influence over global problems. There is a human tendency therefore to perceive environmental problems as increasingly severe the farther they are (geographically and temporally) from an individual (Stedman, 2004). While previous studies have employed either a quantitative framework to investigate physical systems or a qualitative framework to examine social processes at multiple scales of analysis, to date, however, there is a lack of research on socio-ecological processes at multiple scales of analysis.

**Case Study**

To demonstrate the mixed method multi-scale research framework, we examined physical and social dimensions of extreme heat at multiple scales of analysis throughout the Phoenix metropolitan area for the summer of 2005 (Table 7). Specifically, we used the Weather Research and Forecast (WRF) climate model to simulate environmental conditions at the regional and neighborhood scales. Public perceptions of temperature were measured via the Phoenix Area Social Survey (PASS) which interviewed over 800 local residents among selected neighborhoods throughout the Phoenix metropolitan area. We also conducted a text analysis of media reports on extreme heat for the summer of

2005 to help better understand social perceptions of temperature throughout the study area. This case study serves to build upon existing research methods by testing the mixed method framework at multiple scales of analysis.

Table 7

*Research Frameworks Employed in this Study to Investigate Physical and Social Dimensions of Extreme Heat*.

| Scale of Analysis | Research Framework | | |
|---|---|---|---|
| | Biophysical | Social | Mixed Method |
| Single Scale | WRF | PASS/Text | WRF; PASS/Text |
| Multi Scale | WRF | PASS/Text | WRF; PASS/Text |

**Climate Change**

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 Earth has experienced periods of warming and cooling many times during its 4.5 billion year history (naturally caused by volcanic eruptions, changes in orbit, among other causes), the Earth is currently experiencing a warming period well beyond normal variation in its natural cycle (IPCC 2001). An overwhelming majority of scientists argue that anthropogenic heat (e.g., vehicles, industry, air conditioners) is largely responsible for the accelerated trend (Arnfield, 2003; IPCC, 2007; Kellstedt et al., 2008; Lowry, 1967; Oke, 1997). Human vulnerability and the impacts associated with a changing climate makes climate change one of the most pressing challenges of the 21st century (Geller, 2003; Kalkstein and Davis, 1989).

Physical changes in climate are well documented. For instance, earth scientists have recognized a rise in global sea level, retreating polar ice caps, as well as increased average global temperature over the past century (IPCC, 2007). Research on extreme heat also shows that the intensity, duration, and frequency of heat waves have increased, and projections indicate these trends will continue to intensify over the next century (Kalkstein and Green, 1997; Meehl and Tebaldi, 2001). The IPCC (2001) also anticipates more severe weather conditions over the next century, and depending upon geographic region, one can expect increases in extreme weather conditions such as more frequent and intense precipitation patterns, a rise in the number pest and disease outbreaks, as well as more frequent forest fires. An observable trend on climate change is that impacts are largely unpredictable and varied throughout the world with each region suffering its own unique consequences (Cox, 2007). Understanding changes in the physical climate is a major concern due to the significant impacts it has on human, ecological, and economic systems (Geller, 2003).

Although less researched, it is also critical to understand social dimensions of climate change, such as people’s perceptions and experiences of climate (Leiserowitz, 2005). While studies have examined how climate change has been constructed by environmentalists, scientists, policy-makers and other stakeholders, understanding how the general public views climate change has been relatively under-researched (Buttel, 1987; Dunlap, 1998; Lowe and Rudig, 1986). Public perceptions of climate change, however, are important because is assumed that such perceptions have a significant impact on policy-making (Kempton, 1993; Morgan, 1995). Environmental perception studies indicate that perceptions vary based on how people experience a given problem

(Aitken et al., 1989). For instance, environmental problems that strike swiftly and/or fiercely are often associated with heightened perceptions of risk. For example, heat waves in Philadelphia (1993), Chicago (1995), and Europe (2003) helped elevate awareness and perceptions on the human risks associated with extreme heat. Alternatively, environmental problems that occur at a slow and/or deliberate pace (e.g., climate change) are perceived as less threatening. Public perceptions of environmental problems, therefore, are correlated by the way in which people experience events.

**Methodology and Data Sources**

**Study Area**

Encompassing over 1,800 square miles of the Sonoran Desert in central Arizona, the Phoenix metropolitan and is home to over 65 percent of the state's 6.1 million residents (Figure 9) (Census Bureau, 2006). Metropolitan Phoenix is an ideal setting for studying physical and social dimensions of climate change. For instance, although it has a naturally warm climate, average annual temperatures have increased by more than 3$^{o}$C (or 5.4$^{o}$F) in Maricopa and Pinal counties over the 20$^{th}$ century (Brazel, 2003). While the average annual regional temperature has risen steadily, temperatures in urban areas have increased by 4.2°C compared to an increase of 1.3°C in rural areas, representing a warming rate over three times higher in urban areas (Brazel et al., 2000). According to the National Weather Service, the average number of heat days is also on the rise in the Phoenix metropolitan area. High heat days, defined as local temperatures of 43.3°C (or 110°F) or higher, averaged ten days per summer between 1971 to 2000; however, the summer of 2005 recorded a record 24 heat days only to be surpassed in 2007 with 33 heat days.

The impacts of extreme temperature on human health and comfort are also expected to increase as the threshold of human tolerance to rising temperatures are crossed more frequently and for longer periods of time (Kalkstein and Green, 1997). Although heat-related mortality already accounts for more deaths than all other weather-related events combined, human vulnerability to heat is expected to rise as the frequency, intensity, and duration of heat waves are projected to increase of over the next century (CDC, 2005; Meehl and Tebaldi, 2004). While Arizona led the nation in heat-related deaths from 1993-2002, this trend is likely to continue as temperatures are projected to increase the most in arid environments (IPCC, 2007). Changes in physical climate (i.e., temperature) increasingly threaten human health and well-being which underscores the need to examine public perceptions of climate change in the region.

The present study further concentrates on 40 diverse Phoenix area neighborhoods under study as part of the 2006 Phoenix Area Social Survey (PASS) project. These neighborhoods offer insight into the spatial distribution of temperature variability throughout the region during a summer heat event, in addition to a survey of residents' perceptions of temperature. 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). Census data by block group were assembled for all 94 sites and classified by location (urban core, suburban, and fringe), median income, and ethnic composition. All types of neighborhoods in the Phoenix area were represented among the sample of 40. Second, a random sample of households within each neighborhood was selected to participate in a social survey, which is described in more detail below.

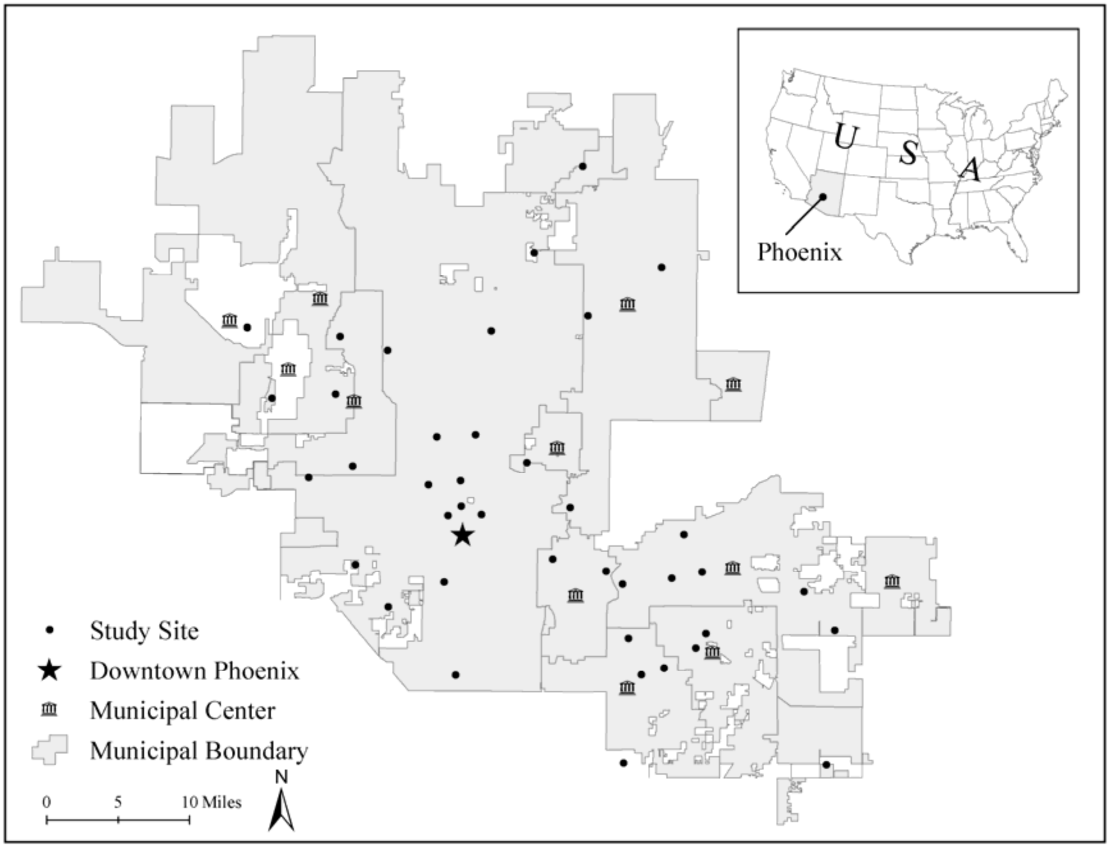


*Figure 9*: Map of Metropolitan Phoenix, Arizona.

**Simulated Physical Conditions**

This study utilized the meso-scale Weather Research and Forecast (WRF) climate model developed by the National Center for Atmospheric Research (NCAR) (Shamrock et al., 2005) to simulate environmental conditions throughout the Phoenix metropolitan area. Temperature variability was determined by employing WRF to simulate environmental conditions throughout the study area (Ruddell et al., 2009). Reporting 2m surface air temperature at a spatial resolution of 1km, the climate model calculated fine-scale temperatures throughout the study area by considering various input variables (e.g., air temperature, wind speed, horizontal and vertical advection, LULC). To accurately represent urban heterogeneity of LULC, we used remote sensing techniques as input data. Finally, as a surrogate for measuring the temperature in the Phoenix metropolitan area for the entire summer of 2005, we used a four-day heat wave (July 15-19, 2005) to measure temperature variability throughout the Phoenix metropolitan area for the summer of 2005 (Meehl and Tebaldi, 2004).

**Public Perceptions of Temperature**

To investigate public perceptions of climate change, we analyzed self-reports of the 2006 Phoenix Area Social Survey (PASS), which asked respondents about their weather-related experiences and perceptions during the summer of 2005. In each of the 40 PASS neighborhoods, described above, 40 randomly selected households were recruited for participation in PASS until a minimum 50 percent response rate was achieved in each neighborhood. Overall survey response rate was 51% (n=808). Data were collected using a multi-modal approach (online, telephone, or personal interview). The survey was administered by the Institute for Social Science Research (ISSR) at Arizona State University from April 29 through September 27, 2006.

The following PASS question was analyzed to measure perceptions of climate change: 1) During the summer of 2005, do you think your neighborhood was a lot cooler, a little cooler, a little hotter, or a lot hotter than most other neighborhoods in the Valley or do you think it was about the same temperature as other neighborhoods? (herein referred to as Perceived Temperature). The term “Valley” is a local expression that refers to the Phoenix metropolitan area.

**Media Coverage**

While output from the WRF climate model characterized physical conditions throughout the study area and PASS 2006 captured social perceptions of temperature, we also conducted a text analysis of media coverage on extreme heat for the summer of 2005 to determine if social perceptions were influenced by local media reports (Creswell, 2003). The data were obtained from an academic keyword search of “heat advisory” and “heat warning”. Three primary media sources (i.e., local reports, wires, and broadcasts) were identified via the Lexus-Nexus search engine, and results were narrowed to the state of Arizona. News reports were provided by the Arizona Department of Health Services (ADHS) which issues local and state-wide advisories for the National Weather Service (NWS). We also analyzed wire reports via the Associated Press State and Local Wire Media, and archived television coverage provided by Global Broadcasts.

**Procedures**

To evaluate the mixed method multi-scale research framework investigating physical and social dimensions of climate change in the Phoenix metropolitan area, data analyses were organized into four primary steps. The first phase of analysis examined physical differences in exposure to extreme heat via the WRF climate model which simulated local temperatures throughout the study area for the four-day period of July 15-19, 2005. Once the temperatures were calculated, GIS was used to map temperatures for the region as well as each of the forty neighborhoods in the study. The second phase of analysis was to calculate perceived temperature among survey respondents at two spatial scales of analysis (e.g., regional and neighborhood). Responses were analyzed collectively (e.g., the regional scale) and aggregated to the neighborhood scale (Census block group) then mapped in GIS.

The third step in the analysis employed the confirmation/comprehension framework. Integrating physical and social data sets, we tested confirmation of results via a chi-square test to compare the distribution of observed frequencies to expected frequencies at multiple scales of analysis (Dunning et al., 2008). We then examined comprehension by using a Pearson's product-moment correlation to measure the strength of association between physical and social variables at the regional and neighborhood scales. Interpreting Pearson's *r* is such that a score of 0.00-0.20 is little to no relationship while 0.80-1.00 is a very strong relationship between variables (Miller and Salkind, 2002). The fourth and final step of the analysis examined media coverage (e.g., heat advisories) on summer temperatures for the summer of 2005. We used a discourse analysis to investigate media attention on extreme heat, and focused on three characteristics of media coverage: 1) how the temperature is reported; 2) suggestions residents should follow; and 3) the spatial scale of the heat advisory. The text analysis aimed to ascertain whether or not media coverage on extreme heat influenced social perceptions.

## Results

### Environmental Conditions: A Biophysical Multi-Scale Investigation

Regional and neighborhood temperatures were calculated by the meso-scale Weather and Research Forecast (WRF) climate model. WRF considered various global, regional, and local inputs for estimating surface air temperature at 2 meters above the ground with a spatial resolution of 1 km. Although this technique enables microscale temperature analyses, WRF output was also aggregated to reflect a regional temperature for the Phoenix metropolitan area for a four-day period in the summer of 2005.

*Regional Climate Conditions*

The data represent a four-day period for the summer of 2005, and report regional average temperatures for mean average, mean high, and mean low temperature (Table 8). Temperatures represent daily average temperatures for the metropolitan region, with the average high temperature for the four-day period at 45.66°C (or 114.2°F) while the low was 30.87°C (or 87.6°F) and the average was 38.29°C (or 100.9°F), respectively.

Table 8

*Simulated Mean Average, High, and Low Regional Temperature for July 15-19, 2005.*

| Simulated Temperature | Temperature (Celsius) |
|---|---|
| Mean Average | 38.29 |
| Mean High | 45.66 |
| Mean Low | 30.87 |

*Neighborhood Climate Conditions*

To investigate temperature variability within the urban area, the WRF climate model simulated local conditions at a spatial resolution of 1km. Table 9 provides empirical insight into local environmental conditions by reporting mean average, mean high, and mean low temperatures for each of the forty neighborhoods in the study area. The mean average temperature for the four-day period was 38.29°C; however, the range of temperatures among the forty neighborhoods reported a low of 34.65°C to 39.62°C in the warmest neighborhood, representing a difference of 4.97$^{o}$C (or 8.9°F). Mean low temperature reported the greatest range (5.16°C or 9.3°F) among individual observations which is particularly significant since minimum temperatures often increase faster in urban areas compared to maximum temperatures (Karl et al., 1993). Results, therefore, indicate significant differences in exposure to summer-time temperatures among neighborhoods within the Phoenix metropolitan area for the summer of 2005.

Table 9

*Descriptive Statistics on Simulated Temperatures for July 15-19 2005 at the Neighborhood Scale*.

| Simulated Temperature | Descriptive Statistics (Temp in Celsius) | | | | |
|---|---|---|---|---|---|
| | Min | Max | Mean | SD | Range |
| Mean Average | 34.65 | 39.62 | 38.29 | 1.08 | 4.97 |
| Mean High | 42.16 | 46.78 | 45.66 | 0.98 | 4.62 |
| Mean Low | 27.2 | 32.36 | 30.87 | 1.17 | 5.16 |

**Perceived Temperatures: A Social Multi-Scale Investigation**

Similar to the analysis of environmental conditions at multiple spatial scales, social perceptions also vary by scale of analysis. Analyses examined responses for perceived temperature of neighborhood relative to others at the regional and neighborhood scales, and results indicate varying perceptions of temperature throughout the Phoenix metropolitan area for the summer of 2005.

*Regional Climate Perceptions*

At the regional scale of analysis, the majority of survey respondents perceived temperature in their neighborhood was about the same compared to other Valley neighborhoods for the summer of 2005 (Table 10). Although most respondents (51.2 percent) reported that the temperature in their neighborhood was about the same as other Valley neighborhoods for the summer of 2005, about a quarter of respondents (24.6 percent) believed their neighborhood was either a little cooler or a lot cooler than other Valley neighborhoods. Similarly, just less than a quarter of respondents (24.1 percent) perceive their neighborhood as either a little hotter or a lot hotter than other metropolitan neighborhoods.

Table 10

*Descriptive Statistics and Frequency of Survey Respondents on Perceived Temperature for Summer 2005*.

| Dependent Variable | Descriptive Statistics | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | N | Mean | SD | Lot Cooler | Little Cooler | Same | Little Hotter | Lot Hotter |
| Perceived Neighborhood Temp | 767 | 3.04 | 0.870 | 2.3 | 22.3 | 51.2 | 17.5 | 6.6 |

Note: Perceived Temperature was measured on a 5-point scale. Responses ranged from 1: a lot cooler; to 5: a lot hotter.

*Neighborhood Climate Perceptions*

An analysis of survey responses aggregated at the neighborhood scale indicates varying degrees of perception for perceived temperature. For example, Table 11 shows the range of responses for perceived temperature aggregated among the forty neighborhoods. Although the mean response for perceived temperature is 3.04 (temperature in my neighborhood is about the same as the temperature in other Valley neighborhoods for the summer of 2005), perceptions range from 2.35 to 3.70, representing significantly different perceptions of temperature relative to other Valley neighborhoods. Respondents in some neighborhoods therefore perceive their local environment as either cooler or warmer compared to other metropolitan areas for the summer of 2005.

Table 11

*Descriptive Statistics on Perceived Temperature for Summer 2005 at the Neighborhood Scale*.

| Respondent Perceptions | Descriptive Statistics | | | | |
|---|---|---|---|---|---|
| | Min | Max | Mean | SD | Range |
| Perceived Temperature | 2.35 | 3.70 | 3.04 | 0.31 | 1.35 |

**Data Synthesis: A Mixed Method Multi-Scale Investigation**

The third step in the analysis employed the confirmation/comprehension framework by synthesizing physical and social data on temperature at the regional and neighborhood scales of analysis. Although research findings fail to confirm results, comprehension is enriched. These conclusions require the mixed method approach to be performed at multiple scales of analysis.

*Confirmation*

A chi-square test was used for statistical confirmation to compare simulated temperature to social perceptions at the regional and neighborhood scales of analysis. Mean low neighborhood temperature served as the measure of environmental conditions and the temperature range (5.16°C) was divided into five classes to match the 5-point Likert scale at which residents reported perceived temperature for the summer of 2005. Tables 11-14 reflect the range of minimum temperature divided into equal intervals; however, we also analyzed the data using other methodological classifications (e.g., quantile, natural breaks, geometric interval, standard deviation), and found similar results at the regional scale of analysis but results varied at the neighborhood scale.

Analyses at the regional scale reported significant differences (chi-square = 0.000) between environmental conditions and perceived temperature (Tables 12 and 13).

For instance, perceived temperature exhibits a normal distribution while the distribution of environmental conditions is negatively skewed. The distribution of environmental conditions suggests that an overwhelming majority of respondents live in relatively warm local environments; however, the majority of respondents perceived the temperature in their neighborhood to be about the same as other metropolitan neighborhoods for the summer of 2005. We then aggregated survey responses by neighborhood and compared perceived temperature with temperature at the neighborhood scale, and analyses showed modest differences between the two samples (chi-square = 0.321) (Tables 14 and 15). Again perceived temperature displayed a normal distribution while environmental conditions were negatively skewed. A one way analysis of variance (ANOVA) confirmed significant differences between data sets at the regional scale while reporting modest differences at the neighborhood scale (Table 16). When analyzing individual responses (e.g., the regional scale), results indicate that social perceptions of relative neighborhood temperature are not congruent with local environmental conditions. Most respondents feel they live in an average (or even cooler than average) neighborhood when, in fact, their neighborhoods are hotter than others. When responses are aggregated to the neighborhood level, however, perceived neighborhood temperature is more closely aligned with simulated conditions.

Table 12

*Crosstabulation of Perceived Relative Neighborhood Temperature Compared to Simulated Temperature in Neighborhood at Regional Scale*.

| Class | Perceived Temp | Simulated Temp | Residual |
|---|---|---|---|
| 1 (cooler) | 18 | 41 | -23 |
| 2 (a little cooler) | 171 | 60 | 111 |
| 3 (ambient) | 393 | 35 | 358 |
| 4 (a little hotter) | 134 | 291 | -157 |
| 5 (hotter) | 51 | 340 | -289 |

Table 13

*Chi-square Results of Perceived Relative Neighborhood Temperature Compared to Simulated Temperature in Neighborhood at Regional Scale*.

| Test | N | Value | Significance |
|---|---|---|---|
| Pearson Chi-Square | 767 | 75.8 | 0.000 |

Note: We also analyzed the range of mean low temperature using four other methodological classifications and found similar results. Quantile: r = 61.5; sig. = 0.000; Natural Breaks: r = 71.2; sig. = 0.000; Geometric Intervals: r = 78.6; sig. = 0.000; Standard Deviation: r = 81.6; sig. = 0.000.

Table 14

*Crosstabulation of Perceived Relative Neighborhood Temperature Compared to Simulated Temperature in Neighborhood at Neighborhood Scale*.

| Class | Perceived Temp | Simulated Temp | Residual |
|---|---|---|---|
| 1 (cooler) | 3 | 2 | 1 |
| 2 (a little cooler) | 8 | 3 | 5 |
| 3 (ambient) | 16 | 2 | 14 |
| 4 (a little hotter) | 7 | 15 | -8 |
| 5 (hotter) | 6 | 18 | -12 |

Table 15

*Chi-square Results of Perceived Relative Neighborhood Temperature Compared to Simulated Temperature in Neighborhood at Neighborhood Scale*.

| Test | N | Value | Significance |
|---|---|---|---|
| Pearson Chi-Square | 40 | 18.1 | 0.321 |

Note: We also analyzed the range of mean low temperature using four other methodological classifications and found similar results. Quantile: r = 14.9; sig. = 0.535; Natural Breaks: r = 28.1; sig. = 0.031; Geometric Intervals: r = 27.3; sig. = 0.038; Standard Deviation: r = 20.5; sig. = 0.200.

Table 16

*ANOVA Results of Perceived Relative Neighborhood Temperature Compared to Simulated Temperature in Neighborhood at Regional and Neighborhood Scales*.

| ANOVA | F | Significance |
|---|---|---|
| Regional Scale | 10.9 | 0.000 |
| Neighborhood Scale | 3.8 | 0.011 |

Note: We also conducted a one way ANOVA using four other methodological classifications and found similar results. Results at the regional scale of analysis: Quantile: F = 9.1; sig. = 0.000; Natural Breaks: F = 9.5; sig. = 0.000; Geometric Intervals: F = 10.8; sig. = 0.000; Standard Deviation: F = 11; sig. = 0.000. Results at the neighborhood scale of analysis: Quantile: F = 3.2; sig. = 0.026; Natural Breaks: F = 2.9; sig. = 0.034; Geometric Intervals: F = 3.8; sig. = 0.011; Standard Deviation: F = 3.7; sig. = 0.013

*Comprehension*

Although the tests of confirmation indicate the two data sets are statistically different, we then examined the data for comprehension. We used a Pearson's $r$ to test the strength of association between mean low neighborhood temperature and perceived temperature relative to others at the regional and neighborhood scales of analysis. Analyses report mixed levels of statistical significance between variable pairs (Table 17). For example, there is a relatively weak correlation between simulated temperature and social perceptions of temperature when analyzed at the regional scale ($r = 0.232$).

Alternatively, social perceptions aggregated to the neighborhood scale report a strong correlation to environmental conditions ($r$ = 0.636). Analyses show that survey responses aggregated to the neighborhood scale are congruent with local environmental conditions (respondents within a given neighborhood accurately perceived their neighborhood as relatively cooler or warmer); however, individual perceptions of temperature relative to others report a weak correlation with local temperature (individual respondents did not accurately perceive temperature in their neighborhood relative other others for the summer of 2005).

Table 17

*Pearson's Correlation Results for Perceived Relative Temperature Compared to Simulated Temperature at the Regional and Neighborhood Scales of Analysis*.

| Pearson's Correlation | N | Pearson's *r* | Sig (2-tailed) |
|---|---|---|---|
| Regional Scale | 767 | 0.232 | 0.000 |
| Neighborhood Scale | 40 | 0.636 | 0.000 |

**Media Analysis**

The final step of the analysis examined media coverage on summer temperatures for the summer of 2005 to determine whether the media may have influenced social perceptions on extreme heat throughout the Phoenix metropolitan area. A key word search of "heat advisory" and "heat warning" produced three primary media sources reporting on heat stress during the summer of 2005. Excerpts from news releases provided by the Arizona Department of Health and Services (ADHS) are presented in Table 18; the report by the Associated Press State and Local Wire is summarized in Table 19; and finally, Table 20 reflects excerpts of television broadcasts.

Table 18

*News Release Excerpts from Arizona Department of Health and Services for Summer 2005.*

| Date | Press Title |
|---|---|
| June 16, 2005 | Staying Healthy In Arizona's Deadly Summer Heat |
| *-With daytime temperatures stuck in triple digits, Arizona summers turn dangerous and deadly;*<br>*-Last summer, 34 residents died as a direct result of excessive exposure to heat;* | |
| July 18, 2005 | Health Department Urges Caution as Deadly Heat Grasps Arizona |
| *-These are some of the hottest days of summer and people need to be diligent about staying indoors, wearing light clothing, and drinking water;*<br>*-Young children and the elderly are also at greater risk to suffer from heat-related illness;* | |
| August 29, 2005 | Return Of Extreme Summer Heat Brings Deadly Dangers |
| *-Temperatures over 110 degrees means taking special precautions to protect ourselves and our loved ones from the risk of heat-related illness and death. The best way to combat this is to stay hydrated and out of the sun;*<br>*-People who work outdoors are at especially high risk. People that have outdoor occupations need to take more breaks and get more of their work done in the early morning hours if possible.* | |

Table 19

*News Reports by the Associated Press State and Local Wire on Heat in Phoenix, AZ for Summer 2005.*

| Date | Press Title |
|---|---|
| May 24, 2005 | Weather Service warns of problems associated with record heat |
| *-The heat is on in the Phoenix metropolitan area and authorities are warning residents of possible health problems associated with record-setting temperatures;*<br>*-The National Weather Service has issued an excessive-heat warning for the past four days since Friday with another heat advisory for Wednesday;*<br>*-Experts say a high of 109 degrees now is more dangerous than the same temperature in mid-July, when people's bodies have had a chance to acclimate to the heat.* | |

Table 20

*Excerpts from Global Broadcast on Heat in Phoenix, AZ for Summer 2005.*

| Date | News Provider |
|---|---|
| July 19, 2005 | CBS |
| *-Police say there were four more heat-related deaths today (Tuesday) raising the toll to twelve since the heat wave started Saturday;* *-At least ten of those who have died were homeless and the other two were elderly women;* *-Heat advisories and warnings are in effect as the temperatures hover around 113 degrees.* | |
| July 20, 2005 | Fox |
| *-At least two-dozen deaths are being blamed on the extreme heat in Arizona;* *-Officials say many of those who have died are illegal immigrants living in cramped quarters often without air.* | |
| August 5, 2005 | ABC |
| *-People who work outdoors are at especially high risk. People that have outdoor occupations need to take more breaks and get more of their work done in the early morning hours if possible.* | |

Analyses of the three media sources highlight some general trends. First, results indicate that heat advisories are applied at broad spatial scales, such as there is a heat advisory in Phoenix, Arizona from Saturday to Tuesday. Another trend is that the data communicate evidence of extreme heat and report outcomes of human health, e.g., *x* number of people have died as a direct result of excessive heat. A third finding is that the media source typically offers recommendations regarding individual decision-making, e.g., drink lots of water, stay in indoors or in the shade, wear light clothing. The message of the three media sources on extreme heat is consistent: use caution and be prepared. Although recent studies have found evidence of significant temperature variability within the same urban environment (Harlan et al. 2003; Ruddell et al. 2009), media reports are applied at broad (e.g., metropolitan) scales of analysis.

**Discussion**

This paper aimed to examine the effectiveness of a mixed method multi-scale research framework by investigating environmental conditions and public perceptions of temperature at regional and neighborhood scales of analysis in the Phoenix metropolitan area as a case study. Our analyses utilized both quantitative (WRF) and qualitative (PASS; Media Coverage) methods for examining temperature, and both techniques observed differences based on spatial scale. For instance, WRF simulations showed variable levels of exposure in temperature between regional and neighborhood scales. Similarly, perceived temperature also varied by spatial scale whereby respondents in some neighborhoods perceived their local environment as either cooler or warmer compared to regional trends for the summer of 2005. Thus, we first employed a single methodology (e.g., quantitative, qualitative) to examine physical and social dimensions of temperature at multiple scales of analysis, and found variable results.

An important objective of this study, however, was to apply the confirmation/comprehension framework at multiple scales of analysis. Utilizing physical and social data on temperature, we tested for confirmation via a chi-square test and found significant differences between observed and expected frequencies at the regional scale and modest differences at the neighborhood scale of analysis. While analyses showed a lack of empirical congruence between the methodological approaches, comprehension was enriched. Pearson's *r* compared environmental conditions to social perceptions and reported varying strengths of association based on spatial scale. For instance, there was a relatively weak correlation between environmental conditions and social perceptions at the regional scale; however, the strength of association was much stronger when aggregated to the neighborhood level. This research finding is significant in two ways: first, it suggests there may be an optimal level of aggregation on which to report environmental perceptions. Aggregating survey responses minimizes outlying perceptions while providing an average for each group (in this case a neighborhood). While there was a significant amount of variability when analyzing individual survey responses, aggregating responses at too broad of a scale (e.g., by municipality) may conceal interesting differences between groups. The second way in which this finding is significant is that the mixed method multi-scale framework allowed us to identify this observation. It would not have been possible to compare social perceptions with environmental conditions at multiple scales without employing this approach. Our contribution therefore is the introduction of the mixed method multi-scale research framework to help identify new and valuable research observations.

A review of the media analysis, however, may lend insight into social perceptions on extreme heat. The three sources of media coverage on extreme heat in the Phoenix metropolitan area for the summer of 2005 consistently reported on the broad regional scale of analysis. Although reports failed to specify where temperatures were the most or least intense within the Valley, the coverage on heat advisories may have influenced individual perceptions regarding neighborhood temperature. For instance, perceived neighborhood temperature reported a weak correlation with local environmental conditions when analyzing individual survey responses. While 51 percent of survey respondents believed their neighborhood was about the same temperature relative to others, simulated temperatures indicated that 82 percent of those interviewed lived in warm metropolitan neighborhoods. Thus, the general perception that a respondents’ neighborhood temperature is about the same as other metropolitan neighborhoods may have been influenced by media coverage reporting on the regional scale of analysis. Since there is significant temperature variability within urban environments, local media sources (e.g., neighborhood newsletter) may want to begin reporting information and strategies on extreme heat at intraregional spatial scales (e.g., neighborhood).

**Conclusions**

This study aimed to contribute to research on scale by building upon existing methods to understand physical and/or social processes. Specifically, we tested the effectiveness of a mixed method multi-scale research framework by examining temperature as one dimension of climate change in the Phoenix, AZ metropolitan area for the summer of 2005. Although analyses reported a lack of confirmation between the quantitative and qualitative methods employed in this study, our comprehension was enriched. Our research finding indicating that social perceptions of environmental conditions are more accurate at finer spatial scales compared to broader scales of analysis was only visible via the mixed method multi-scale research framework that we introduced and tested in this study. Moreover, it would not have been possible to identify this observation using existing methodological approaches. This case study on temperature, therefore, validates the effectiveness of the mixed method multi-scale research framework. So in addition to enhancing our comprehension of climate change and environment perception research, mixed method analyses has also contributed to understanding of research on scale.

# CHAPTER FIVE: SCALES OF PERCEPTION: PUBLIC AWARENESS OF REGIONAL AND NEIGHBORHOOD CLIMATE CHANGE

## About this Chapter

This chapter is a paper that has been submitted to *Risk Analysis*. The title of the article is “Scales of Perception: Public Awareness of Regional and Neighborhood Climate Change.” The authors are Darren Ruddell, Sharon L. Harlan, Susanne Grossman-Clarke, and Gerardo Chowell.

Increasing global temperature, particularly in cities, has precipitated an influx of research on climate change. While physical changes in climate are well documented (e.g., mounting temperature, sea level rise, retreating polar ice caps), social perceptions of climate are relatively under-researched. Understanding public perceptions, however, is critical for developing an effective strategy to mitigate the effects of human activity on the natural environment and to reduce human vulnerability to the impacts of climate change. While assessments of climate have traditionally examined broad spatial scales (e.g., global, national) as well as broad themes (climate), this paper investigated people’s perceptions of temperature within one urban area. Specifically, temperature is examined as one dimension of climate change by relating self-reported perceptions on temperature from a social survey of Phoenix, AZ (USA) metropolitan area residents to output from the Weather Research and Forecast (WRF) climate model. The analysis offers a comparison of perceived temperature with simulated temperature at the neighborhood and regional scales. Results indicated that residents are variably exposed to high temperatures throughout the Phoenix metropolitan area; public perceptions of temperature are more strongly correlated with proximate environmental conditions than with distal conditions; and perceptions of temperature are related to social characteristics and situational variables.

*Decision-makers operating in an environment base their decisions on the environment as they perceive it, not as it is—Harold Brookfield (1969)*

**Introduction**

Although human-induced climate change has been the subject of scientific investigation as early as the 1800s, only in the past few decades has the problem become widely recognized (Dunlap, 1998; Kowalok, 1993). One reason for increased concern is that changes in the physical climate have been accompanied by intensified weather patterns around the world, which, in turn, have increased human vulnerability to weather-related events (e.g., drought, flooding, extreme heat). Heat, for example, was the leading cause of death among weather-related fatalities in the US from 1995-2004 (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 and reveal the dangerous threat that extreme heat presents to human health and well-being. Scientists anticipate an increase in intensity, duration, and frequency of heat waves over the next century (Meehl and Tebaldi, 2004) and predict that illness, mortality, and displacement resulting from various environmental threats associated with climate change will pose a serious threat to public health throughout the world (Geller, 2003; McMichael et al., 2006; IPCC, 2007).

To help organize and implement effective strategies to reduce human vulnerability to global and/or local impacts of climate change (via mitigation or adaption), it is imperative to understand public perceptions of climate change. Public perceptions of environmental conditions are important, for it is assumed that such perceptions have a significant impact on policy-making (Kempton et al., 1993; Morgan, 1995). For instance, Leiserowitz (2006) notes that public support or opposition to climate policies (e.g., treaties, regulations, taxes, subsidies) are greatly influenced by public perceptions of the risks and dangers of global climate change. Although scholars have studied perceptions of climate change among scientists, policy-makers, environmentalists (Mazur and Lee, 1993; Ungar, 1992), and other stakeholders, studying public perceptions of climate change is critical because one cannot predict how people will respond to an issue without knowledge of how a given threat is perceived (Fischhoff, 1985).

Slovic and Peters (2006) argue that people act upon their perceptions by incorporating logic, reason, and scientific deliberation into their risk assessments and decision-making. An important factor in assessing risk is the way in which the public experiences a given risk. Events that proceed at slow and deliberate paces (e.g., global climate change), are typically associated with weak or placid public perceptions of risk for a given threat. Swift and/or fierce change (e.g., earthquakes, hurricanes, heat waves) often precipitate heightened perceptions of risk among the general public. 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 make decisions toward risk adaptation or mitigation based on catastrophic events rather than slow changes.

An individual's risk assessment is comprised of a complex linkage of awareness, concern, and perception of risk (Dunlap and Scarce, 1991). For instance, individuals develop perceptions of risk by obtaining awareness or knowledge on a particular event or process (e.g., extreme heat, wildfire, climate change). Awareness is often translated via experience, oral history, media coverage, observation, scientific research, among other forms (Uzzell, 2000). Individuals then assign or associate a level of concern for a particular threat. Concern is also couched by local context, such that residents living on or near a major fault-line express greater concern about earthquakes compared to residents living in areas with high incidents of hurricanes (Ho et al., 2008). As concern rises for a particular event or process, the perception of risk for a given environmental threat becomes more severe. Threats that are perceived as real and dangerous are more likely to be the focus of an action plan to reduce human vulnerability.

Physical changes in climate and social perceptions of climate operate at different spatial scales (e.g., global, regional, neighborhood) and, therefore, understanding these processes at various scales of analysis is important. For example, although the average global surface temperature increased by 0.74°C between 1906-2005, there is significant variability from region to region. Temperature changes in higher northern latitudes report rises ranging from 2-3.5°C but surface temperature in northern latitudes and the Antarctic show cooling trends of 0.2-1°C during this period (IPCC, 2007).

Scales of measurement also matter for predicting environmental perceptions. For instance, people express greater concern over global environmental problems compared to similar local problems despite the fact that individuals have significantly less influence over global problems (Ingold, 1993; Murch, 1971). Although some studies have recognized the global/local divide, there is a limited amount of research exploring relationships between global and local perceptions of environmental issues (Uzzell, 2000). Such an investigation, however, could yield critical information regarding the public's awareness of changing weather conditions in immediate and distant environments.

This article improves the current understanding of environmental perceptions by focusing on scalar differences in climate perceptions. Climate assessments have traditionally examined broad spatial scales (e.g., global, national) but this study investigated sociospatial variability in people's perceptions of climate within one urban area. Temperature represents a key variable in climate change scenarios due to the impacts it has on ecological processes (Geller, 2003) as well as its direct impact human comfort, health, and general well-being. 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 a wide range of climate regimes (e.g., desert, tropic) comprised of variable temperatures, people are highly sensitive to weather and climate as a result of physical interactions as well as social preferences and discussions on their local environment (IPCC, 2001; List, 2004).

Specifically, we analyzed self-reported perceptions of temperature from a social survey of Phoenix, AZ (USA) metropolitan area residents, and combined these data with output from the Weather Research and Forecast (WRF) climate model at the neighborhood and regional scales. The four following research questions are addressed in the analysis: *1) Is there a spatial pattern of temperature perceptions among residents throughout the Phoenix metropolitan area? 2) Does the pattern of temperature perceptions correspond spatially with scientifically-derived measures of temperature? 3) Is the correspondence 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?*

## Background

### Climate Change: Examining Spatial Scale

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) (IPCC, 2007). Although average annual global temperatures have steadily increased over the last 100 years, due to a variety of physical and anthropogenic causes, scientists have observed significantly warmer temperatures in urban areas compared to rising temperatures in rural areas (Brazel et al., 2000; Lowry, 1967; Oke, 1997). Processes associated with rapid urbanization such as impervious surfaces, urban vegetation, diverse building materials, and increased anthropogenic heat alter the surface energy balance (Oke, 1982; Arnfield, 2003). Surface cooling, for example, is inhibited by reduced outgoing long-wave thermal radiation due to the vertical structure of buildings, and sources of anthropogenic heat (e.g., vehicles, air conditioners, and industry) exhaust heat into the air near the urban surface (Grossman-Clarke et al., 2005). Urbanization produces what has been described as the urban heat island (UHI) effect, where cities experience higher nighttime temperatures and generally higher but more variable daytime temperatures than the surrounding less built-up areas (Lowry, 1967; Oke, 1997; Voogt, 2002).

While the UHI effect describes significant differences in regional temperature between urban and rural environments, recent studies have also identified significant temperature variability within the same urban area (Arnfield, 2003; Sheridan and Kalkstein, 2004; Souch and Grimmond, 2006). An emerging theme of research on urban climate systems is that UHIs comprise a range of microclimates created by heterogeneity of soil, vegetation, and engineered surfaces. Harlan et al. (2006) and Ruddell et al. (2009) document that neighborhood microclimates are associated with significantly uneven levels of human exposure to heat and health outcomes among residents of the Phoenix metropolitan area during the summers of 2003 and 2005, respectively. For example, 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. investigated the spatial distribution of extreme heat throughout 40 diverse Phoenix metropolitan neighborhoods in 2005, and findings indicated: 1) exposure to extreme temperatures (greater than or equal to 113°F) and self-reported heat-related illnesses were variably distributed throughout the region; and 2) exposure to extreme temperatures was correlated with land use and land cover. There is a pressing need, therefore, to examine fine-scale intraregional temperature variation and human exposure within an urban environment.

**Environmental Perception: Physical and Social Constructions**

Although the physical signs of changing climate are well documented (e.g., mounting temperature, sea level rise, retreating polar ice caps), social perceptions of climate are more elusive. Understanding public perceptions, however, is critical for developing an effective strategy to mitigate the effects of human activity on the natural environment and to reduce human vulnerability to the impacts of climate change. Aitken et al. (1989) observe that environmental perception is rooted in the local context of space and place whereby 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 theme focuses on the ecological dimensions of person-environment relationships, such as integrating knowledge of natural Earth processes and social perceptions. The second theme, derived from comparative research involving varied social and cultural groups, provides insight into the social and cultural relativity of perception.

Environmental perception literature provides a key link between perception and risk. Garcia-Mira et al. (2005), for example, explain that people perceive environmental problems (e.g., pollution, climate change) as serious threats when the problem poses an immediate risk. For instance, De Groot (1967) found that residents in North Carolina perceived air pollution with greater concern when it posed an immediate risk to their family or community, and that residents were likely to take abrupt and focused action to reduce immediate threats. Alternatively, the public is less likely to take action when an environmental problem is perceived as innocuous. Such tendencies may explain why a majority of Americans demonstrate high awareness to climate change, a strong belief that it is real, and high levels of concern about the issue, yet studies consistently show that Americans 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). Americans, in general, do not perceive climate change as a serious and immediate environmental threat to themselves.

The theoretical frameworks described above offer valuable insight into how individuals construct environmental perception. Environmental perceptions characterized through person-environment and ecological considerations are based on experience and exposure to environmental processes (Aitken et al., 1989). Perceptions of environmental problems (e.g., heat waves, hurricanes, earthquakes) vary depending upon local frequency and intensity of events. Perceptions of heat waves in cities such as Phoenix, Chicago, and Philadelphia, for example, are heightened based on recent experiences with extreme heat (Sheridan and Kalkstein, 2004). While human exposure to environmental processes helps construct perception, it is also important to compare social and cultural variation.

The second theoretical framework examines social and cultural components of individual environmental perception. Social and cultural consideration is critical when evaluating environmental perceptions, which are often built upon past inequities and injustices or political ideologies. Race and equity issues, for example, have been linked to perception studies with the hypothesis that non-white minorities have fewer resources to cope with environmental problems, and therefore, are more vulnerable to associated health risks (Brody et al., 2004). Demographic characteristics (e.g., gender, ethnicity, age) are also highly correlated with perceptions of climate change. Studies consistently show that women and racial minorities are more fearful of the risks of climate change (Bord et al., 1998; O'Conner et al., 1999), which corresponds to literature demonstrating that these groups are more concerned about other environmental threats (Kellstedt et al., 2008; Tuan, 1990). Environmental perception is tied to political affiliation as Lorenzoni et al. (2005) explain that public opinion on climate change has become a partisan issue where Democrats are significantly likely to favor actions in response to impacts of climate change while Republicans are somewhat less inclined to support government policies. Further, Zahran et al. (2006) found that persons of liberal ideology are more likely to regard climate change as risky, and are more likely to support costly risk mitigation public policies. Thus, experience with environmental conditions as well as social and cultural frames of reference help to explain individual constructions of environmental perception.

Another point regarding the literature on perceptions of climate change is the lack of research at fine spatial scales of analysis (e.g., intraregional). While some studies have examined climate perceptions at broad spatial scales (e.g., global, national) (Dunlap, 1998; Kempton et al., 1995; Leiserowitz, 2006; Mazur and Lee, 1993), others have compared environmental perceptions from global to regional scales of analysis (Leiserowitz, 2005; Murch, 1971; Uzzell, 2000). Notable findings indicate that people perceive nearby environmental problems as less serious than similar environmental problems in places farther away, unless the problem poses an immediate and dangerous threat. Thus, there is a human tendency to perceive environmental problems as increasingly severe risks the farther they are (geographically and temporally) from an individual (Stedman 2004). There is a need, however, to test this assertion with examinations of environmental perceptions at the micro scale, particularly since recent studies of urban climate suggest that temperature poses varying degrees of risk to people within urban microclimates (Harlan et al., 2006 and Ruddell et al. 2009).

Our first hypothesis is that, consistent with the person-environment framework, individual experience with the surrounding environment will predict environmental perceptions. Furthermore, experience will be a stronger predictor of perceptions at finer scales of analysis. The second hypothesis is that social and cultural frames of reference will predict heightened awareness to environmental problems, specifically for those groups that traditionally lack coping resources and therefore face greater risks from environmental hazards.

## Research Methods

### 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 percent of the state's 6.1 million residents (Census Bureau, 2006). 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 predictions indicate the region's future vulnerability to high temperatures will increase. The Center for Disease Control (CDC) (2005) recently reported that Arizona led the nation in heat-related deaths from 1993-2002. Upon examination of death certificates for the years

2005-2007, the Maricopa County Department of Public Health (county in which Phoenix is located) concluded that heat or heat exposure was a direct or contributing cause of 215 deaths (MCDH, 2008). Global climate change models agree that the desert southwest, including Phoenix, will become increasingly warmer and drier and will experience more frequent and intense heat waves (Diffenbaugh et al., 2005; Seager et al., 2006). Thus, risks of heat-related mortality and morbidity are likely to rise in the future.

Recent studies have observed warming temperatures throughout central Arizona. Brazel et al. (2000) found that average annual temperatures have increased 1.7°C in Maricopa and Pinal counties over the 20$^{th}$ century. While the Phoenix regional average annual temperature has risen steadily, temperatures in urban areas have increased by 4.2°C compared to an increase of 1.3°C in rural areas, representing a warming rate over three times higher in urban areas (Brazel et al., 2000). Hedquist and Brazel (2004) measured average nighttime maximum temperature variation on a rural to urban gradient equal to 7.3°C in 2001. According to the National Weather Service, the average number of heat days is also on the rise. High heat days are defined as local temperatures of 43.3°C (or 110°F) or higher. Phoenix reported an average of ten heat days per summer during 1971 to 2000; however, the summer of 2005 recorded a record 24 heat days only to be surpassed in 2007 with 33 heat days.

Historical conditions of temperature in the Phoenix metropolitan area, therefore, indicate that local temperature is changing much faster than global trends alone would indicate. In Arizona, urban centers have warmed faster than the rest of the state (Brazel et al., 2000), a pattern that seems to be occurring worldwide (Oke, 1997). Urban climatologists agree that the Urban Heat Island effect, which associates urban development and population growth with rising temperatures, is responsible for accelerating temperature changes in cities (Arnfield, 2003; Lowry, 1967; Taha, 1997; Voogt, 2002).

**Simulated Weather Conditions**

While some studies have observed a general increase in temperatures throughout the Phoenix metropolitan area, others have also noted significant temperature variability within the cities that comprise this region (Harlan et al., 2006; Jenerette et al., 2007; Stefanov et al., 2001). To investigate spatial temperature variability within the urban area, we used the meso-scale Weather Research and Forecast (WRF) model developed by the National Center for Atmospheric Research (NCAR) (Shamrock et al., 2005) to simulate local weather conditions. WRF considers various global, regional, and local factors to calculate surface air temperature at a height of 2 meters with a spatial resolution of 1 km.

WRF represents a highly sophisticated atmospheric climate model. The meso-scale model works by quantifying air temperatures via a complex computer code which considers intricate relationships governing the spatial and temporal state of the atmosphere (e.g., air temperature, pressure, specific humidity and wind speed). Advances in regional atmospheric models have significantly improved in terms of accurately simulating urban air temperature over the past 10 years, and today such models are widely employed to enhance scientific understanding of processes related to neighborhood scale climate and air quality (Taha, 1997; Civerolo et al., 2000; Seaman, 2000; Lin et al., 2008). Grossman-Clarke et al. (2005; 2008) demonstrated that a well-tested mesoscale model is suited to simulate air temperature variability in the Phoenix metropolitan region. The model output was compared to National Weather Service temperature readings with the simulations reporting close agreement to the local measurements (see Ruddell et al., 2009 for analysis of model validity).

Hourly temperatures were obtained for a four-day summer heat event from July 15 to 19, 2005. This temporal snapshot allowed us to examine spatial variability in local conditions throughout the Phoenix metropolitan area during a period of elevated risk to extreme heat for the entire region. The heat event period was identified by using the definition developed by Meehl and Tebaldi (2004) which considers historical temperatures to determine periods of extreme heat in a local context. We examined temperature readings from Phoenix, AZ's Sky Harbor International Airport (a commonly used regional weather station) to compare normal temperature variability (1961-1990) to present day (2005) conditions. Meehl and Tebaldi's (2004) criteria were used to identify periods of extreme heat, and our analyses indicated that local threshold temperatures were: T1= 45°C (113°F); and T2=42°C (108°F), where T1= the 97.5 percentile of the observed distribution; and T2= the 81 percentile. Temporal periods satisfying all three of the following conditions were considered to be extreme heat events: 1) daily maximum temperature must be above T1 for at least three days; 2) average daily maximum temperature must be above T1 for the entire period; and 3) daily maximum temperature must be above T2 for the entire period. According to these conditions, there were three periods of extreme heat in the Phoenix metropolitan area during the summer of 2005 (June 6-9; July 15-19; and August 1-3). This study examined the longest and most intense heat event of the year which was the four-day heat event from July 15-19.

**Sample Survey of Neighborhoods**

This study focused on 40 diverse neighborhoods that are part of the 2006 Phoenix Area Social Survey (PASS). Conditions in these neighborhoods were indicative of spatial distribution of temperature variability throughout the region. 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 social 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 percent 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, 2006). The survey was administered by the Institute for Social Science Research (ISSR) at Arizona State University from April 29 through September 27, 2006.

**Measures Used in the Analysis**

Two PASS questions were used as dependent variables in the study: “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)?” “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?” (“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. The first question measures respondents’ perceptions of how the climate in the metropolitan region is changing over time and the second question measures how respondents perceived their neighborhood thermal environment relative to others in the same urban area during the summer of 2005.

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: age (years), ethnicity (Anglo=0; minority=1), gender (male=0; female=1), and self-identified political ideology (liberal, moderate, conservative). Self-reported annual household income (log transformed) and time spent away from the Phoenix area in the summer of 2005 (1=not at all; 2=one month or less; 3=two to three months;

4=entire summer) measured coping resources that could enable residents to voluntarily reduce their exposure to hot summer weather. Experiences with living in Phoenix and in specific neighborhood environments were measured by three variables. Length of residency, signifying acclimation to the Phoenix climate, was based on how long each respondent had lived in the Valley (years). Household experience with heat-related illnesses in summer 2005 (no=0; yes=1) was used to measure the effect of experiential knowledge about temperature. Finally, the local temperature for each neighborhood during a summer 2005 extreme heat event derived from WRF was used as the scientifically-derived neighborhood condition.

**Procedures**

Data analyses were organized into 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. We used Moran's *I* 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 (Moran, 1950; Fotheringham et al., 2000):

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij} z_i z_j}{\left[\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right]\left[\sum_{k=1}^{n} z_k^2\right]} \qquad \text{Eq. (1)}$$

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 individual survey responses to perceived regional and neighborhood temperature questions from PASS. GIS was used to map those variables at a neighborhood (block group) scale congruent with the WRF-predicted temperatures. We used Spearman's rank correlation (Spearman's rho) to test the strength of empirical relationships between climate condition and perception. The final step of the analysis disaggregated the survey responses to perceived temperature questions in order to examine the predictors of individual responses, using local temperature and a suite of individual-level variables. We used two types of regression (multinomial logistic and ordinal) to investigate respondents' awareness of regional climate change and relative temperature in their neighborhood, respectively. Analysis of variance (ANOVA) (Neter and 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.

## Results

### Spatial Variability in WRF-Predicted Neighborhood Temperatures

The WRF-predicted mean average, mean high, and mean low temperatures for the Phoenix region for one four-day heat wave in July 2005 are presented in Table 21. The

"Mean" column represents daily average temperatures for the metropolitan region, with an average high temperature of 45.67°C (or 114°F), an average low of 30.87°C (88°F) and an average of 38.28°C (101°F), respectively. The range of mean averaged temperatures among the 40 neighborhoods was a difference of 4.97°C (or 8.9°F) between the warmest and coolest neighborhood. Mean low temperatures reported the greatest neighborhood range (5.16°C or 9.3°F), thus, indicating significant differences in exposure to variable temperatures within the metropolitan area. The variability among mean low neighborhood temperature is particularly interesting because Karl et al. (1993) found that minimum neighborhood temperatures often increase in cities faster than maximum temperatures.

A snapshot of temperature variability throughout the Phoenix metropolitan area is represented in Figure 10 as the surface air temperature at 2 meters (m) above the ground for July 17, 2005, at 5pm, 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 are concentrated west of downtown and in central Phoenix. Warm daytime temperatures are particularly significant in the central Phoenix area where the high concentration of buildings and impervious surfaces also correlate with the warmest minimum temperatures.

The spatial autocorrelation test, Moran's *I,* indicated mixed levels of statistical significance for the mean average, mean high, and mean low temperature readings for July 15-19, 2005 (Table 22). For example, mean average and mean low were statistically significant at the 90 percent confidence level, whereas the mean high temperature was randomly distributed across the 40 neighborhoods. Although results exhibit modest positive spatial autocorrelation, the 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, 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.

Table 21

*Simulated Mean Average, High, and Low Temperature (C) for July 15-19 2005.*

| Simulated Temperature (C) | Descriptive Statistics | | | | |
|---|---|---|---|---|---|
| | Mean | SD | Min | Max | Range |
| Mean Average | 38.28 | 1.08 | 34.65 | 39.62 | 4.97 |
| Mean High | 45.67 | 0.98 | 42.16 | 46.78 | 4.62 |
| Mean Low | 30.87 | 1.17 | 27.2 | 32.36 | 5.16 |

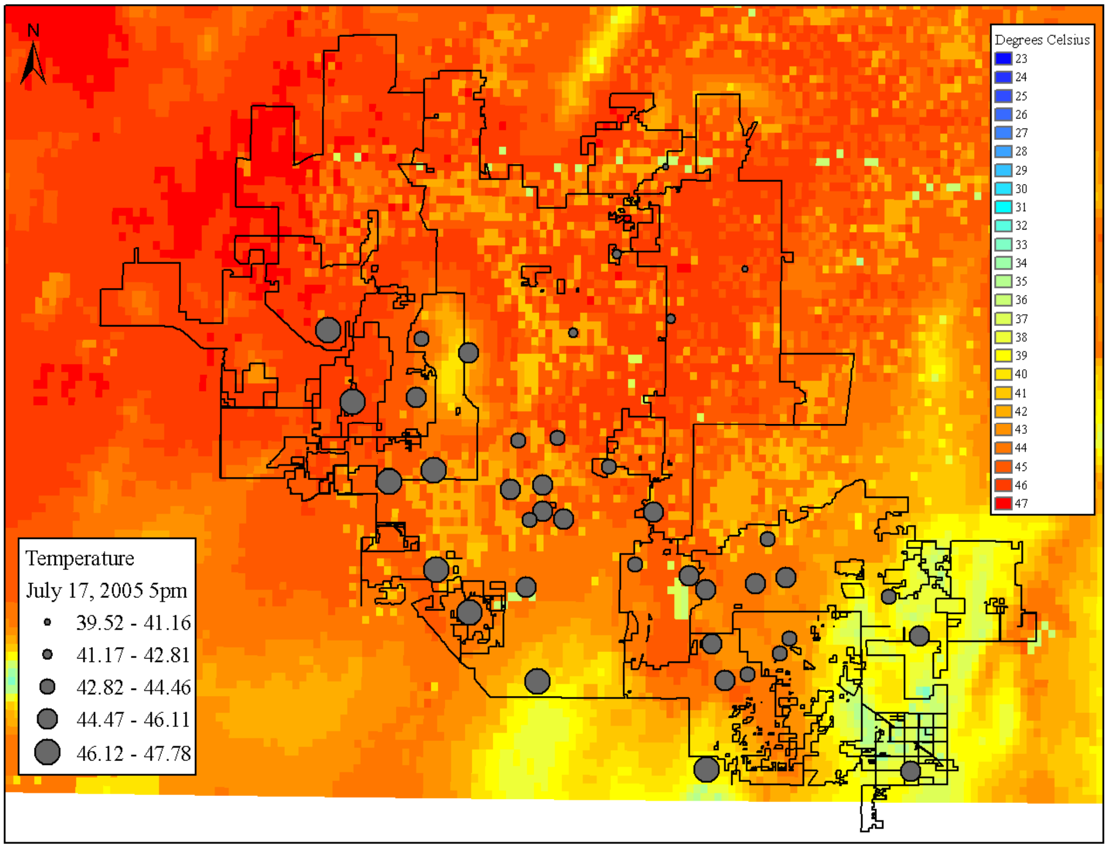


*Figure 10*: Simulated Air Temperature for the Phoenix, AZ Metropolitan Area for July 17, 2005 at 5pm.

Table 22

*Global Spatial Autocorrelation Results for Survey Responses.*

| Simulated Temperature | | Global Spatial Autocorrelation | | |
|---|---|---|---|---|
| | Mean (sd) | Moran's *I* | Z-Score | Significance |
| Mean Average | 38.28 (1.08) | 0.03 | 1.73 | 0.10 |
| Mean High | 45.67 (0.98) | 0.03 | 1.62 | Random |
| Mean Low | 30.87 (1.17) | 0.03 | 1.82 | 0.10 |

**Temperature Perceptions among Phoenix-area Residents**

There was wide agreement among survey respondents that the region is getting warmer over time: 82.1 percent said that it was getting a little hotter or a lot hotter (Table 23). Only 17.8 percent of respondents reported that temperature in the region was staying the same. About half (51 percent) thought their neighborhood was about the same temperature as other neighborhoods in the summer of 2005. Of the remaining respondents, however, 24.6 percent perceived their neighborhood was cooler than others and 24.1 percent believed their neighborhood was warmer.

An analysis of the survey responses aggregated at the neighborhood level indicates there is spatial variation in perception of whether the region is getting warming over time, as well as how respondents perceive temperatures in their neighborhood compared to the temperature of other Phoenix area neighborhoods for the summer of 2005 (Table 24). For example, Table IV shows the range of mean neighborhood responses for the two measures of temperature perception examined in this paper. Average neighborhood perceptions ranged from 1.71 to 2.61 on a 3-point scale, representing spatially varying perceptions that regional temperature is increasing over time.

Figure 11 illustrates the variable spatial distribution of average perceived temperatures throughout the 40 neighborhoods. In both maps, the circles represent aggregated responses for each neighborhood where larger circles reflect warmer/higher perceptions of temperature. The spatial distribution of perceived changes in regional temperature (map on left) generally follows a structured pattern in which neighborhoods near downtown centers perceived temperatures to be getting warmer while 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 urban neighborhoods perceived their neighborhood as cooler environments compared to the rest of the area, whereas respondents in fringe communities reported that their neighborhood is 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 was spatially significant, whereas the distribution of perceptions of relative neighborhood temperatures was spatially random (Table 25).

Table 23

*Descriptive Statistics and Frequency of Survey Respondents for Regional and Local Measures of Perceived Temperature during Summer 2005.*

| Dependent Variable | Descriptive Statistics | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Lot Cooler | Little Cooler | Same | Little Hotter | Lot Hotter | N | Mean | SD |
| Regional Temp Change | - | - | 17.8 | 46.6 | 35.5 | 774 | 2.18 | 0.709 |
| Neighborhood Relative Temp | 2.3 | 22.3 | 51.2 | 17.5 | 6.6 | 767 | 3.04 | 0.870 |

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

Table 24

*Descriptive Statistics for Perceived Temperature Responses Aggregated to Neighborhood Scale during Summer 2005.*

| Respondent Perceptions | Descriptive Statistics | | | | |
|---|---|---|---|---|---|
| | Mean | SD | Min | Max | Range |
| Regional Temp Change | 2.17 | 0.21 | 1.71 | 2.61 | 0.9 |
| Neighborhood Relative Temp | 3.04 | 0.31 | 2.35 | 3.70 | 1.35 |

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

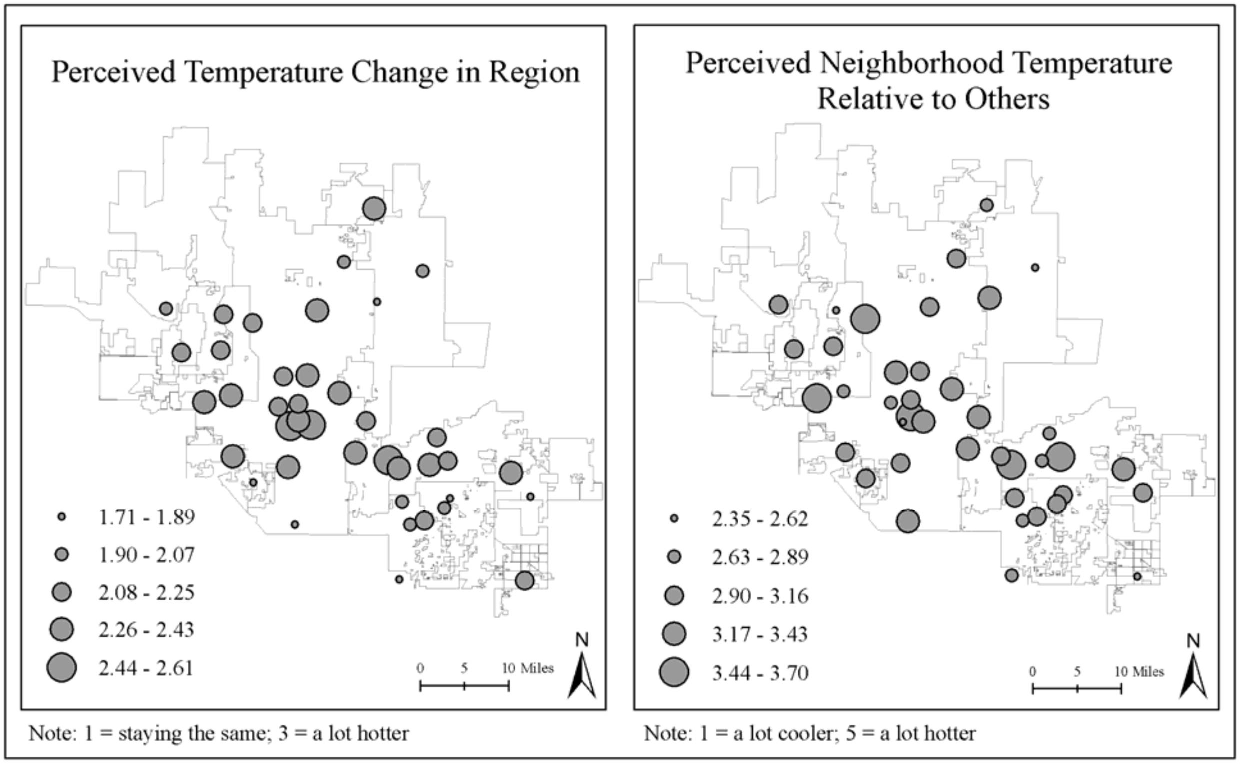


*Figure 11*: Survey Responses for Perceived Temperature in Phoenix, AZ Aggregated to Neighborhood Scale during Summer 2005.

Table 25

*Global Spatial Autocorrelation Results on Perceived Temperature.*

| Respondent Perceptions | Global Spatial Autocorrelation | | | |
|---|---|---|---|---|
| | Mean (sd) | Moran's *I* | Z-Score | Significance |
| Regional Temp Change | 2.17 (0.21) | 0.1 | 3.79 | 0.01 |
| Neighborhood Relative Temp | 3.04 (0.31) | -0.04 | -0.48 | Random |

**Correlation of WRF-Predicted Neighborhood Temperatures with Temperature Perceptions**

Spearman's rank correlation was used to compare neighborhood environmental conditions to social perceptions in the 40 neighborhoods. Tests indicate a modest association between the three measures of WRF-predicted neighborhood temperatures and respondents' aggregated perceptions of change in regional temperatures over time. On the other hand, predicted neighborhood temperatures had strong, positive and statistically significant correlations with respondents' aggregated perceptions of temperature in their neighborhood relative to others (Table 26). Strong relationships were evident for mean average, mean high and mean low WRF-predicted temperatures with perceptions for the 2005 heat wave. These results show that people exhibit greater sensitivity to environmental conditions (temperature) at the proximate neighborhood scale than to the more distal regional scale.

Table 26

*Spearman Correlation Comparing Perceived Temperature with WRF-Predicted Temperatures for Neighborhoods.*

| Bivariate Correlation | N | Spearman's rho | Sig (2-tailed) |
|---|---|---|---|
| *Regional Temp Change* | | | |
| Mean Average | 40 | 0.327* | 0.039 |
| Mean High | 40 | 0.333* | 0.035 |
| Mean Low | 40 | 0.262 | 0.102 |
| *Neighborhood Relative Temp* | | | |
| Mean Average | 40 | 0.470** | 0.002 |
| Mean High | 40 | 0.479** | 0.002 |
| Mean Low | 40 | 0.606** | 0.001 |

*Correlation is significant at the 0.05 level (2-tailed)
**Correlation is significant at the 0.01 level (2-tailed)

**Social Characteristics Associated with Perceptions of Temperature**

The final part of the analysis utilized multinomial logistic and ordinal regression to investigate how social characteristics, resources, and experiences are associated with individuals' perceptions of temperature. Descriptive statistics for the nine independent variables used in the equations are presented in Table 27. The regression model examining perceptions of regional temperature over time reports significant findings

(Table 28). Results are organized by respondents reporting “a little hotter” and “a lot hotter” with “not hotter” serving as the reference category. People who were significantly more likely to say it was a little hotter were more likely to be women, politically moderate or liberal, to have spent more summer time away from the Valley, and to live in neighborhoods with higher temperatures. Respondents reporting a lot hotter tended to be older, minorities, women, politically moderate or liberal, long-time residents, and to have experienced a heat-related illness in the household. Analyses indicate that a mixture of variables representing social frames of reference (e.g., age, ethnicity, gender, political affiliation), resources (e.g., time away), and experience (e.g., illness, length of residency, and mean low neighborhood temperature) are strong predictors of perceived temperature in the Valley.

Ordinal regression results on perceived temperature in own neighborhood relative to other neighborhoods are presented in Table 29. In contrast to perceived temperature at the regional scale, the only two statistically significant predictor variables were time away in summer 2005 and mean low neighborhood temperature. Specifically, the more time respondents spent away from the Valley during the summer of 2005, the more likely they are to report that their neighborhood was warmer compared to other Valley neighborhoods. Analyses of mean low neighborhood temperatures indicate that respondents who actually lived in relatively cooler neighborhoods were more likely to report that their neighborhood was cooler compared to other Valley neighborhoods. Age, ethnicity, gender, and illness do not appear to be related to perceived relative neighborhood temperature. Results suggest that situational variables – time away summer 2005 and mean low neighborhood temperature – are very strong predictors for perceived temperatures in the neighborhood.

Analyses of survey data, therefore, support our hypotheses and supply more insight into scales of perception. Neighborhood temperature, a scientifically-derived measure of an individual's experience with the surrounding environment, is a significant predictor of climate perception but the effect of experience on perception is much stronger at the neighborhood scale than at the regional scale. On the other hand, perception of climate at the regional scale is much better predicted by social frames of reference (i.e., age, gender, ethnicity, and political affiliation) than by neighborhood temperature. The social variables, however, do not predict perceptions about neighborhood climate differences. They are overwhelmed by the effects of resource/experience variables (i.e., time away summer 2005 and mean low neighborhood temp) at the more proximate scale.

Table 27

*Descriptive Statistics for Independent Variables*.

| Independent Variable | Descriptive Statistics | | | | |
|---|---|---|---|---|---|
| | N | Mean / Proportion | SD | Min | Max |
| Age (years) | 797 | 48.2 | 16.42 | 19 | 93 |
| Ethnicity (minority) | 791 | 0.27 | 0.45 | 0 | 1 |
| Gender (♀) | 801 | 0.56 | 0.49 | 0 | 1 |
| Political Affiliation [a] | 756 | 2.16 | 0.796 | 0 | 2 |
| Household Income [b] | 718 | 4.13 | 2.78 | 1 | 11 |
| Time Away Summer 2005 [c] | 786 | 1.80 | 0.635 | 1 | 4 |
| Residency (years) | 808 | 20.57 | 16.28 | 0.5 | 83 |
| Heat-Related Illness (yes) | 763 | 0.27 | 0.442 | 0 | 1 |
| Mean Low N'hood Temp (C) | 40 | 30.87 | 1.17 | 27.2 | 32.36 |

Note: [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) one month or less; (3) two to three 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 28

*Multinomial Logistic Regression Results for Perceived Temperature Change in the Region.*

| Variables | Parameter Estimates | | | | |
|---|---|---|---|---|---|
| | B | Std Error | Wald | Sig | Exp(β) |
| *Nagelkerke Pseudo $R^2 = 0.170$* | | | | | |
| **A little hotter** | | | | | |
| *Social Frames of Reference* | | | | | |
| Age | 0.027 | 0.039 | 0.477 | 0.490 | 1.027 |
| $Age^2$ | 0.000 | 0.000 | 0.482 | 0.488 | 1.000 |
| Ethnicity (minority) | -0.280 | 0.304 | 0.845 | 0.358 | 0.756 |
| Gender (♀) | 0.649 | 0.229 | 8.007 | **0.005** | 1.913 |
| Politically Moderate | -0.150 | 0.311 | 0.234 | 0.629 | 0.860 |
| Politically Conservative | -0.484 | 0.294 | 2.710 | **0.100** | 0.616 |
| *Resources* | | | | | |
| Income (log) | 0.003 | 0.439 | 0.000 | 0.995 | 1.003 |
| Time Away Summer 2005 | 0.365 | 0.221 | 2.730 | **0.098** | 1.440 |
| *Experience* | | | | | |
| Illness (yes) | -0.146 | 0.269 | 0.293 | 0.588 | 0.864 |
| Residency | -0.001 | 0.007 | 0.024 | 0.877 | 0.999 |
| Mean Low N’hood Temp | -0.171 | 0.101 | 2.892 | **0.089** | 0.843 |
| **A lot hotter** | | | | | |
| *Social Frames of Reference* | | | | | |
| Age | 0.095 | 0.043 | 4.936 | **0.026** | 1.099 |
| $Age^2$ | -0.001 | 0.000 | 5.168 | **0.023** | 0.999 |
| Ethnicity (minority) | 0.650 | 0.303 | 4.605 | **0.032** | 1.915 |
| Gender (♀) | 0.790 | 0.246 | 10.297 | **0.001** | 2.203 |
| Politically Moderate | -0.307 | 0.327 | 0.883 | 0.347 | 0.736 |
| Politically Conservative | -0.694 | 0.313 | 4.917 | **0.027** | 0.500 |
| *Resources* | | | | | |
| Income (log) | -0.734 | 0.467 | 2.476 | 0.116 | 0.480 |
| Time Away Summer 2005 | 0.056 | 0.232 | 0.059 | 0.808 | 1.058 |
| *Experience* | | | | | |
| Illness (yes) | 0.664 | 0.271 | 6.006 | **0.014** | 1.943 |
| Residency | 0.014 | 0.008 | 3.206 | **0.073** | 1.014 |
| Mean Low N’hood Temp | -0.005 | 0.117 | 0.002 | 0.963 | 0.995 |

Reference category: Not hotter
Note: We also analyzed mean average and mean high WRF-predicted temperatures and found similar results

Table 29

*Ordinal Regression Results for Perceived Temperature Relative to Other Neighborhoods.*

| Variables | Parameter Estimates | | | |
|---|---|---|---|---|
| | Est | Std Error | Wald | Sig |
| *Nagelkerke Pseudo $R^2$ = 0.093* | | | | |
| *Social Frames of Reference* | | | | |
| Age | 0.028 | 0.027 | 1.007 | 0.316 |
| $Age^2$ | 0.000 | 0.000 | 0.970 | 0.325 |
| Ethnicity (minority) | -0.278 | 0.198 | 1.970 | 0.160 |
| Gender (♀) | 0.089 | 0.158 | 0.317 | 0.573 |
| Politically Moderate | 0.212 | 0.200 | 1.122 | 0.289 |
| Politically Conservative | 0.028 | 0.194 | 0.022 | 0.883 |
| *Resources* | | | | |
| Income (log) | -0.371 | 0.298 | 1.558 | 0.212 |
| Time Away Summer 2005 | 0.393 | 0.151 | 6.817 | **0.009** |
| *Experience* | | | | |
| Illness (yes) | 0.092 | 0.173 | 0.281 | 0.596 |
| Residency | -0.007 | 0.005 | 2.127 | 0.145 |
| Mean Low N'hood Temp | 0.457 | 0.071 | 41.912 | **0.000** |

Link function: Logit
Note: We also analyzed mean average and mean high WRF-predicted temperatures and found similar results

**Discussion**

This paper examined simulated and perceived temperature as one dimension of climate change, and our findings offer four research contributions to risk analysis. Our first contribution substantiates variable levels of risk due to heat hazards within the same urban environment. The distribution of WRF-predicted temperatures indicates significant temperature variability within the Phoenix metropolitan area. We identified a largely heterogeneous spatial pattern regarding the distribution of daily average, high, and low temperatures throughout the study area. Although there has been a rise in average regional temperature over the last century and the number of high heat days has increased during the summer season, residents within the metropolitan area are exposed to varying degrees of intense conditions.

The second research contribution is the finding that there is spatial variability in perceived temperatures when individual concerns are aggregated to the neighborhood level. Individual perceptions of temperature in the region show that an overwhelming majority of respondents perceive the region to be getting warming over time; however, when individual responses are aggregated to the neighborhood level, results also indicate spatial variability in their concern. Whereas respondents in some neighborhoods perceive regional temperature to be staying the same over time, other neighborhoods report that the temperature is getting a lot hotter. When considering perceived temperature relative to others, analyses again report varying perspectives. The majority of respondents reported that temperature in their neighborhood is about the same as other neighborhoods for the summer of 2005. Nevertheless, responses aggregated to the neighborhood level reflect a variety of perspectives: some neighborhoods perceive their local environment as either cooler or warmer than others in the metropolitan area.

The third research contribution investigates the relationship between WRF-predicted temperature and perceived temperature aggregated to the neighborhood scale. Averaged neighborhood perceptions that temperature is changing over time has a modest correlation with modeled conditions of neighborhood temperature. In other words, respondents' perceptions of temperature largely align with environmental conditions. Alternatively, averaged perceptions of own neighborhood temperature relative to others exhibits a strong correlation to scientifically-derived temperature, which indicates that respondents living in relatively cooler neighborhoods perceive their local environment as relatively cooler while respondents in relatively warmer neighborhoods perceive their environment as relatively warmer. Analyses suggest that respondents are very sensitive to temperatures at the local neighborhood scale.

The fourth and final contribution of this paper explores social characteristics associated with perceived temperature. Analyses of survey data indicate that social characteristics (e.g., age, gender, ethnicity, and political affiliation) predict perceptions of changes in regional temperature, while resources (e.g., time away summer 2005) and exposure (mean low neighborhood temperature) predict temperature perceptions when comparing neighborhoods relative to others. Research findings verify previous studies regarding perceived temperature at broad scales of analysis. For instance, scholars (Bord et al., 1998; Hamilton, 2008; Lorenzoni et al., 2005; O'Conner et al., 1999) have noted differences among risk perceptions based on age, gender, ethnicity, as well as political affiliation, all of which have been described in social and cultural construction paradigms. Interestingly, however, such tendencies are overwhelmed when examining perceived temperature at the neighborhood scale of analysis. Thus, research findings suggest that social construction paradigms of risk perception may predict perceptions at broad or distal spatial scales, but do not always explain perceptions at fine scales of analysis (e.g., neighborhood). Moreover, this finding suggests that exposure and experience explain environmental perception at fine spatial scales.

**Conclusions**

Research on climate change is an increasingly important topic as scientists search for clues to better understand the changing physical climate as well as human experience and perceptions of climate change. This study is unique in three ways. Unlike most research investigating climate change, which examines environmental perceptions at large spatial scales (e.g., global or national), our efforts focused on social perceptions at the regional and neighborhood scales of analysis. Findings show significant intra-urban variability with respect to measured temperature and perceived temperature throughout the study area. The second aspect of this study that is unique is the focus on temperature as one dimension of climate change. Since climate change is highly complex and not fully understood, examining temperature as one aspect of climate change attempts to disentangle its various processes. The integration of physical and social data sources is the final characteristic that makes this study unique. While most studies either quantify environmental conditions or look only at social perceptions of climate change, this paper investigates the relationship between the quantitative and qualitative data sets. Results indicate mixed levels of congruence: while social perceptions correlate with measured conditions at fine spatial scales (the neighborhood), perceived temperature reports a weak association to environmental conditions at the regional scale.

Placing these findings within the context of current literature, we conclude that public perceptions of environmental risks become increasingly distorted as spatial scale broadens. Our study indicates that public perceptions of environmental conditions are highly correlated at fine scales where people experience a given process (in this case temperature), but as the scale of analysis increases public perceptions progressively rely on social frames of reference which report weaker association to environmental conditions. One of the difficulties in pursuing policy to adapt to or mitigate the impacts of climate change, therefore, is that global environmental problems (e.g., climate change) are largely perceived via social frames of reference rather than based on experience.

# CHAPTER SIX: CONCLUSIONS

## Overview

This study aimed to contribute to scale research in four ways. The first effort focused on synthesizing existing literature on scale among five dominant research themes in geography. The second way in which this dissertation contributed to scale research is through the introduction and evaluation of a new theoretical paradigm for operationalizing scale. The third component of this study investigated methodological frameworks for analyzing processes at individual or multiple scales of analysis, and introduced and tested the viability of a new mixed method multi-scale framework. The fourth contribution of this dissertation was a case study on scale which investigated physical and social dimensions of temperature at multiple scales of analysis. The following discussion summarizes the major findings of the dissertation while couching these results in the broader context of scientific research. The chapter then concludes with an overview of directions for future research.

## Summary of Findings on Scale

The review of literature on the ways in which scale is understood among five research themes in geography is the first contribution of this dissertation. The five research themes examined in the study (e.g., physical geography; human geography; MAUP; GIScience; and nature and society) help clarify the various definitions of scale, the ways in which scale is used and operationalized, as well as highlight current challenges in scale research. Analyses paid particular attention to theoretical conceptions and methodological frameworks geographers commonly employ in their investigations of scale-related issues. Although the five research themes explored in this paper reflect wide-ranging topics, there is considerable commonality among research themes. These similarities lend themselves to the integration of theoretical and/or methodological techniques employed in one sub-discipline to help resolve research challenges in another.

The second component of this dissertation investigated theoretical frameworks for operationalizing scale. Although research on scale ranges from physical to social processes at discrete to multiple scales of analysis, currently there are only two theoretical frameworks to operationalize scale (e.g., downscaling and upscaling). Our study discussed limitations of each of the existing frameworks while introducing and testing the hybrid framework. Research findings indicated that either of the existing theoretical frameworks is suitable when investigating single systems (e.g., physical or social processes) at discrete or multiple scales of analysis. Studies of complex processes (e.g., physical and social systems), however, require a hybrid framework. Analyses indicated that the hybrid model possesses the strengths of both the upscaling and downscaling models without the limitations. Specifically, the hybrid framework is a theoretical approach designed to synthesize data from multiple perspectives (e.g., top down and bottom up) at a common spatial resolution. This model also provides the platform to carrying out statistical tests which may yield new and innovative findings when studying a given process.

An investigation of methodological approaches to study issues of scale was the third part of this dissertation. This section identified two distinct research trends related to inquiries of scale. The first trend is that studies examining processes at multiple scales of analysis often identify non-linear relationships, thus it is important to examine a given process at multiple scales to gain a better understanding of the system. The second trend is that multi-scale studies have been limited to either quantitative or qualitative research frameworks. The problem, however, is that mixed method analysis provides a unique and enriching perspective on a process that is often compromised when employing either quantitative or qualitative approaches. Our paper tested the effectiveness of a mixed method multi-scale research framework, and results substantiated the value of integrating this new methodological approach.

The fourth contribution of this dissertation is a case study on scale which investigated climate change via physical and social measures at multiple scales of analysis. Scholars have investigated climate change at various discrete spatial scales (e.g., micro, regional, global) in addition to studying interactions across multiple scales for both physical and social systems. Research is limited, however, to either multi-scale studies utilizing quantitative or qualitative methods, or studies of single scales employing the mixed method framework. Our study examined temperature as one dimension of climate change at multiple scales of analysis by comparing environmental conditions to social perceptions (i.e., a mixed method multi-scale study). Results provided a unique perspective into research on climate change by indicating that the correlation between physical conditions and social perceptions varied by scale of analysis. Public perceptions of environmental conditions were highly correlated at fine spatial scales (where people experienced local temperature), but as the scale of analysis increased public perceptions reported weaker association to environmental conditions (by relying on social frames of reference rather than experience).

**Broader Implications of Study**

Although this dissertation offers four specific contributions to understanding scale, the results of this study provide a much broader contribution to the scientific community. Specifically, the unique research findings identified in this dissertation reflect theoretical and/or methodological integration among wide-ranging research techniques. For instance, the mixed theoretical approach discussed in chapter three represents an integration of quantitative and qualitative paradigms. Developing new theories helps drive scientific discovery by providing the framework to investigate outstanding research challenges from a fresh and innovative perspective. Science therefore continuously evolves as researchers build upon existing studies by developing and testing new theories and methodologies to investigate pressing research challenges.

This dissertation also contributes to better understanding complex socio-ecological processes, quality of life (QoL) research, as well as human health and vulnerability. Socio-ecological issues, for instance, present distinct challenges to the scientific community. Unlike naturally occurring variation among physical processes, socio-ecological issues represent changes in the physical environment that are a direct result of human activity. This dissertation investigated urban climate as a socio-ecological issue, and found significant variability with respect to the spatial distribution of temperatures as well as the perceptions of respondents living throughout the Phoenix metropolitan area. These findings provide clear evidence that human behavior is driving temperature change within urban environments in the form of urban heat islands.

Changes in the physical environment at regional and/or global scales of analysis are also correlated with Quality of Life (QoL). The overall assessment of the human experience is commonly expressed by the term QoL which has long been studied by individuals, universities, and governments across multiple disciplines including psychology, medicine, economics, geography, sociology, among others (Costanza et al., 2007). Although assessments of QoL have provoked considerable debate regarding its definition and measurement, it is generally accepted that QoL consists of two components: 1) one's physical environment; and 2) the quality of one's life in a personal sense (Rogerson et al., 1989). Scholars have identified a complex set of social and natural indicators of QoL organized around three fundamental and interdependent spheres of social life: the economy, society, and the environment (National Academy of Sciences (NAS) 2002). The environment, a particularly important and sensitive measure of QoL, is consistently ranked among the top issues that matter most for a good quality of life by Phoenix area residents (MI, 2004). This dissertation lends insight into QoL by identifying significant intraregional variability of physical and social measures of temperature.

The physical and social changes taking place within the Phoenix metropolitan landscape are closely aligned with issues of environmental justice as well as human health and vulnerability. Environmental Justice research refers to the unequal burden of environmental hazards among population groups (Pellow, 2000). This dissertation examined physical and social dimensions of urban climate within the Phoenix metropolitan area and found significant differences in hours of exposure to extreme heat among sample neighborhoods. High levels of exposure to the physical conditions of extreme temperatures increase human vulnerability to the negative health outcomes associated with heat stress (e.g., dehydration, exhaustion, sunstroke, among other symptoms). Exacerbating uneven levels of exposure to extreme heat are the resources and coping capacity residents employ to combat summer temperatures. For example, 2000 Census block group data (population density, median household income, age, and ethnicity) show significant differences in the social composition of the 40 sample neighborhoods. Residents living in the warmest neighborhoods had the highest population density, lowest household incomes, larger percentage of elderly, and were largely minority as compared to cooler neighborhoods. The Phoenix metropolitan urban heat island, therefore, represents an environmental justice issue due to the uneven burden of heat stress on low-income, elderly, and minority residents.

**Future Research**

The four primary components of this dissertation (e.g., an in-depth literature review, a theoretical discussion on scale, an examination of scale-related methodologies, and a case study on scale) have provided solid footing for future research efforts. Although this dissertation helped synthesize disjointed literature and illustrate the value of theoretical and methodological integration, many important issues remain unresolved. For instance, while this dissertation examined implications of scale via physical and social measures of temperature, additional studies on similar and different research topics would help validate research findings identified in this dissertation. A second area for future research is applying the mixed method multi-scale research framework on processes at broader scales of analysis. Despite the need to examine the implications of scale at regional and sub-regional scales of analysis, it would be interesting to compare the results of this dissertation to studies investigating processes at global and/or national scales. A third direction for future research is to investigate non-spatial scales of analysis.  While research on scale tends to focus on spatial scales of analysis, temporal and attribute scales may yield interesting results in analyses utilizing new theoretical or methodological techniques introduced in this dissertation.

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