SPATIO-TEMPORAL ASSESSMENT OF CLIMATE CHANGE VULNERABILITY IN GEORGIA AND ITS PREDICTION INTO THE FUTURE

by

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(Under the Direction of J Marshall Shepherd and Marguerite Madden)

ABSTRACT

The accelerated warming of the Southeast United States after the 1980s has affected the coupled human-environment system. Long term increases in temperature and precipitation, as well as more frequent and intense extreme weather and climate events are increasing vulnerability. Moreover, the most adverse impacts of climate change are manifested through these episodic extreme weather and climate events. Increasingly, climate change vulnerability assessment incorporating both long-term change in climate as well as episodic extreme weather and climate events is required to help individuals, communities and nations adequately prepare for the future.

The first objective of this dissertation provides spatial and temporal assessment of climate change vulnerability in the state of Georgia using historical temperature and precipitation records. A composite vulnerability index is prepared by combining social, climatic, and place-based components to quantify vulnerability. The second objective is to predict climate change vulnerability for the state of Georgia into the future by integrating projections of both climate and societal demographics, respectively. The third objective is to test the hypothesis that African Americans suffer a disproportionate burden of climate extremes. African American mortality from extreme temperature conditions is statistically-evaluated against White American mortality in the analysis.

The finding of this study reveals that both urban and rural counties in Georgia are at greater risk from climate change. Metro Atlanta counties and rural counties in southwest Georgia emerged as the most vulnerable and similar trend is projected into future. African Americans suffer most casualties due to the extreme climatic conditions compared to White Americans. This elevated mortality can be attributed to poor housing and low socioeconomic status of African American population.

INDEX WORDS: climate change, vulnerability, race, marginalization, extreme events, and projection

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A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2014

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DEDICATION

I would like to dedicate this dissertation to my husband Sudip Shrestha, my parents Kehar Singh Khatri and Samjhana KC, and my son Niket KC Shrestha.

ACKNOWLEDGEMENTS

I would like to acknowledge the United States Department of Agriculture Forest Service, NASA Precipitation Measurement Mission Program, and the Center for Geospatial Research.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Introduction

Climate change is a departure in the mean state of climate or in its variability that persists for a decadal time span (IPCC 2007). A differential rate of warming has been observed across the United States since the 1970s (Melillo *et al.* 2014). According to Karl *et al.* (2009), average temperature has risen by 1.1^{o}C in the Southeast United States since the 1970s. The Southeast United States include states namely, Georgia, Florida, North Carolina, South Carolina, Alabama, Mississippi, Virginia, Tennessee, and Kentucky. While maximum temperatures have increased, minimum temperatures have declined to the lowest levels since 1911. Such changes are also characterized by a significant decline in number of frost days per year (Melillo *et al.* 2014, Karl *et al.* 2009). Similarly, Tebaldi et al. (2012) report that the "warming hole," which is the slow warming in parts of the Southeast Unite States, including Georgia, has disappeared in recent decades. This observation is consistent with the warming trend in the Southeast. Southern cities such as Atlanta, Miami, New Orleans, and Tampa are already facing hot days and nights, and the decade of the 2000s was the warmest on record in the continental US (Zhou and Shepherd, 2010, Jones *et al.* 2013, Mellillo *et al.* 2014).

The Southeast United States is located in the transition zone between projected wetter conditions to the north and drier conditions to the Southwest (Mellillo *et al.* 2014). While much of the continental US had increased precipitation during the last century, the Southwest and the Southeast has proven to be less conclusive with areas of increased and decreased precipitation, respectively (Carter *et al.* 2014). There was an increase in very heavy precipitation events in the Southeast from 1958 to 2012 (Mellillo *et al.* 2014). At the same time, the Southeast was relatively drier with moderate to severe droughts (Manuel 2008, Seager *et al*. 2009, Pederson *et al.* 2012).

In addition to long-term increases in temperature and precipitation, studies show increased frequency and intensity of heat waves in recent decades (Easterling *et al*. 2000, Tebaldi *et al.* 2006, Zhou and Shepherd 2010). Furthermore, the Southeast, along with the southwest and midwest are predicted to experience more intense heat waves in the future (Meehl and Tebaldi 2004, Meehl *et al.* 2009, Kunkel *et al.* 2010) due to increases in both maximum temperatures and minimum temperatures (Dole *et al.* 2011, Otto *et al.* 2012, Rahmstorf and Coumou 2011). The heat waves would be intensified by urban heat islands at the local scale (Zhou and Shepherd 2010). Such changes result in decreased crop production and increased heat related mortality and morbidity (Changnon and Kunkel 1996). Shepherd and Knutson (2007) also suggest possible increased intensity of hurricanes.

1.2 Vulnerability Frameworks

Vulnerability frameworks have emerged from different schools of thought that emphasize various policy responses to climate change (Kelly and Adger 2000). Scholars distinguish between "starting and end point vulnerability". The end point approach as reviewed by Fussel (2005) and by O'Brien *et al.* (2007) estimates the residual impacts of a climate event or disturbance to society, after adaptation is determined. The starting point approach, defines vulnerability as a pre-existing state, generated by socio-economic processes that determine the ability of societal members to respond to environmental stresses. O'Brien *et al.* (2007) refer to the starting and end point approach to vulnerability as "contextual" and "outcome" vulnerability, respectively. “Outcome” vulnerability can be quantified, measured and reduced through adaptation measures, for example, by reducing greenhouse gas emissions. In contrast, the “contextual” perspective frames human vulnerability to climate change as a transformative process and defines vulnerability as a broader state of being, related to a host of factors that make people more susceptible to loss. It is influenced by dynamic social, economic, political, institutional, and technological structures and processes. Adger and Kelly (1999) suggest incorporating the ‘architecture of entitlements’ into vulnerability structures. This paradigm represents access to (not simply the presence of) available resources which allow people to cope with and adapt to stress.

Vulnerability has been viewed as biophysical vulnerability, which is the first order impact from natural hazards (Brooks 2003) and social vulnerability, which has to do with the internal characteristics of a social system (Kelly and Adger 2000, Cutter *et al.* 2003, Emrich and Cutter 2011, Reams *et al.* 2012). The biophysical vulnerability is viewed as outcome associated with the physical component, that is, the nature of the hazard (frequency and intensity) and its first-order physical impacts on human or social well beings measured in terms of monetary cost, human mortality, and ecosystem damage. Social vulnerability is commonly viewed as the state or internal characteristics of the system before it encounters any disaster events and exists independent of their occurrences. Social vulnerability can be determined at the individual or collective level by factors such as poverty and inequality, marginalization, food entitlements, access to insurance, and housing quality (Blaikie *et al.* 1994, Adger and Kelly 1999, Cross 2001). These studies point to poverty as a driving factor in vulnerability (O’Brien *et al.* 2007).

Vulnerability also depends on where populations choose to live or are forced to live due to various circumstances. For example, the people residing in the coastal region in the United States are primarily wealthy population (not the marginalized community) with high socioeconomic status (Pielke *et al.* 2008). However, they are most vulnerable to flooding due to sea level rise and storm surge from hurricanes. The starting point and end point approach as defined by Kelly and Adger (2000) and O'Brien *et al.* (2007) are blurred when we consider the hazard-of-place model of Cutter (1996), Heinz Center of Science, Economics and the Environment (2000) and Cutter *et al.* (2003). In addition to social factors, they also consider inequalities of place - characteristics of communities and the built environment, such as level of urbanization, growth rates, economic vitality and its geography (proximity, elevation). Collectively, this is known as the hazard-of-place model (Cutter 1996, Cutter *et al.* 2003, and Heinz Center of Science, Economics and the Environment 2000). Hazard-of-place models couple the human and environment systems. Polsky *et al.* (2007) urge vulnerability assessments to be carried out with "*biophysical, cognitive, and social dimensions*". Based on this framework, vulnerability of human-environment systems is due to exposure, sensitivity and ability to adapt, which is similar to the IPCC (2007) definition of vulnerability. Hence, the dissertation paradigm is derived from the IPCC (2007) framework of vulnerability.

1.3 Study Area

This study focuses on Georgia, one of the fastest growing states in the nation. The state of Georgia covers an area of 148 sq. km and consist of 159 counties. Much of the state's population growth and economic expansion in recent decades has centered in and around metropolitan Atlanta counties in the north part of the state (Hartshorn and Ihlanfeldt 2000). In the southern part of the state, the economy is linked to agricultural production and in general counties in that part of the state are poorer than those in the northern part of the state.

Georgia's 2010 population is 9,687,653. From 2000 to 2010, Georgia's population increased by 18.3 percent (compared to a national population increase of 9.7 percent for the same period) (U.S. Census Bureau 2011); and Georgia ranked tenth in terms of percent change in population from 2010 to 2012 (U.S. Census Bureau 2012b). Georgia still contains a substantial number of rural, "Black Belt" counties, mostly in the southern part of the state, with resource-based industries as an economic mainstay (Wimberly and Morris 1997). Despite the Great Migration of African Americans to the North in the early 1900s following the Civil War in the United States, many blacks returned to South in the 1970s, and a majority of the African American population still remains concentrated in the Southern states (Tolnay 2003).

The Black Belt is a band of mostly rural counties stretching from southern Virginia down through the Carolinas, Georgia, Alabama, Mississippi, and over to east Texas. This region has higher than average percentages of African-American residents (Wimberly and Morris 1997, McDaniel and Casanova 2003). African Americans residing in this region have relatively higher poverty compared to the rest of the United States (Hoppe 1985, Falk and Rankin 1992, Falk *et al*. 1993), and a notable gap persists in social well-being of African Americans in this region compared to Whites and even African Americans outside this region (Doherty and McKissick 2002, Webster and Bowman 2008). Importantly, the historically-rooted, racial bifurcation of the state's population into "black" and "white" subcultural groupings has given way to a significant third force, manifested as the unprecedented growth in immigrant/migrant populations of both Hispanics and Asians across Georgia (Zúñiga and Hernández-León 2001, Yarbrough 2007). Between 1990 and 2000, Georgia's Hispanic population increased 324 percent and 96.1 percent from 2000 to 2010; Asians increased 155 percent and 82 percent, respectively, during these decades (U.S. Census Bureau, 1990, 2000a, 2000b, 2002, 2012a).

1.4 Research Objectives

Vulnerability research stemming from the hazards literature accounts for the amount of potential damages from an unexpected climate-related event or hazard (Nicholls *et al.* 1999, Patt *et al.* 2010). Vulnerability in relation to specific hazards, for example, floods (Baum *et al*. 2008), drought (Wilhelmi and Wilhite 2002, Nelson and Finan *et al.* 2009), heat waves (Reid *et al.* 2009), and hurricanes (Frazier *et al.* 2010) have been targeted to examine the effect of these events on services and functions such as water supply (Barnett *et al.* 2008, Dawadi and Ahmad 2012), food security (Bohle *et al.* 1994), or public health (Guan *et al.* 2009, English *et al.* 2009). However, limited studies have been performed that integrate long-term change in climate, episodic hydroclimatic events, social vulnerability and place.

The major goal of this dissertation is to develop an integrated approach to climate change vulnerability assessment and to determine whether racial minorities are disproportionately affected by climate change and variability. The specific objectives are as follows:

Objective 1

The first objective of this dissertation is to perform a spatio-temporal assessment of climate change vulnerability in the state of Georgia from 1980 to 2010. Vulnerability is assessed at county level in decadal spans. The research provides answers to following questions:

1) How can a composite vulnerability index be derived using social and climatic components?
2) How has climate change vulnerability changed spatially over time (1980-2010) in the state of Georgia?

Objective 2

The second objective is to project climate change vulnerability in the state of Georgia into the future, specifically the 2030s (2025-2034). Vulnerability projection is performed at the county level by combining future climate projections with socioeconomic projections. This objective seeks to answer the following questions:

1) Can the future climate vulnerability of Georgia be projected?
2) How can we project social vulnerability into the future?

Objective 3

The third objective is to determine the impact of climate change on a marginalized racial group, specifically the African American population. A state level analysis is preformed from 1969-2008 to test whether African Americans suffered excessive mortality due to extreme heat and cold compared to White Americans. This objective answers the following research questions:

1) Are socially marginalized groups more likely to bear the brunt of climate change and extremes?
2) How is the mortality rate changing at state level both spatially and temporally?

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CHAPTER 2

SPATIO-TEMPORAL ASSESSMENT OF CLIMATE CHANGE VULNERABILITY IN GEORGIA[1]

2

[1] KC, B., J. M. Shepherd, and C. Johnson Gaither (2014). Spatio-temporal Assessment of Climate Change Vulnerability in Georgia. To be submitted to *Southeastern Geographer*.

Abstract

Climate change is occurring in the Southeast United States and one manifestation is changes in frequency and intensity of extreme events. A vulnerability assessment is performed in the state of Georgia (United States) at the county level from 1975 to 2012 in decadal increments. One unique aspect of this project is we combine climatic, social, land cover and hydrological components into a unified vulnerability assessment capturing both long-term as well as hydroclimatic events. Climate change vulnerability indices are derived for the 1980s, 1990s, 2000s, and 2010s. Exposure is measured as departure in decadal mean temperature and precipitation against baseline temperature and precipitation (1971-2000) using the United States Historical Climatology Network version 2.5. Exposure is also measured with extreme hydroclimatic hazards indicated by flood, heat wave and drought events. Sensitivity and adaptive capacity are measured by well-established methods using socioeconomic variables. Impervious surface and flood susceptibility area are also incorporated to account for place-based vulnerability. Overall climate vulnerability is measured by combining background climate (departure in decadal mean temperature and precipitation), extreme events, socioeconomic and demographic variables, and geography.

Greater anomalies in temperature and precipitation with an overall trend towards drying and warming have been observed. The anomalous cooling period in Georgia during the 1970-1980 period as well as the post-1980 warm-up have been captured in the recent decades with a clearly established increase in extreme hydroclimatic events. Climate vulnerability is highest in some metropolitan Atlanta and coastal counties. However, the southwestern region of Georgia, and part of the rural Black belt running through Georgia’s mid-south region are found to be especially climate change-vulnerable.

2.1 Introduction

Vulnerability to climate change is the degree to which a system is adversely affected by climate related stimuli and its inability to cope with them (IPCC 2007). It is typically characterized as some function of exposure, sensitivity, and adaptive capacity (equation 1). We conceptualize climatic variations as a measure of system exposure, for example in terms of biogeophysical impacts to the system. Sensitivity is understood as the effect of variations on human capabilities within the system, and adaptive capacity is the ability of a system to adjust to climate related stimuli (IPCC 2007). The physical causes, that is, exposure and their effects are explicitly defined, and the social context is encompassed by the notions of sensitivity and adaptive capacity in IPCC (2007). The IPCC's Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) report (IPCC 2012) and (IPCC 2014) provide a slightly different approach to vulnerability such that exposure (referred to as the location of people, livelihoods and assets) and vulnerability are determinants of disaster risk.

$$\text{Vulnerability} = f\,(\text{Exposure, Sensitivity, and Adaptive Capacity}) \qquad (1)$$

This study focuses on climate change at the county level in Georgia, considering both biophysical and socio-demographic indicators of vulnerability. In terms of biophysical measures, we propose a vulnerability index that captures both longer-term changes in precipitation and temperature as well as episodic events such as floods, heat waves and drought events. The index includes pertinent socio-demographic and topographical variables indicating humans' abilities to absorb or withstand biophysical manifestations of climate change. A number of studies have considered both the biophysical and social dimensions of climate change, but ours is one of the first to include both background (or longer-term) indicators of climate change with measures of episodic events (Azar and Rain 2007; Gbetibouo and Ringler 2009; Emrich and Cutter 2011).

Socio-demographic changes have important implications for climate hazard preparedness among Georgia's sub-populations. The IPCC Fourth Assessment Report (2007) states that climate change impacts will vary not only according to climate and geography but also by socio-demographic groupings because of the variation in human communities' ability to anticipate, withstand, and recover from natural disasters. The remainder of this paper discusses populations that are at greater risk for climate hazard exposure, conceptualizations of climate change vulnerability and its measurement, the development of a climate change vulnerability index, and the implications for hazard assessment.

2.2 Hazards and Vulnerability

Both urban and rural populations are confronted by climate change through complex feedback mechanisms affecting infrastructure, economic, social, and political systems. Extreme precipitation increases flood risks as well as disease spread via vector-born microbes. Flood risk is more frequent in urban areas where built environments alter the hydrology and geomorphology of streams (Reynolds *et al.* 2008). The impact is more severe in poor households without insurance coverage to rebuild homes (Coninx and Bachus 2007). O'Brien and Leichenko (2000) draw on Castells (1998) and Jargowsky (1997) to discuss how climate change and globalization act simultaneously as "double exposures" among poor residents of large cities to increase the spatial concentration of poverty within central city areas. In addition to increased flood and disease risks, urban areas are also more vulnerable to the heat-related manifestations of climate change because of urban heat islands (UHI), which concentrate solar energy and "waste heat" from sources such as automobile exhaust to heat up downtown areas in particular (Zhou and Shepherd 2010; Uejio *et al*. 2011). According to Zhou and Shepherd (2010), heat islands amplify extreme heat events by slowing nocturnal cooling. Also, in their examination of Atlanta, Georgia's heat island and heat extreme in the city, the authors found that a heat wave occurred in one-half of the years 1984 to 2007, and the average duration was roughly two weeks. Urban Heat Islands, together with heat waves, have a more detrimental effect on neighborhoods where there are few trees and shrubs to regulate temperature and in areas where residents are less likely to be able to afford health insurance or air conditioning. Because some urban racial/ethnic minority communities tend to have relatively less vegetation than more affluent White communities, the former may be more vulnerable to both gradual and episodic heat events (Schultz *et al*. 2002, Williams and Collins 2004, Morello-Frosch *et al*. 2009).

As indicated, rural economies in the South are still largely dependent upon resource-based industries, which are very sensitive to changes in temperature and precipitation. Temperature and precipitation alter the length of growing seasons (Wolfram and Roberts 2009; Malcolm *et al.* 2012) and extreme events, such as heat stress and frost, may lead to total crop failure. Social vulnerability also plays a crucial role here because socio-economic and institutional preparedness determine whether an agricultural drought transforms into an "economic drought." Hispanics have largely replaced African Americans as laborers in Georgia's various rural, low-skilled industries, including agriculture and timber (McDaniel and Casanova 2003). The precariousness of undocumented immigrants with limited English language proficiency, in particular, increases with their employment in climate-dependent industries (Arcury and Marín 2009; Chow *et al.* 2012). For instance, McDaniel and Casanova (2003) detail the arduous working conditions and exposure of Hispanic work crews to weather, climate, and terrain in the Southern forest industry. As well, temperature extremes affect human health, especially for elderly populations, and those with pre-existing medical conditions such as cardiovascular and respiratory illnesses (Knowlton *et al.* 2009; O'Neill *et al.* 2005). Age will continue to be an important factor in climate vulnerability, given the increase in projected heat waves and elderly populations in the United States population (Karl *et al.* 2009; Melillo *et al.* 2014).

Finally, less educated populations are more likely to have low socioeconomic status and be more sensitive to climate variability as they are less likely to have risk management strategies such as health insurance. Also, Hayward et al. (2000), Bullard, (2008) and Wilson *et al.* (2010) noted that racial/ethnic minorities bear an unequal health burden resulting from climate extremes resulting from low socioeconomic status or racial differences relating to housing characteristics, access to healthcare, and differential prevalence of certain predisposing medical conditions. Race has been seen to modify the effect of heat on mortality, with consistently higher deaths among African Americans in several studies (O'Neill *et al.* 2003; Medina-Ramon *et al.* 2006; Kaiser *et al.* 2007).

Vulnerability has been viewed as biophysical vulnerability, which is the first order impact from natural hazards (Brooks 2003) and social vulnerability, which is the internal characteristic of the system (Adger 1999; Kelly and Adger 2000; Cutter et al. 2003; Emrich and Cutter 2011). Kelly and Adger (2000) suggest incorporating the 'architecture of entitlements' into vulnerability structures, that is, people's access to (not simply the presence of) available resources which allow them to cope with and adapt to stress. Scholars distinguish between "starting and end point vulnerability". The end point approach as reviewed by Fussel (2005) and by O'Brien et al. (2007) measures the residual impacts of climate change after the adaptation is determined, as opposed to the starting point approach, which sees vulnerability as a pre-existing state generated by socio-economic processes that determine the ability to respond to stress. These studies point to poverty as a driving factor in vulnerability. Our aim is not to debate which school of thought is superior; instead, our focus is to quantify vulnerability by integrating coupled human-environment systems and provide a more holistic approach rather than isolating outcome from contextual vulnerability. We integrate place based vulnerability (geographic vulnerability), social vulnerability and biophysical vulnerability together following IPCC (2007) and Cutter *et al.* (2003) vulnerability frameworks.

We have developed a novel climate change vulnerability methodology by coupling indicators of long-term climate vulnerability with measures of extreme climate events (i.e., tails of the distribution). To these biophysical factors we add indicators of pre-existing social vulnerability (e.g., age, poverty, and race). However, in the SREX (IPCC 2012) and IPCC (2014) frameworks, vulnerability is considered independent of physical events, and the social vulnerability is explicit. We are using a pre-SREX vulnerability framework, but we understand that in the context of the SREX and IPCC (2014) frameworks our vulnerability metric would be partly considered disaster risk. Since we are characterizing long term climate change coupled with extreme weather and climate events, and our goal is a first order estimate of vulnerability and the framework that we use here, based on literature, is still viable for this type of analysis. The assessment is performed by decade, at the county level in Georgia from 1975 to 2012.

2.3 Data and Methods

We operationalized the IPCC's climate vulnerability equation (1) using our vulnerability framework shown in figure 2.1. The vulnerability framework includes mean temperature and precipitation and extreme weather hazard events as the climatic exposure and social vulnerability as sensitivity net of adaptive capacity. Geographic vulnerability (for example settlement in flood zone and built up environment) is also included in the overall vulnerability.

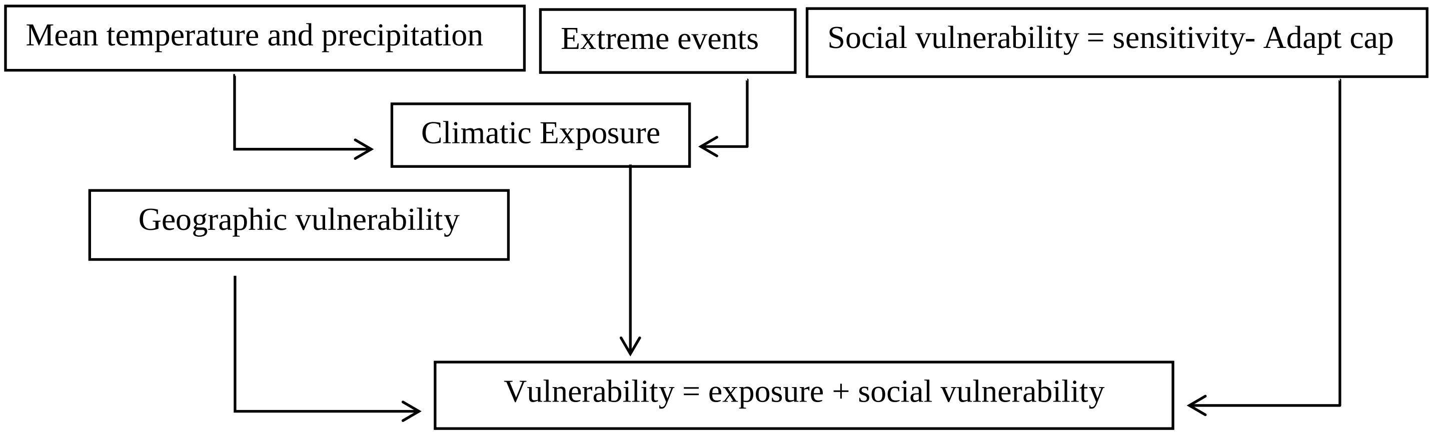

Figure 2.1: Flow chart of climate change vulnerability framework used in this study

For exposure variables, historical climate data were downloaded from the National Oceanic and Atmospheric Administration's (NOAA's) United States Historical Climatology Network (USHCN), which includes Cooperative Observer Program (COOP) stations. Version 2.5 temperature and precipitation data (Menne *et al.* 2009) were obtained for 77 stations including 23 stations in Georgia and 54 stations in neighboring states from 1971 to 2012. Temperature and precipitation values, respectively, were averaged for 10-year periods -1975-1984, 1985-1994, and 1995-2004 to represent decadal periods (e.g., 1980s, 1990s, and 2000s except for 2010s which includes only 8 years average 2005-2012). These decadal spans are centered on the census data sets of 1980, 1990, 2000 and 2010. We chose to perform the climate change analysis starting at 1971 for two reasons. First, cooling preceded the rapid warming after mid 1970 (Tebaldi *et al.* 2012). Second, consistent socioeconomic variables for each decade were available only after 1980. For each of the stations, baseline temperature and precipitation were also calculated for a 30-year period (1971-2000).

The extreme hydroclimatic event (or tails of the distribution) variability is indicated by frequency of occurrences of flood, heat wave and drought from 1975 to 2012. We used NOAA's divisional Historical Palmer Drought Severity Index (PDSI) (Palmer 1965) measuring the duration and intensity of the long-term drought. PDSI values less than -3 (indicating severe to extreme drought conditions) were considered to measure drought frequency. Similarly, flood and heat wave data were obtained from the SHELDUS (Hazards & Vulnerability Research Institute 2013), which provides a county-level hazard database (http://webra.cas.sc.edu/hvri/products/sheldus.aspx). We only included heat wave, drought and flood to measure extreme climate events because a strong linkage between these events has been well established through scientific studies (IPCC 2007; Wigley 2009; Karl et al. 2009; Seneviratne *et al.* 2012). These events in SHELDUS data were originally taken from National Climatic Data Center, Asheville, NC, "Storm Data and Unusual Weather Phenomena." They were comprised of events with more than $50,000 in losses (1990-1995) and every fatal event; whereas between 1960 and 1989 and since 1995, all loss causing events (no thresholding) were included in the database. For events that covered multiple counties, the dollar losses, deaths, and injuries were equally divided among the affected counties.

Variables measuring “sensitivity” and “adaptive capacity” are consistent with those discussed in the literature (Adger 1999; Kelly and Adger 2000; Cross 2001; Cutter et al. 2003; Cutter and Finch 2008; Wood et al. 2010). These data were acquired from the United States Census Bureau (socio-demographic variables), American Medical Association (physician availability), United States Department of Agriculture-National Agricultural Statistics Service (irrigated land), and United States Bureau of Economic Analysis (per capita income). People with limited mobility, racial/ethnic minorities, persons of low socioeconomic status (US Census Bureau), or those that are natural resource dependent (e.g., agriculture, forestry, fishery, and mining) increase the sensitivity of the social system to climate change. On the other hand, education establishes a path for attaining upward occupational, economic, and social mobility. Hence, populations with a bachelor's degree, adequate availability of physicians (indicated by the American Medical Association's physician to population ratio) and per capita income increase the adaptive capacity of the social system to recover from adverse effects of climate change. Similarly, irrigated land provides farmers with coping resources in drought conditions. The climate and social variables used to measure exposure, sensitivity and adaptive capacity are listed in Table 2.1.

Table 2.1: Climatic and social variables used to measure exposure, sensitivity and adaptive capacity to climate change

Exposure	Sensitivity	Adaptive capacity
temperature change	age group > 65	physician to population ratio
precipitation change	age group < 5	education
drought	poverty	per capita income
flood	racial/ethnic minorities	irrigated land
heat wave	occupation	
	urban / rural population	
	female headed household	
	inmate population	
	non- English speaking	
	Unemployment	
	renter population	
	mobile home residence	

Apart from socioeconomic vulnerability, geographic vulnerability is considered. This type of vulnerability is described as "hazard of place" by Cutter (1996), Cutter et al. (2000) and Cutter et al. (2003). Coastal counties are more vulnerable to floods compared to inland counties because they are in high flood risk zones. Similarly, a high percentage of impervious surface coverage indicates areas vulnerable to flooding, urban heat island effects, and heat stresses (Zhou and Shepherd 2010; Shepherd *et al.* 2011). The higher the percentage coverage of special flood hazard areas and impervious surface in a county, the greater is the geographic vulnerability. High flood risk areas requiring mandatory flood insurance purchase are identified from Federal

Emergency Management Agency (FEMA) flood maps. Special flood hazard zones A, AE, A1-30, AH, AO, AR, A99, V, VE, and V1-30 are areas vulnerable to a 1% annual chance of flooding or the 100-year flood. Herein, we utilize FEMA (http://www.fema.gov/national-flood-insurance-program-1/special-flood-hazard-area) flood maps for our analysis. Impervious surface maps were acquired from Georgia Land Use Trends through the Georgia GIS Clearinghouse (https://data.georgiaspatial.org/index.asp) and National Land Cover Database (http://www.mrlc.gov/nlcd2001.php) and were used to calculate impervious surface coverage for 1991, 2001 and 2008.

Exposure to Climate Change

Mean annual temperature and precipitation for 1975- 2012 were derived from monthly mean temperature and monthly accumulated precipitation. Ordinary Kriging was used to produce a mean annual temperature map, whereas Inverse Distance Weighted (IDW) was used to interpolate the mean annual precipitation maps to capture the localized variation in precipitation patterns (Brown and Comrie 2002). Using map algebra, decadal temperature and precipitation values were calculated for the 1980s (1975-1984), 1990s (1985-1994), 2000s (1995- 2004), 2010s (2005-2012) and baseline temperature and precipitation were calculated for 30 years (1971-2000) similar to the maps prepared by NOAA's National Climatic Data Center (http://www.ncdc.noaa.gov/oa/climate/normals/usnormalsprods.html). Standard deviations were calculated to measure variations in mean temperature and precipitation across the baseline or "normal" period. Average decadal temperature and precipitation and normal values of each county were calculated from interpolated surfaces. Finally, the z-score of temperature and precipitation was calculated at the county level. The z-score simply indicates by how many standard deviations the mean temperature and precipitation of each decade (1980s, 1990s, 2000s and 2010s) is above (indicated by positive z-score) or below (indicated by negative z score) the baseline climate (1971-2000). The absolute values of temperature and precipitation z scores were summed up to indicate any deviations of decadal values from the baseline temperature and precipitation. Higher deviations in mean temperature and precipitation indicate greater exposures to background climate change.

The frequency of extreme weather events per year indicates climate exposure in terms of extreme events. The total frequency of occurrences of extreme events was calculated for the decadal periods by summing up the total frequency for each decade and normalizing total frequency by number of years in that decade. Equal weights were given to all extreme events in the exposure from extreme events calculation. The total exposure to climate change was calculated by combining composite z-scores of temperature and precipitation with the frequency of extreme weather events per year.

Social Vulnerability

Principal Component analysis (PCA) of variables was performed using IBM SPSS software following the Social Vulnerability Index (SOVI) recipe specified by Cutter et al. (2003). The variables were standardized into percentage values. Ward and Shively (2012) noted that the relationship between social vulnerability and per capita income is linear in natural logarithms. This relationship was reflected by taking the natural logarithm of inflation-adjusted per capita income. PCA was performed with Varimax rotation to identify the variables that provide maximum loading for each of the principal components. The dominant variables in PCA determine the directionality of each principal component. Each principal component score was weighted by its percentage variance such that the components with higher variance contribute more towards overall sensitivity. Each of the weighted principal components was summed to construct the overall social vulnerability score. High social vulnerability score indicates high sensitivity and low adaptive capacity and vice versa. The social vulnerability scores are rescaled to 0 - 4 scale.

Climate Change Vulnerability

The climate change vulnerability index indicates both social vulnerability (sensitivity and adaptive capacity) and exposure to climate change using equation 2.2 and 2.3. Vulnerability has been modeled as a multiplicative or additive model depending on different conceptual frameworks. We chose the additive model over the multiplicative one because in the multiplicative model, zero exposure would make the composite vulnerability zero, which is not true because social vulnerability exists independent of climatic exposure.

$$\text{Climate change vulnerability} = \text{exposure} + \text{social vulnerability} \tag{2.2}$$

$$\text{Climate vulnerability} = \text{climate change vulnerability} + \text{geographic vulnerability} \tag{2.3}$$

Geographic vulnerability is represented here by flood zones and impervious surface. The percent coverage of impervious surface and flood zones are ranked and summed to identify counties that are geographically vulnerable to flood and urban heat risks. The summed scores are transformed to a 0-4 scale and added to the climate change vulnerability index to identify an overall climate vulnerability index.

2.4 Results and Discussion

Greater anomalies in temperature have been observed in recent decades. Figure 2.2 shows the transition from cooling (1975-1984) and warming thereafter. Our finding is in agreement with the conclusions drawn by Tebaldi et al. (2012) and Karl et al. (2009) who noted that the Southeast reversed from a period of cooling to warming after 1980. Equally encouraging, this result illustrates that we are capturing background temperature changes consistently reported in the literature. Our target was to identify counties experiencing the greatest changes in temperature and precipitation.

Background Climate and Extreme Events

The results clearly indicate the warming trend in north Georgia. The increase in temperature after the mid-1970s has been attributed to several hypotheses such as decreases in aerosols due to the Clean Air Act (Leibensperger et al. 2012), reduced agricultural development and reforestation (Bonfiles et al. 2008; Portmann et al. 2009) and thermal inertia of sea surface temperatures (Robinson et al. 2002; Kunkel et al. 2006; Meehl 2009; Wang et al. 2009; Meehl et al. 2012).

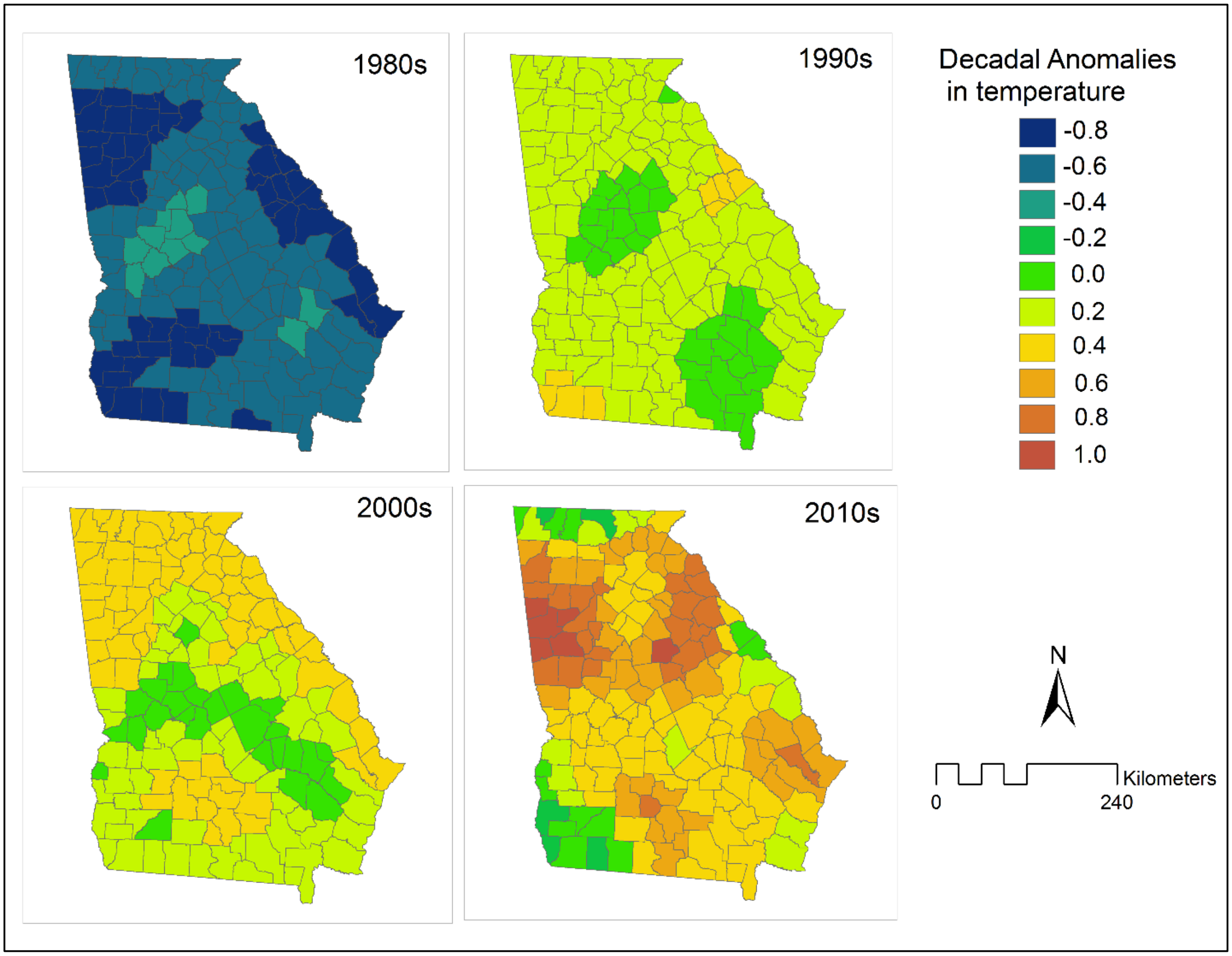

Figure 2.2: Anomalies in decadal temperature in the 1980s (1975-1984), 1990s (1985-1994), 2000s (1995-2004), and 2010s (2005-2012) compared to the 30-year climate normal (1971-2000) measured as z score.

Figure 2.3 reveals drier conditions in Georgia in recent decades. This observation parallels Karl et al. (2009), which reported increase in areas of moderate to severe drought over the past three decades. It is also reflected in two significant droughts in 2007-2009 (Campana *et al.* 2012, Pederson *et al.* 2012) and more recently in 2012 (Karl *et al.* 2012). The severity of drought is worsened by population growth as was evident in the 2007-2009 drought in Georgia (Campana *et al.* 2012, Pederson *et al.* 2012). Further, the drier conditions lead to higher temperature due to decrease in evaporation from the soil surface which further increases the chances of droughts (Koster *et al.* 2009).

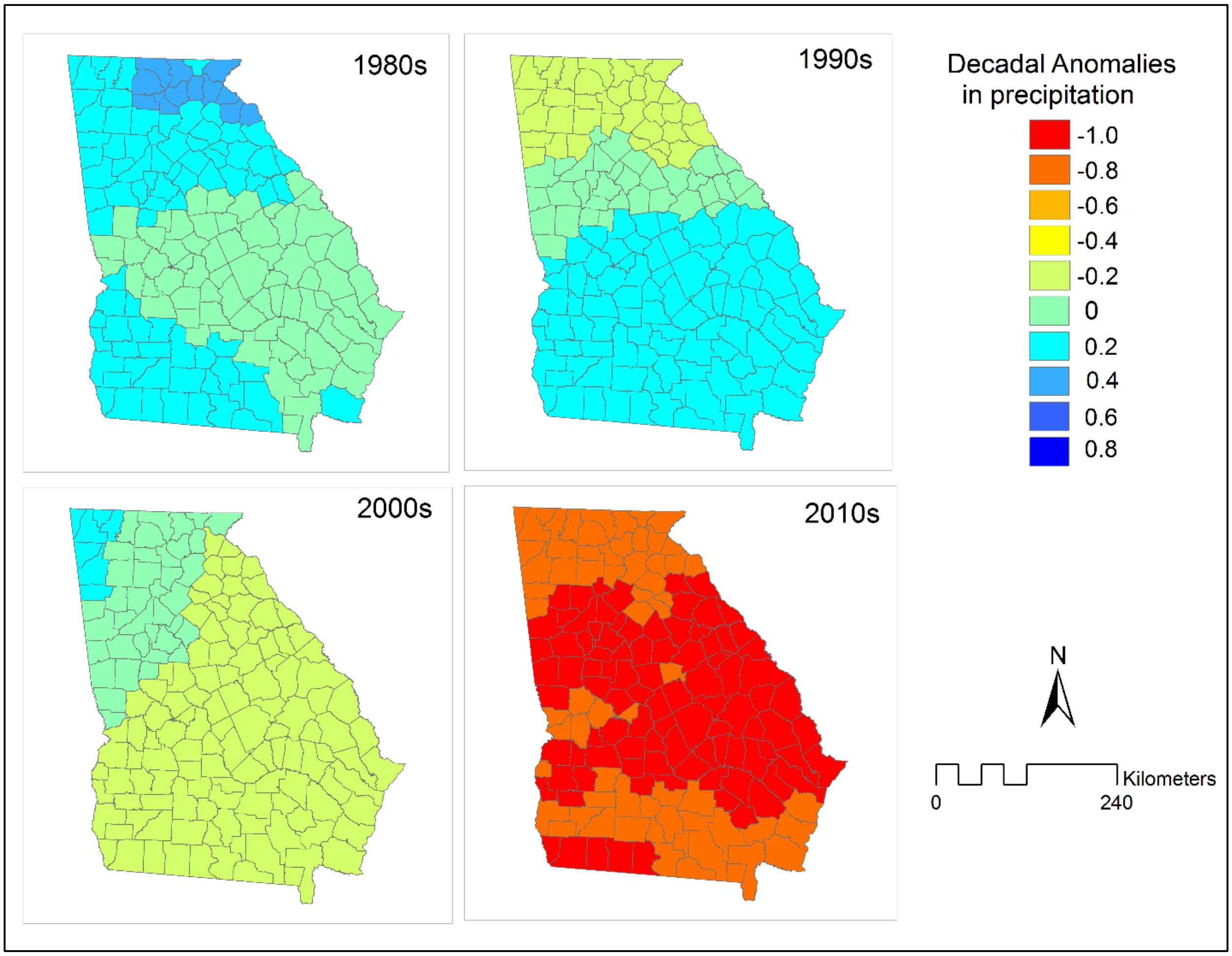

Figure 2.3: Anomalies in decadal precipitation in the 1980s (1975-1984), 1990s (1985-1994), 2000s (1995-2004), and 2010s (2005 -2012) compared to the 30-year climate normal (1971-2000) measured as z score

Among the three extreme hazard events, floods occurred most frequently whereas heat wave was least frequent. The frequency of floods spiked in recent decades, especially in metro Atlanta and Chatham, a coastal county. For example, in Fulton County alone, 24 floods were recorded in a 10-year period from 1995 to 2004, and 16 floods were recorded in an 8-year period from 2005 to 2012. Similarly, in Chatham, a coastal county, 4 floods were recorded in a 10-year period from 1995 to 2004, whereas 12 floods affected the county in 8 years from 2005 to 2012. This is consistent with the literature assertions that flood frequency and rainfall intensity will increase as the climate warms (Andersen and Shepherd 2013). Droughts were also frequent in recent decades. In west-central and southeast Georgia, the frequency of severe drought increased from 1 drought per decade in the 1980s (1975- 1984) to 5 droughts in an 8 year period from 2005 to 2012. North Georgia, which experienced the least number of droughts in the1980s, had 2- 4 droughts in the 2010s. Contrary to flood and drought, the frequency of heat waves decreased in recent years. For example, in the 1990s, 6 heat waves occurred in Muscogee County, 3 occurred in Dodge and Bibb counties, but no heat waves were recorded in these counties in the 2010s.

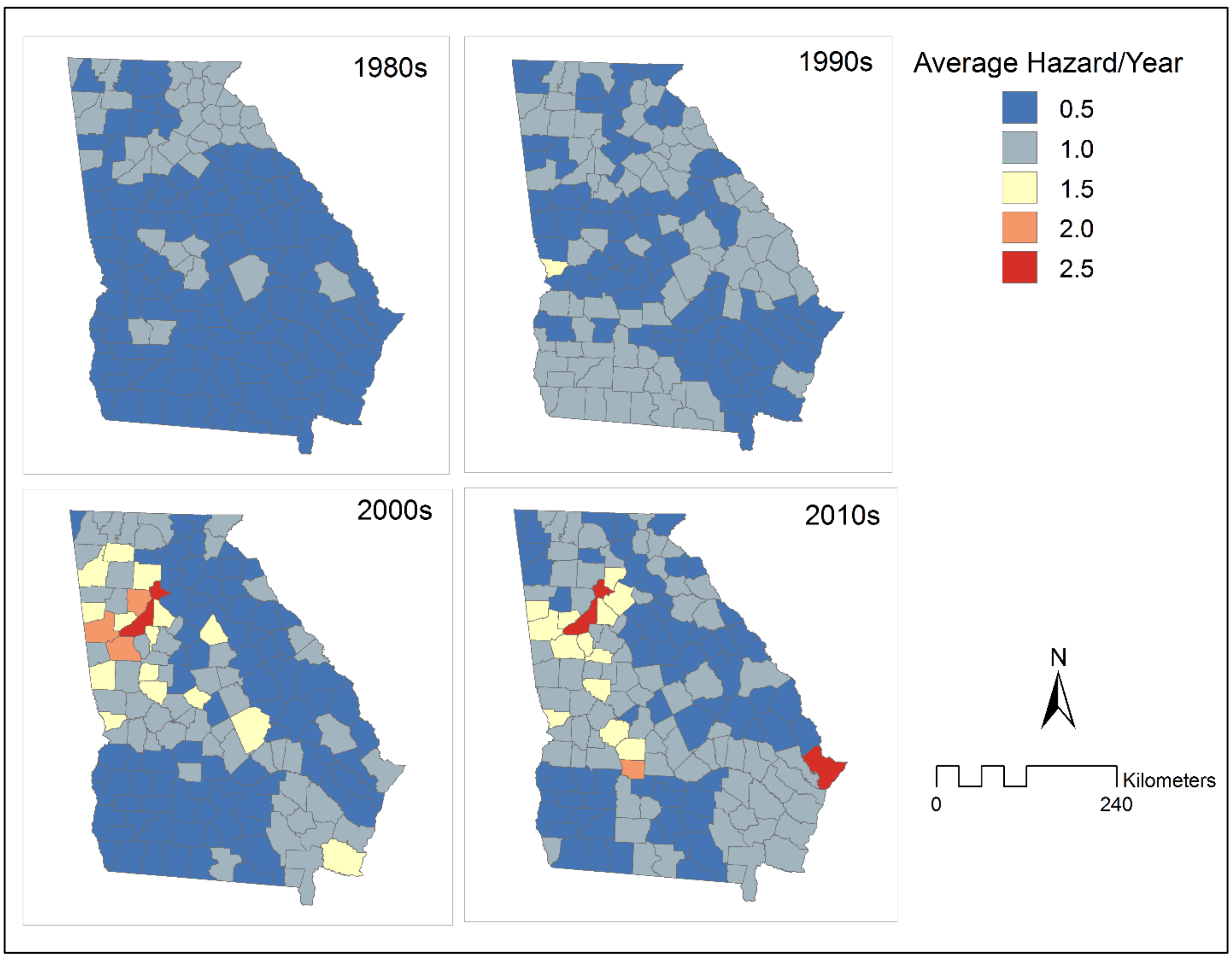

Figure 2.4: Normalized frequency of climate hazard extremes (flood, drought, and heat wave) in the 1980s, 1990s, 2000s, and 2010s

The overall frequency of extreme hydroclimatic events are captured in Figure 2.4 which shows an increase in aggregate extreme events – flood, drought and heat wave over recent decades with the highest concentration of these events in metro Atlanta counties and coastal counties. This finding is consistent with several findings: an upward trend in frequency of extreme events in North America (Kunkel *et al.* 2008), increasing frequency of heavy rainfall in the central U.S. (Villarini *et al.* 2013), frequent floods in Northeastern Illinois (Hejazi and Markus 2009), record heat in the United States (Climate Central 2012), and increases in extreme events globally (Goodness 2012). Since the 2000s, the increase in frequency of these extreme events in metro Atlanta is mainly due to flooding. Apart from intense rainfall, Shepherd et al. (2011) draw on Reynolds et al. (2008) to speculate that impervious surface in Atlanta might be altering the hydrological cycle, that is, increasing runoff and decreasing infiltration, to produce frequent floods. Similarly, Hejazi and Markus (2009) attributed flood in Northeastern Illinois to intensive urbanization, as well as frequent heavy rainfall events. The counties in west central Georgia experienced frequent droughts in recent years, which is reflected in Figure 2.4. Though the southeast experienced a similar number of droughts; this trend is not captured in this figure. This might be due to equal weights being given to all extreme events.

Exposure to background climate changes and hydroclimatic extreme events was found to be clustered in metro Atlanta. High exposure in metro Atlanta is mainly driven by drier, hotter background climate and more frequent extreme events, particularly flooding. On the other hand, the high exposure in south and east Georgia was due to drier than normal conditions accompanied by frequent droughts. However, higher exposure in Chatham County and Crisp County compared to surrounding counties was amplified by frequent floods in the 2000s and 2010s.

Social Vulnerability

Figure 2.5 identifies metro Atlanta counties as relatively more vulnerable in social terms, compared to some elsewhere in the state. This is true for each of the decades examines. Counties in the southwest and part of east Georgia also have higher social vulnerable scores. Counties in southwest Georgia are included in Georgia's Black Belt region. These counties have historically high African American populations and increasing concentrations of Hispanics. Again, many of these residents are highly dependent on natural resource-based industries such as agriculture, and forestry for their livelihoods.

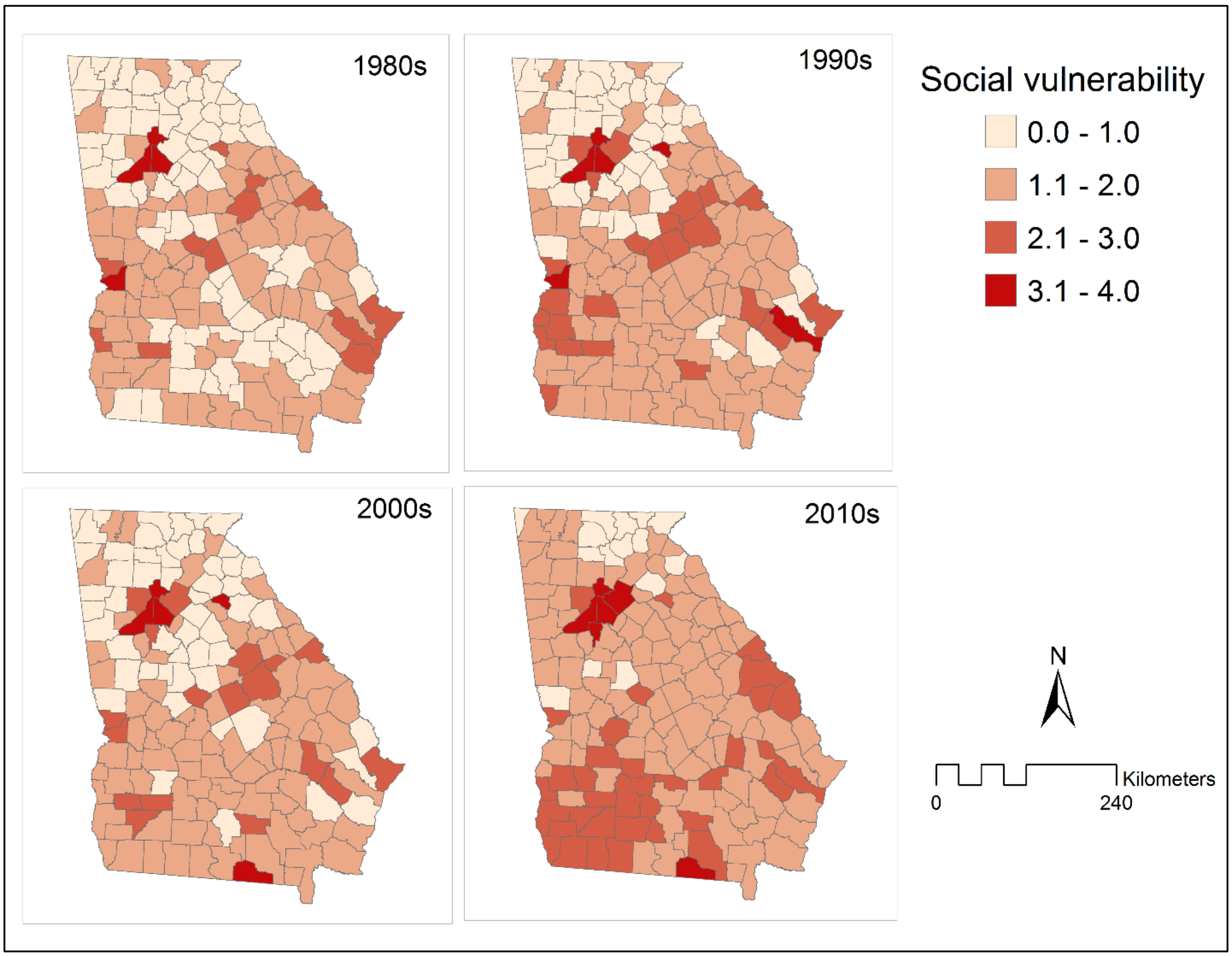

Figure 2.5: Social vulnerability index in the 1980s, 1990s, 2000s, and 2010s.

Language barriers for more recently-arrived Hispanics and generally low educational attainment may also contribute to higher social vulnerabilities in these areas of the state. Female-headed households were also found to be concentrated in the Black Belt region of the state, especially in southwest and east Georgia. A study by Snyder et al. (2006) and Driskell and Embry (2007) conclude that poverty is highest among female headed households of racial/ethnic minorities residing in rural communities compared to urban centers because of less economic opportunities available to the former in rural areas. Between 2001 and 2007, 1 million people moved from the Black Belt to other parts of south, particularly to suburban metropolitan counties in search of affordable housing and economic prosperity (Ambinakudige et al. 2012). Atlanta is an attractive destination with an affordable housing market for blacks and Hispanics (Flippen 2010). Apart from this, black populations migrate to metro and sub metropolitan areas in search of opportunity and as a means of escaping from poverty; however, Driskell and Embry (2007) conclude that it may not always serve as a means of escape from poverty. In recent years, there has been migration of Hispanic population towards the north in urban and suburban counties of metro Atlanta in search of job opportunities. The flow of Hispanic population peaked in 2010s especially in Gwinnett, Hall, Cobb, and Clayton counties. Migration of Hispanics and Black population seems to have played significant role in increasing the vulnerability of metro Atlanta counties in recent years. Based on our analysis, the high concentration of ethnic/ racial minorities and consequently language barriers are the dominant factors increasing social vulnerability in the metro Atlanta counties in the recent decades.

The counties in east Georgia- Richmond, Burke, Jenkins, and Screven emerge as socially vulnerable counties in 2010s. Hence, most of the counties in the black belt region of Georgia are found to be socially vulnerable. Throughout the study period, ethnic minorities, female headed households, age group, poverty and major occupation played dominant roles to increase sensitivity of the system whereas populations that cannot speak English well, unemployment, and renter populations emerged as dominant variables in recent decade. Education remained a dominant variable that increased the resilience of the population throughout the decade.

Interaction of social vulnerability with climatic exposures, that is, anomalies in temperature, precipitation and extreme events, resulted in high overall vulnerability in recent decades (Figure 2.6).

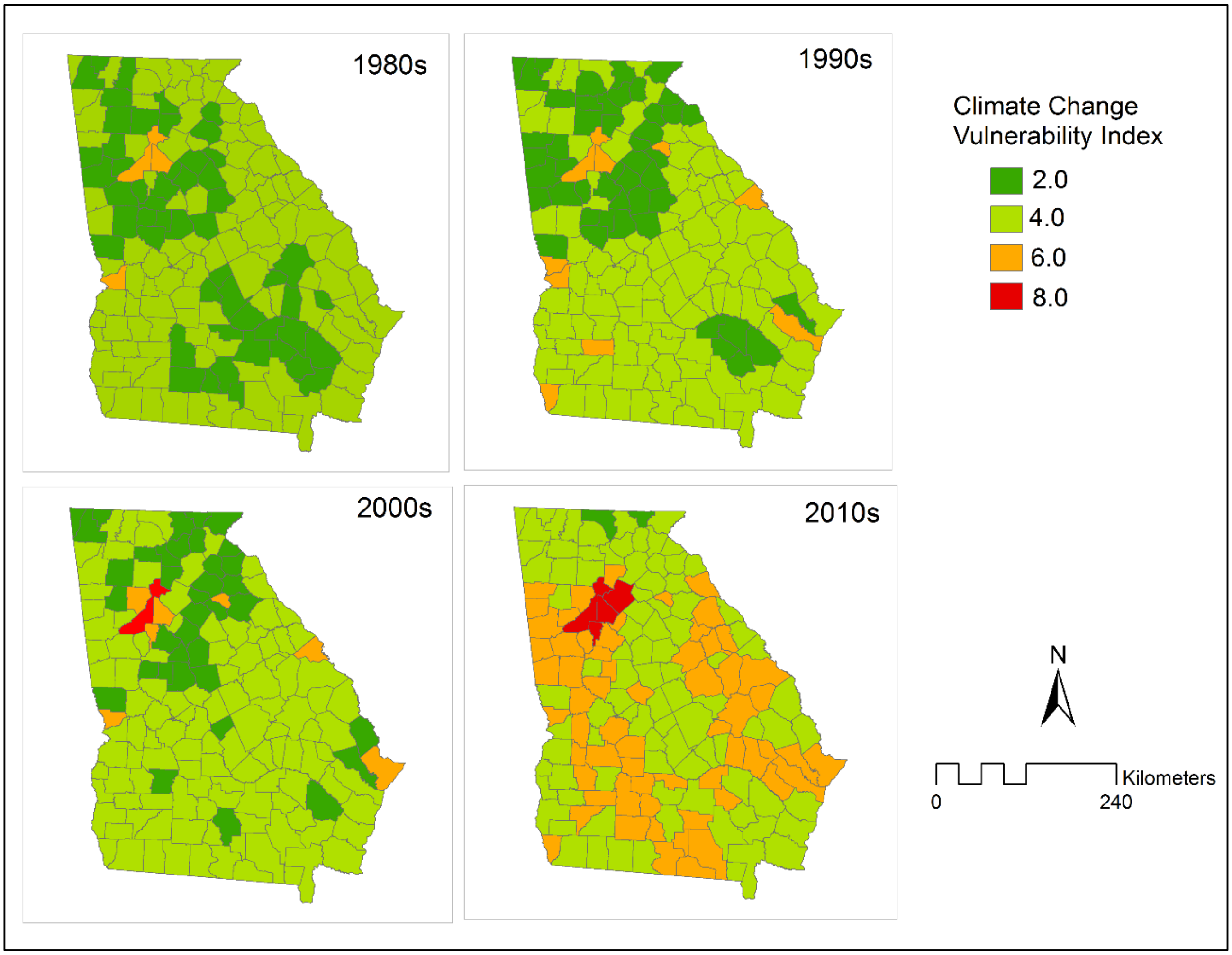

Figure 2.6: Climate change vulnerability index that integrates change in temperature and precipitation, normalized hazard frequency per decade and social vulnerability

The emergence of metro Atlanta counties as vulnerable in recent decades is driven by land cover change, fueled by higher sensitivity. Similarly, a cluster of high vulnerability in southwest Georgia is driven by drier and warmer conditions in rural farming community. Despite high social vulnerability, some counties in Southwest Georgia have low climate change vulnerability, which is reflected in Figure 2.6, because of relatively low climatic exposures (Figure 2.2 and 2.4).

The coastal counties, which are often inhabited by affluent population, are at risk simply because of their geographic location. These counties are prone to flood due to storm surge and potential sea level rise in the future. Based on FEMA's special flood hazard area maps, McIntosh, Clinch, Ware, Camden, Glynn, Liberty, Bryan, and Chatham counties are identified as having more than 50% of their land in high-risk flood zones (Figure 2.7). Similarly, in Figure 2.7, inland counties with high built up or impervious surface area, especially metro Atlanta counties, are at risk of flood and heat island effects.

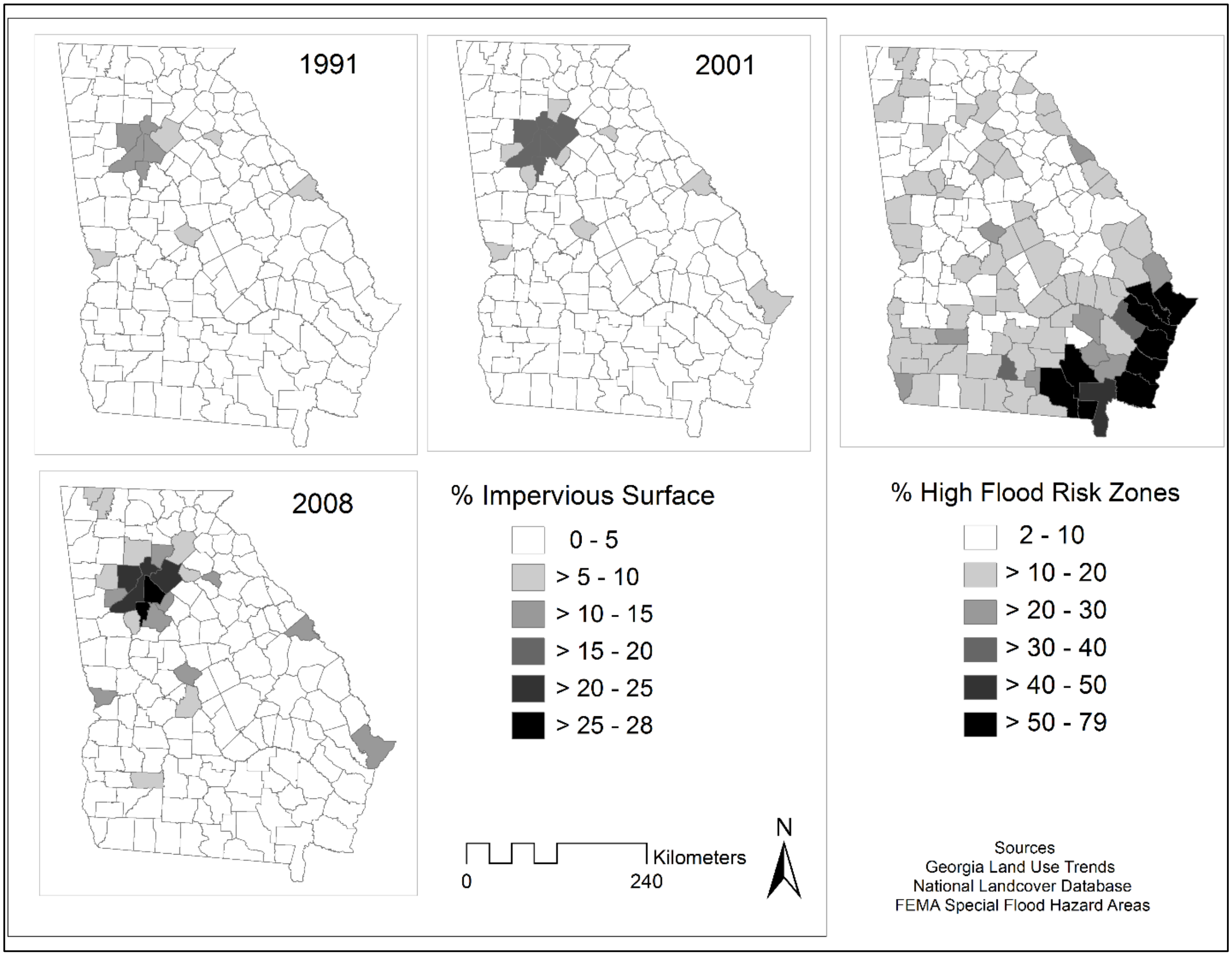

Figure 2.7: Left three maps represent percent impervious surface coverage in 1991, 2001 and 2008, respectively and map to the right represents percentage of county in high flood risk zones calculated from FEMA Special Flood Hazard Areas in 2009.

Our vulnerability model discussed earlier does not consider these potential risks due to future climate change. The percent of counties with high impervious surface coverage together with high flood risk areas are identified here as geographically vulnerability. These geographically hazardous areas were added with the climate vulnerability index to obtain an augmented climate vulnerability index (Figure 2.8). Atlanta metro counties and the southeast part of Georgia, especially coastal counties, are most vulnerable to climate change and potential risk from future climate related stimuli.

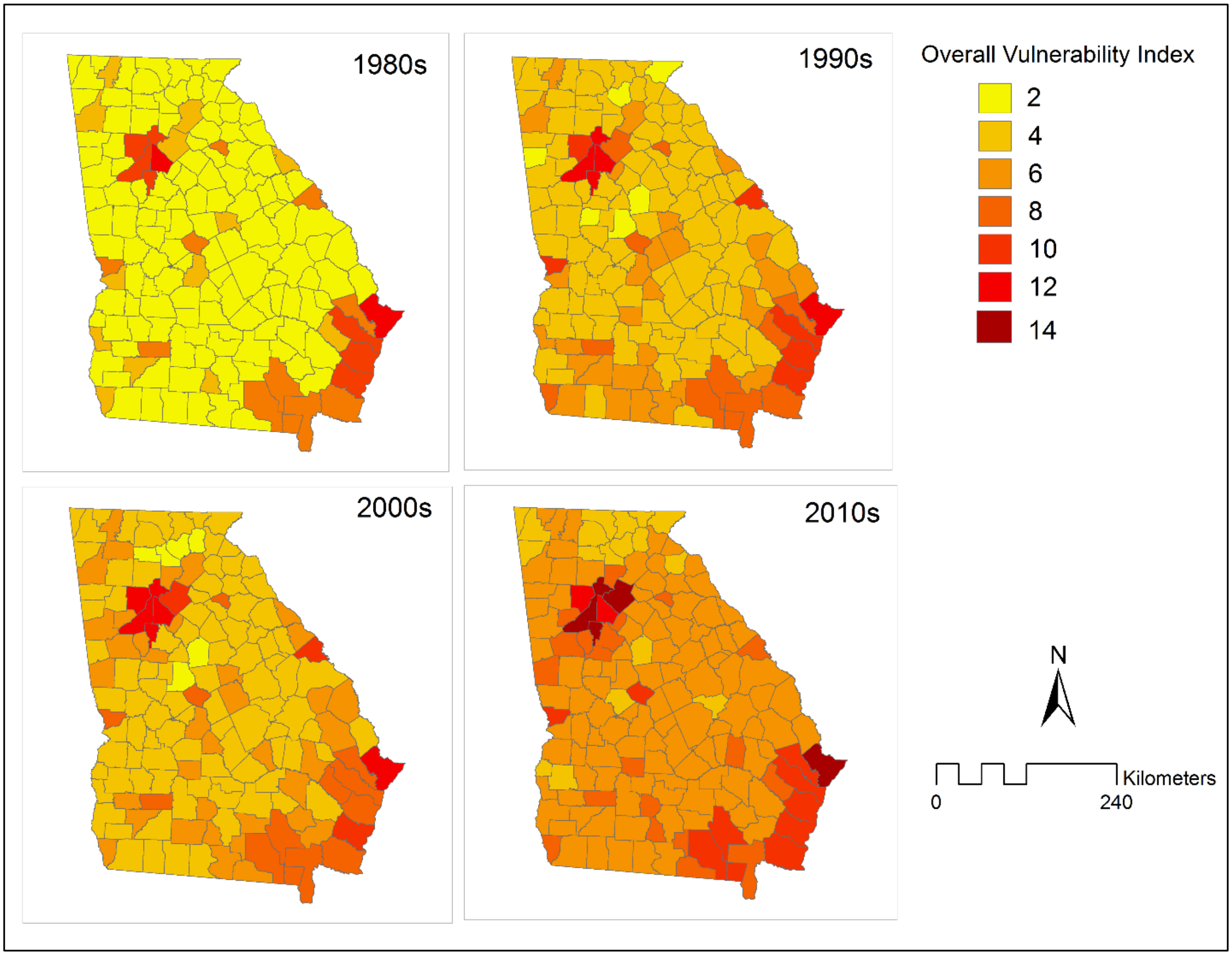

Figure 2.8: Overall vulnerability index derived by combining climate change vulnerability index and geographic vulnerability

2.5 Conclusions

This study quantifies vulnerability to climate change through a holistic approach by integrating biophysical and climate vulnerability with geographic vulnerability. Our approach provides a broader perspective into vulnerability from past climate change as well as helpful to determine risk from potential climate change in future. Our results conclude that anomalies in temperature and precipitation have increased in recent decades with warmer and drier conditions than during 30-year period from 1971 to 2000. Extreme hydroclimatic events like flood and drought have also increased in frequency in the study region, particularly metropolitan Atlanta. The metro Atlanta counties and Black belt counties in Georgia emerged as socially and climatologically vulnerable. Based on geographic location, the coastal counties are at high risk because of potential sea level rise and storm surge flooding. Quantifying current social vulnerability and biophysical vulnerability helps to predict how climate change may affect our society in the future. This in turn helps to enhance adaptation strategies and ultimately meet our goal of economic vitality and environmental sustainability. This integrated approach could also be used in developing countries where the poor population are always forced to live in geographically hazardous areas and are the ones bearing the heavy burden from climate change related damages.

Future iterations of the vulnerability index will seek to incorporate additional exposure threats. Of particular significance to coastal regimes will be inclusion of sea level rise and hurricane return intervals. However, the initial intent herein was to establish a credible and scalable approach for climate change vulnerability assessment.

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CHAPTER 3

3 CLIMATE CHANGE VULNERABILITY PROJECTION IN GEORGIA [2]

[2] KC, B., and J.M Shepherd (2014). Climate Change Vulnerability Projection in Georgia. To be submitted to *Journal of Geophysical Research*

Abstract

Climate change vulnerability is projected for 2030s (2025-2034) in the state of Georgia at county level. Climate change vulnerability is measured as exposure, sensitivity and adaptive capacity. Future exposure is measured as anomalies in projected mean temperature and precipitation compared to the historic baseline (1971-2000) temperature as well as frequency of heat waves and extreme precipitation days using CMIP5 projections. Similarly, future sensitivity and adaptive capacity is measured as social vulnerability which is derived through cohort component projection. Hence, this study captures both climatological and social vulnerability in out to the 2030s.

Warmer and dryer conditions, indicated by greater anomalies in mean temperature and precipitation compared to the historical baseline climate, are projected in metro Atlanta counties, as well as in the western part of the state. Extreme precipitation events are expected to occur in the northern counties whereas most heat wave events are projected in metro Atlanta counties especially under RCP 8.5 scenario. Hence, counties in southwest Georgia, some of which are "Black Belt" counties, and xx number of metro Atlanta counties, will emerge as socially and climatologically vulnerable in 2030s.

3.1 Introduction

With accelerated climate warming (Melillo *et al.* 2014, Tebaldi *et al.* 2012), scientific studies are focusing on long term projection of temperature and precipitation with an aim towards building adaptation and mitigation strategies. These projections have been performed using resources like the World Climate Research Programme's Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl *et al.* 2007) and Phase 5 (CMIP5) (Taylor *et al.* 2011). CMIP5 projections consider a wider range of climate forcing scenarios, (i.e., Representative Concentration Pathways (RCP): 2.6, 4.5, 6.0 and 8.5) than CMIP3: A2, A1B, and B1 (van Vuuren *et al.* 2011). Such improvements increased the confidence in projecting future climate (Reclamation 2013). RCP 2.6 is a mitigation scenario with a very low forcing level, and it assumes immediate and rapid reductions in emissions (i.e., more than 70% cuts from current levels by 2050). RCP 4.5 (similar to B1) and RCP 6.0 (similar to A1B) are medium stabilization scenarios. RCP 8.5 is a very high baseline emission scenario and assumes continuation of the current path of global emissions with 4.5°C of warming (Moss *et al.* 2010, vanVuurenetal 2011).

In the United States, Melillo *et al.* (2014) project temperature to increase by 1.5°C to 2.5°C under a low emission scenario (B1 in CMIP3 and 4.5 in CMIP5) and by 2.5°C to 5.5°C under a high emissions scenario (A2 in CMIP3 and 8.5 in CMIP5) by the end of the century. Similarly, frequent occurrence of heavy precipitation events (once in 20 year events) are projected twice as often under RCP 2.6 and five times as often under RCP 8.5. Decreased water availability has been projected in the Southeast United States, especially Atlanta (Melillo *et al.* 2014). In addition to the long-term changes in temperature and precipitation, the tails of the distribution, indicating extreme events, are more relevant because of the higher intensity of impacts associated with them. Climate projections show increased frequency of extreme heat days by the end of this century. For example, once-in-20-year extreme heat days will occur as often as once-in-two or three year events (Karl *et al.* 2008, Duffy and Tebaldi 2012, Kharin *et al*. 2013).

Exposure to climate change together with socioeconomic projection depicts a clear picture of future vulnerability. However, there are limited studies on climate change vulnerability projection using both climatic exposure and social vulnerability. This study is an extension of a climate change vulnerability assessment performed at the county level in the state of Georgia and follows a similar methodology discussed in KC et al. (2014). As climate changes continue, extreme events will become more frequent, increasing exposure of vulnerable populations. Elderly, infant, natural resource-dependent populations and racial minorities are particularly affected by these extreme events (Adger 1999, Kelly and Adger 2000, Cutter *et al.* 2003, Emrich and Cutter 2011, KC *et al.* 2014).

The main objective of this study is to project climate change vulnerability in the state of Georgia in the 2030s (2025-2034) at the county level for RCP scenarios 4.5 and 8.5. The IPCC (2007) model (i.e., vulnerability is measured as the function of exposure, sensitivity, and adaptive capacity) is adopted. Future exposure is measured as change in mean temperature and precipitation coupled with frequency of extreme events. Sensitivity is measured as future social vulnerability. The mean temperature and precipitation in the 2030s for both RCP scenarios are compared to historic baseline climate (1971-2000) to indicate anomalies in future climate. The number of heat waves and number of days with extreme precipitation events indicate frequency of extreme climatic events in 2030s for two RCP scenarios. Though a limited representation of extreme events, these choices are adequate for the scope of this research. Social vulnerability is measured at the county level using population projections out to 2030. The climatic exposure is coupled with social vulnerability to derive climate change vulnerability for the 2030s.

Downscaling Climate Projections

Global Climate Models (GCMs) projections are used to simulate future climate. GCMs simulate global climate at a coarse spatial resolution (IPCC 2007), hence, there is a need to downscale to a finer spatial resolution in order to perform impact studies. The two widely used GCM downscaling techniques in regional climate assessment are: statistical and dynamical downscaling. Statistical downscaling relates local climate to GCM output based on statistical relationships (Hewitson and Crane, 1996, Wilby and Wigley, 1997; Meehl *et. al*. 2007, Yoon *et al.* 2012); whereas dynamical downscaling uses GCM output to provide the initial and boundary conditions for the regional models. Dynamic downscaling is based on physical processes rather than statistical correlations. Dynamic downscaling provide better estimates than statistical downscaling but is computationally demanding (Giorgi and Mearns 1991, Cocke and LaRow 2000, Kim *et al.* 2000, Yarnal *et al.* 2000, Mearns *et al.* 2009, Bell *et al.* 2004, Leung *et al.* 2004, Salathe *et al.* 2008, Cadwell *et al*. 2009, Qian *et al.* 2010, Pan *et al.* 2011, Gao *et al.* 2012, Gensini and Mote 2014). However, dynamic downscaling is limited to a few decades and fewer scenarios only. Although the major drawback of statistical downscaling is temporal stationarity, that is, the assumption that observed links between large-scale climate and local climate will persist in a changed climate, it enables downscaling of several GCMs and emissions scenarios relatively quickly (Benestad 2002). Herein, statistically downscaled CMIP5 monthly and daily temperature and precipitation projections are applied to project future climate. CMIP5 monthly datasets have been downscaled using Bias Correction with Spatial Disaggregation (BCSD) (described in Wood *et al.* 2002, Wood *et al.* 2004, Maurer 2007); whereas daily datasets have been downscaled using Bias Correction with Constructed Analogues (BCCA) (described in Hidalgo *et al.* 2008, Maurer and Hidalgo 2010).

In BCSD, as described in Wood *et al.* (2004), a comparison is made between historical simulations from GCM and observations. The simulations that are biased wet, dry, cool, or warm at various locations, seasons, and variables are identified and removed from the projection datasets. Quantile maps of monthly GCM and observed historic data are generated to correct bias at that location, for that variable, and during that month such that a quantile map is produced for every projection. The adjusted GCM projections are spatially translated to the targeted downscaled resolution and the same mapping relation is applied to future GCM projections (Wood *et al.* 2004). In BCSD, the mean and standard deviation of projection is similar to the observation. BCCA is based on anomalies rather than absolute simulated values (Hidalgo *et al.* 2008, Maurer and Hidalgo 2008, Maurer *et al.* 2010). As described in Hidalgo *et al.* (2008), BCCA identifies how a GCM historical simulation tends to be too wet, dry, cool, and/or warm compared to observations. Similar to BCSD, quantile mapping removes these biases from the projection datasets and simulates daily sequences from a climate model (Maurer and Hidalgo 2008). Pierce et al (2012) found out that the statistically downscaled (BCSD and BCCA) fields are closer to the original global model simulations than the dynamically downscaled fields. Maurer and Hidalgo (2008) concluded that both BCSD and BCCA have comparable skill when downscaling monthly fields of temperature and precipitation. However, only BCCA preserves the daily sequence of original global model variability. Yoon et al. (2012) suggest combining both dynamical and statistical downscaling to maximize prediction skill.

Global Climate Models

CMIP5 consists of a suite of global models. Based on the assumption that ensemble averages remove individual model biases, the multi-model ensemble (i.e., the equal weighted averages) is preferred to a single best model for climate change assessment (Hagedorn *et al.* 2005, Knutti *et* *al.* 2010). For North America, NARCCAP (Mearns *et al.* 2009; Mearns *et al.* 2013) used four GCMs for providing boundary conditions: the Canadian Global Climate Model version 3 (CGCM3) (Scinocca and McFarlane 2004, Flato 2005); the NCAR Community Climate Model version 3 (CCSM3) (Collins *et al.* 2006); the Geophysical Fluid Dynamics Laboratory (GFDL) Climate Model version 2.1 (CM2.1) (GFDL 2004, Delworth *et al.* 2006) and the United Kingdom Hadley Centre Climate Model version 3 (HadCM3) (Pope *et al.* 2000, Gordon *et al.* 2000). Similarly, Wear *et al.* (2014) used four CMIP3 models to calculate ensembles of climate models in the Southeast: CGCM3, CCSM3, HadCM3, and GFDLCM2.1. Though Reclamation (2013) cautions that CMIP5 projections should be considered an addition to (not a replacement of) the existing CMIP3 projections until sufficient comparative studies are performed, better performance of CMIP5 compared to CMIP3 has been concluded by Sillman *et al.* (2013). Hence, similar to Wear *et al.* (2014) and Mearns *et al.* (2009), a newer version of the four GCMs from CMIP5 are applied to project mean temperature and precipitation in the 2030s: Canadian Centre for Climate Modeling and Analysis (CanESM2: 5 runs), National Center for Atmospheric Research (CCSM4: 5 runs), NOAA Geophysical Fluid Dynamics Laboratory (GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M), and Met Office Hadley Centre (HadGEM2-AO, HadGEM2-CC, HadGEM2-ES). These were used for RCP scenario 4.5 and 8.5. Whereas only two models CCSM4 (2 runs) and GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M projections were available to project daily maximum temperature and precipitation.

Some (Meehl *et al.* 2007) considered all CMIP3 models equally, others (Giorgi and Mearns 2002, 2003, Tebaldi *et al.* 2004, 2005, Greene *et al.* 2006) weighted climate models based on current climatology and observed trends and some (Gleckler *et al.* 2008; Brekke *et al.* 2008) have ranked the models. Moreover, recent studies (Pierce *et al.* 2009, Knutti *et al*. 2010, Santer *et al.* 2009, Brekke *et al.* 2008, Mote and Salathé 2010) argue that results from randomly selected GCMS are very similar or with little difference to those produced by a combination of the “best” models and multi-model ensembles is regarded as the superior estimates to any selected best model (Phillips and Gleckler 2006, Gleckler *et al.* 2008). Others have demonstrated that weighting may simply serve to increase uncertainty (Christensen *et al.* 2010, *Weigel et al.* 2010). Mote *et al.* (2011) suggest that model picking needs to be further assessed using CMIP5 model outputs. Hence, whether weighting scheme is more credible than equal weighted ensemble is inconclusive. *Rupp et al.* (2013) found the CESM1/CCSM4, CanESM2, CNRM-CM5-2, the four models from the Hadley Center, and EC-EARTH as the best performers while evaluating 20th century climate simulations in Northwest US. In this study, ensemble average is calculated by equally weighting all the models.

Socioeconomic Projection

Population projection is a key to understanding the population dynamics in the future. Samson *et al.* (2011) highlight the importance of considering current and predicted demographic trends in vulnerability assessments. Population projection is used for planning, public health research, setting adaptation strategies, and predicting climate change vulnerability and societal impact of climate change (IPCC 2007, Boyle *et al.* 2001, Huang *et al.* 2009, Ziegler-Graham et al. 2008, Heidenreich *et al.* 2011, Raftery *et al.* 2014). Current literatures suggest both individual-based models such as micro-simulation and macro-simulation (example, cohort component model). Apart from the cohort component model, other macroscopic models suggested in literature are - extrapolation (Smith and Shahidullah 1995, Smith and Tayman 2003), Hamilton-Perry method (Hamilton and Perry 1962, Smith and Tayman 2003), composite method (Smith and Shahidullah 1995, Rayer 2008, Rayer and Smith 2010), ProFamy model –an extended cohort component approach (Zeng *et al.* 2012), and Bayesian model (Raftery *et al.* 2014).

Micro simulation models are considered better alternatives to macroscopic models; however, micro-simulation requires micro-data which are not easily available. Tian *et al.* (2011) combined multi-agent system and spatial regression model to predict future urban development. Wu et al. (2011) suggests using a hybrid combination of simulation and agent based modeling (ABM) in order to overcome the limitations of micro simulation. The agent based paradigm offers a better platform for modeling social phenomena (Pavón et al. 2008). Despite many strengths, ABM has some limitations, such as lacking predictive power and difficulty in validation and verification (Lempert, 2002; Parker et al. 2003; Matthews et al., 2007). ABM is suitable for small scale modeling. In large scale studies, such as in state level or national level, ABM becomes more complicated.

Though conventional macroscopic modeling, based on aggregate analysis of numbers, oversimplifies the complexity of the urban environment (Ligmann-Zielinska and Jankowski 2007), it is the most widely used approach. The two most commonly used population projection techniques are -extrapolation and cohort component technique. Extrapolation fits the past population trend into curves (for example linear, geometric, parabolic, exponential) and does not account for fertility rate, economic growth, or migration (Chi 2009, Morgenroth 2002, Rayer 2008, Smith and Tayman 2003). However, extrapolation only provides aggregated population (Smith *et al.* 2001) and does not provide insight into details such as the age, gender, and race component of population.

Cohort component modelling is a deterministic approach which disaggregates the population into age, gender and race cohort. It uses birth, death and migration rates to calculate age cohort.

Age cohort is regarded as an important trait in public health studies (e.g., in diabetes studies (Boyle et al., 2001, Huang et al. 2009), cardiovascular disease (Heidenreich et al. 2011), HIV/AIDS population (Heuveline 2003, Thomas and Clark 2011); limb loss (Ziegler-Graham *et al.* 2008), Alzheimer's disease (Brookmeyer and Gray 2000); political affiliation (Kaufman *et al.* 2012); and educational attainment (K.C. *et al.* 2010). Generating good migration estimates is always a challenge in cohort component modeling. Mortality rate is relatively high in the infant, elderly, male and minority populations whereas migration rate is high among young adults (aged x to x (Smith and Tayman, 2003). Furthermore, Smith and Shahidullah (1995), and Smith and Tayman (2003) point out that the error in projection of young children in cohort component is largely associated with uncertainty about fertility rate and women of child-bearing age. Population projections for large areas and for shorter time periods is relatively more accurate than long range forecasting of smaller areas such as the county or census tract level (Smith and Tayman 2003, Rayer and Smith 2010). Smith and Tayman (2003) argue that cohort component projection at the county level is data intensive so they suggest an alternative method called the Hamilton-Perry method (Hamilton and Perry, 1962) when projections are solely used as forecasts for future population change. In this study, we performed cohort component projection because it preserves the demographic details and does not require modeling expertise.

Coastal Inundation

In addition to social and climatological variables, we should keep in mind geographic location of an area. The coastal areas are at the risk of inundation due to future sea level rise and storm surges. According to Climate Central (Strauss et al. 2014), Georgia has more than 178,000 acres of land at less than 3 feet above local high tide line, also known as Mean Higher High Water (MHHW), after taking into account potential protections from flood control structures such as levees and natural features. It is likely that such factors would also increase coastal vulnerability as shown in KC *et al.* (2014). Hence, our vulnerability assessment also accounts for potential inundation due to future sea level projections or tropical cyclone landfalls.

Climate Central forecasts flood risk by integrating the sea level rise projection scenarios (developed by NOAA, Parris et al. 2012) with tide and storm surges. The local sea level rise projections (after taking into account rising and sinking of coastal area) and coastal flood risk analysis in Georgia by Climate Central (Strauss *et al*. 2014) suggest floods, exceeding historic water level of 3.5 feet above the local high tide line, are likely to take place by 2040 under a mid-range sea level rise scenario. Similarly, under high-range sea level rise scenario, floods above 8 feet are forecasted by the end of century. Under a high-range sea level rise projection scenario, floods exceeding 4 feet become every-year events. Hence, along Georgia coast, with 3-to-8 feet projections, extreme floods are more likely (Strauss *et al.* 2014).

In this study, an online tool called Surging Seas (http://sealevel.climatecentral.org/ssrf/georgia) is used to map the percentage of land inundated by 1, 2, 3, and 4 feet above MHHW to derive vulnerability from future sea level rise, and storm surge. The flood maps are based on a modified "bath tub" approach, modeling hydrological connectivity and locally adjusted Mean Higher High Water levels. However, Surging Seas does not take into account future erosion or the migration of marshes as sea levels rise.

Section 3.2 describes the detailed methodology on cohort component projection, climate change projection and how these social and climatic components are merged into a future vulnerability projection. Section 3.3 presents results of vulnerability projection. Concluding remarks are provided in section 3.4.

3.2 Methodology

Climate Change Projection

Climate projections for the 2030s (2025-2034) were downloaded from downscaled WCRP CMIP5 models (http://gdodcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html). Monthly average surface air temperature, monthly precipitation rate, daily maximum temperature and daily precipitation rate at 1/8 degree spatial resolution (roughly equal to 14 km) were downloaded for the state of Georgia. The datasets were in NetCDF format. Model builder in ArcMap was used to extract monthly and daily datasets. Zonal statistics were performed using model builder to calculate monthly mean temperature and precipitation and to average the monthly observations from 2025 to 2034 for multiple GCMs projections and scenario runs. Z-score was used to calculate the anomalies in temperature and precipitation in the 2030s (ten year period) compared to baseline climate (30 year: 1971 -2000). The positive z-score in temperature indicates warmer than normal climate; whereas negative z-score indicates cooler than normal climate. Similarly, positive-z score in precipitation indicate wetter than normal condition; whereas negative z-score indicates drier than normal conditions. The anomalies in temperature and precipitation were carried out for both 4.5 and 8.5 scenarios.

The extreme events were captured using daily precipitation and maximum temperature projections. The daily maximum temperature and precipitation datasets for a 10-year period from 2025-2034 were extracted from NetCDF files using model builder in ArcMap. The daily maximum temperature at 1/8th resolution was analyzed in model builder through the zonal statistics tool to extract temperature and precipitation values for all counties in Georgia. The relationship between heat waves and vulnerable groups (e.g., elderly, racial minorities) have been well defined in the literature (Kovats and Ebi 2006, Kovats and Hajat 2008, O’Neill and

Ebi 2009, Sherwood and Huber 2010, Maier *et al.* 2014). In this study, an extreme temperature event was calculated as the number of events exceeding the 97.5 percentile of daily maximum temperature (in 2010) for 3 days in a row (Anderson and Bell 2011, Kyselý *et al.* 2011, Zacharias *et al.* 2014). These events were summed up for the 10-year period to produce the total number of heat wave events in a decadal span. The total number of heat waves for the 10-year period were calculated for multiple models, multiple scenarios (RCP 4.5 and 8.5), and multiple runs. Extreme precipitation events are calculated as the total number of days exceeding roughly 25 mm of rainfall (Shepherd *et al.* 2007). These extreme rainfall events were summed up for a ten-year period for multiple GCMs, multiple runs and both RCPs. Average number of rainfall events in the 2030s is calculated from multiple runs and multiple GCMs. The total number of extreme precipitation days and heat wave events were summed up to produce exposure to extreme events in the 2030s. Finally, anomalies in mean temperature/precipitation and extreme events are summed up to calculate future exposure for both RCP scenarios.

Social Vulnerability Projection

Social vulnerability is projected using socioeconomic projections in 2030. Cohort component modeling was performed using age-sex cohorts as inputs to project population in 2030. We used the cohort component model developed by Dr. Tim Chapin at Florida State University to perform the population projection (http://mailer.fsu.edu/~tchapin/garnet-tchapin/urp5261/exercise/models.htm). It applies birth, death, and migration rates (components) to age-sex cohorts, and it also provides control over the changes in population dynamics such as: mortality, fertility and migration. Societal and natural changes that are expected to occur in future such as change in climate, adaptation, and politics are not reflected in cohort component. Age-sex cohorts cover five-year periods (e.g., 0-4, 5-9, 70-74, 75-79, 80+). Projections are made for whites and “other races” because they experience different rates of fertility, mortality, and migration. County-wide data for white male/female, African American male/female, Hispanic male/female and non-white population male /female were obtained from the Georgia Department of Public Health, Office of Health Indicators for Planning (http://oasis.state.ga.us/oasis/oasis/qryPopulation.aspx). This data was acquired for years 2000, 2005, and 2010 and served as the base population for future projection. Survival rate was calculated from Georgia life table. Persons that lived between age x and x+1 (Lx) were obtained from the 1999-2001 Decennial Georgia life table downloaded from Center for Disease Control and Prevention website (http://www.cdc.gov/nchs/nvss/mortality/lewk4.htm). The life table was not available for counties; hence, the state life table was used instead. Persons that lived at specific age (Lx) were summed up to five years periods to calculate the five-year survival rate of the age cohort for White male, White female, African American male and African American female. Since Lx was not available for non-white population, African American male/female survival rate was used to as a proxy for the survival rate of non- white populations.

Five-year fertility rate was calculated using live births per 1000 women within the 10-49 age range for white, nonwhite, Hispanic, and African American female population in all counties. The fertility rates were downloaded from Georgia Department of Public Health, Office of Health Indicators for Planning (http://oasis.state.ga.us/oasis/oasis/qryMCH.aspx). Population of women in fertility age (10-49 and 15-54) for the five year cohorts was obtained from the CDC website (http://oasis.state.ga.us/oasis/oasis/qryPopulation.aspx) for years 2000 and 2005, respectively. The female population in 2000 and 2005 was averaged to calculate the five-year average of the particular age group. The number of babies was calculated using five year fertility rate, average five year population of women in fertility age, and the United States male-female sex ratio in

2000. Male-female sex ratio for the United States was obtained from 2005 National Vital Statistics Report. The survival rate was multiplied with the number of people in 2000 to derive the expected survivors for each population group in 2005. The expected population was subtracted from the observed population in 2005 to determine the migration rate for the five-year age cohort. Similarly, migration for 2005-2010 was calculated and averaged to calculate final migration rate. Finally, survivors in 2015, calculated using observed population in 2010 and survival rate, were applied to migration rate to obtain five-year population. Mathematically, the cohort component projection was performed following:

Five year migration rate = actual pop in 2010 (a2010) - expected pop in 2010 (e2010) (3.1)

Five year fertility rate = (number of live birth per 1000 women/1000)*5 (3.2)

Expected population in 2015 (e2015) = actual population in 2010*survival rate (3.3)

Pop projection in 2015 (p2015) = (e2015) + ((e2015)*five year migration rate) (3.4)

Five year cohort populations of white male, white female, non-white male and non -white female were projected separately for all counties. All these populations were summed up to calculate the total elderly (>65) and infant (<5) population in all the counties. A similar method was used to project African American and Hispanic population of the counties in Georgia. In addition to elderly, infant population and minority projection, natural resource-dependent populations are also regarded as vulnerable groups because they are directly affected by changing climate.

The constant share projection approach assumes that the local share of the economic activity of a larger region remains constant and the employment share for a given industry remains constant (a “constant share”). This method is based on assumption that a local economy is well-integrated with the region’s economy such that the changes experienced in the local economy reflect changes in the state level because a similar set of factors affect both of these geographic regions (the local area is truly an “integrated economy”). It utilizes historic employment data of a larger area (for example, state level) to project the employment status of a component sub-area (for example, county level). A primary assumption of these techniques is that the growth of a smaller area will emulate the growth of its pattern area. A constant share occurs when employment in the industry grows at the exact same rate both in the local economy and in the reference region economy. The 2012 employment data for all the counties in Georgia was obtained from Georgia Department of Labor (http://explorer.dol.state.ga.us/gsipub/index.asp?docid=387).

Employment projection for 2020 for the state of Georgia was obtained from Bureau of labor statistics (http://www.bls.gov/emp/#tables). At first, ten year growth rate in Georgia from 2010 to 2020 is calculated and the same rate is applied at county level to obtain total population projection, population involved in agriculture, forestry, fishery, and hunting and construction in all the counties. Total employment projection as well as people involved in forestry, fishing hunting and construction were obtained for all the counties in Georgia based on the constant share method.

Social vulnerability is calculated simply by summing up the elderly, infant, and African American population as well as population employed in agriculture, forestry, fishery, hunting and construction. Equal weights are given while calculating the social vulnerability score in 2030. The social vulnerability score is rescaled to 1-5 in order to make it comparable to climate exposure.

Climate Change Vulnerability Projection

The climate change vulnerability projection is performed by combining the social vulnerability score with exposure. Rescaled social vulnerability scores together with climatic exposure, which is the integration of anomalies in mean temperature and precipitation and frequency of extreme events are summed up to obtain the climate vulnerability score. Climatic exposure and social vulnerability are equally weighted as there is no conclusive scheme to provide weight to the vulnerability components. IPCC (2007) vulnerability scheme is followed to measure the future climate change vulnerability using exposure, sensitivity and adaptive capacity. However, socioeconomic variables measuring adaptive capacity such as education level or irrigation facility are difficult to quantify in the future. Hence, vulnerability is measured only as climatic exposure and social vulnerability and lacks adaptive capacity component. These are clearly weaknesses of our approach and must be more thoroughly e valuated in future work.

Coastal Inundation and Overall Climate Vulnerability

The percentage of inundated land by 1, 2, 3, and 4 feet water levels above MHHW are derived from Surging Seas, which is an online tool provided by Climate Central. The flood risk map is based on high resolution Lidar elevation datasets adjusted to the nearest average high tide line, instead of a standard zero. Percentage of area inundated are based on the elevation adjusted relative to MHHW. The flood map derived using Surging Seas is combined with the climate change vulnerability projection to derive climate vulnerability map. Based on the suggested sea level rise and flood risks in the Georgia coast, 3 feet water level above MHHW will be very fairly common by 2040 under mid-range scenario and 4 feet water level will be very common by 2060 under high-range scenario (Strauss *et al.* 2014). Hence, the climate change vulnerability index under RCP 4.5 and RCP 8.5 are combined with 3 feet and 4 feet flood risk maps, respectively to derive overall climate vulnerability map.

3.3 Results

A high elderly population (Figure 3.1) is projected in southwest Georgia counties such as Dougherty, Randolph, Quitman, Baker and Seminole. Fannin, Union, Towns, Gilmer counties to the north; Hancock, Greene, and Lincoln counties to the east of Atlanta; and McIntosh counties to the southeast are projected to have high aging population. Clustering is seen in the counties with aging population. African American population is projected to be concentrated in and around Atlanta metro counties, particularly southern metro counties of Rockdale, Henry, Clayton, Newton, and DeKalb counties (figure 3.2). Marion, Hancock, Warren, Macon, Richmond, Randolph, Terrell and Bibb counties in the “Black Belt” region are projected to have high African American population. Majority of Hispanic population will be clustered in southeastern counties, such as: Echols, Clinch, Colquitt, Cook, and Telfair, and northern counties, such as: Barrow, Franklin, Murray and Union. Stewart County in the southwest Georgia will also have high Hispanic population (figure 3.3).

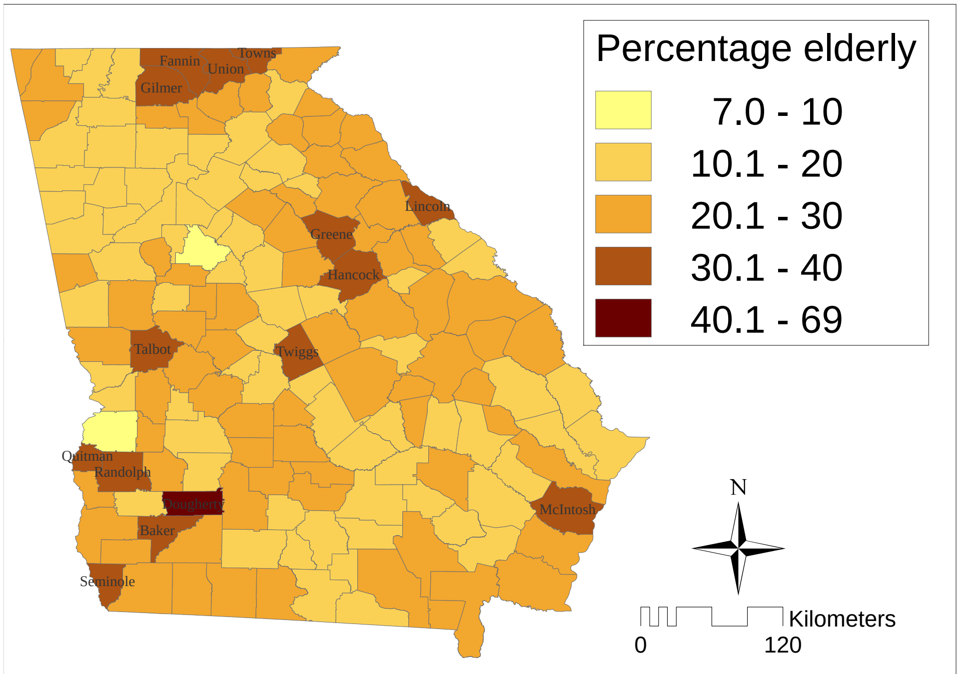

Figure 3.1: Percentage of elderly population in 2030

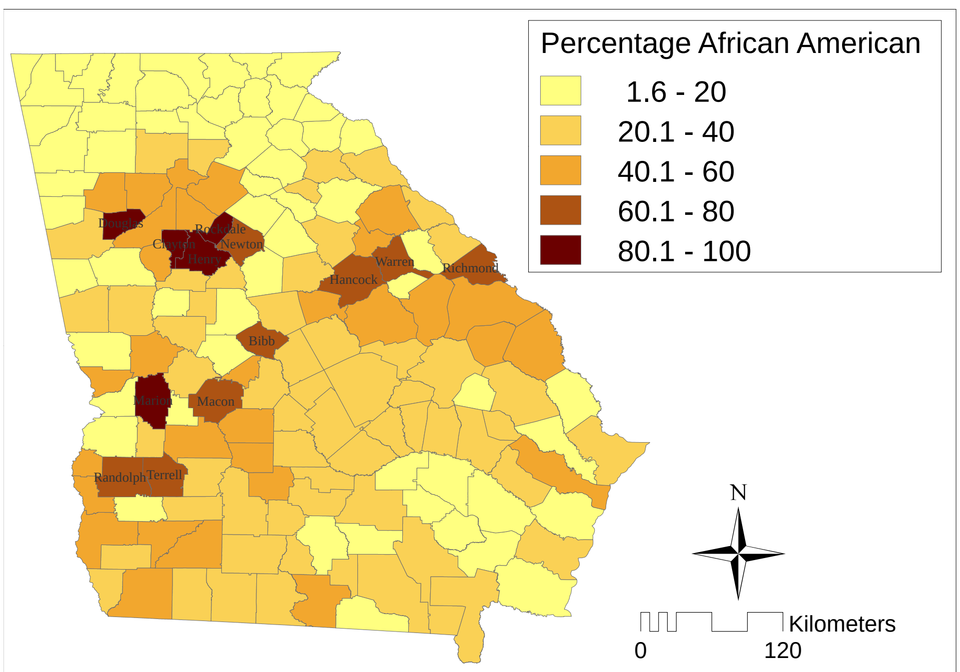

Figure 3.2: Percentage of African American population in 2030

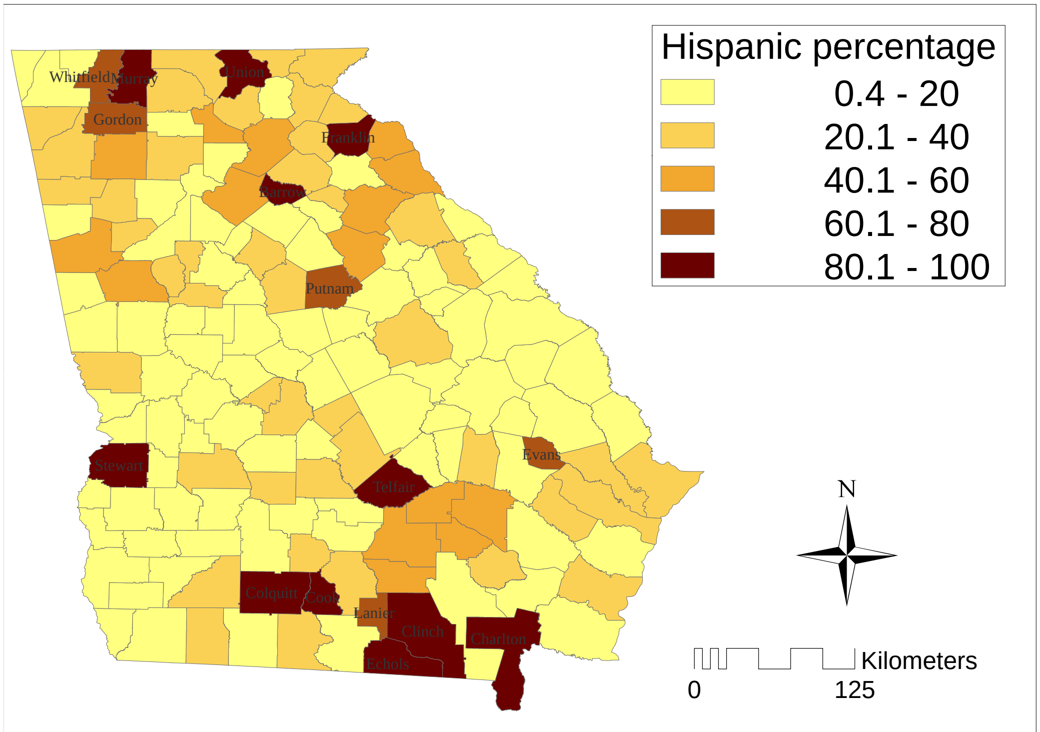

Figure 3.3: Percentage of Hispanic population in 2030

The infant population is projected to be highest in Whitefield, Echols, Hall Clinch and Cherokee county (figure 3.4). Infant population will be mostly concentrated in the metro Atlanta area and in southeast Georgia. People employed in agriculture, forestry, fishery, and hunting sectors will be high in Echols, Baker, Cook and Randolph, Brooks, that is, mostly in the Southwest Georgia (figure 3.5). People involved in construction are most concentrated in Stewart and Talbot Counties, respectively (figure 3.6).

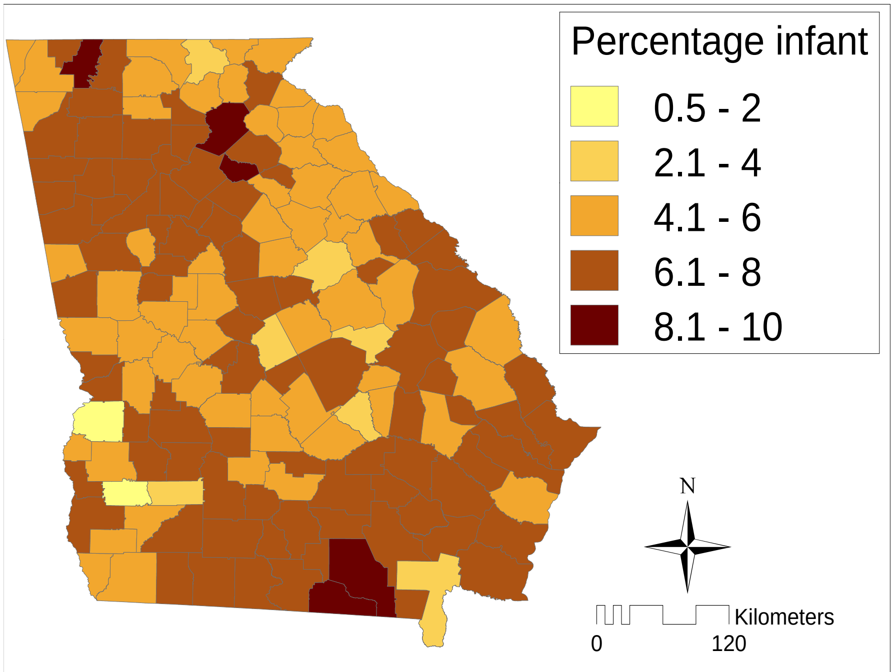

Figure 3.4: Percentage of infant population in 2030

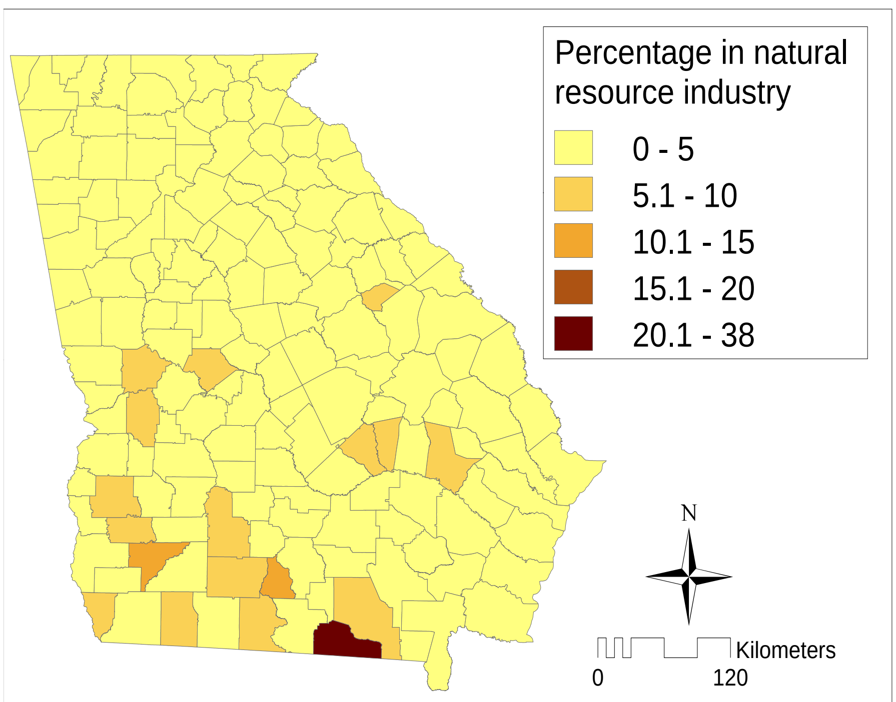

Figure 3.5: Percentage population involved in natural resource based industry

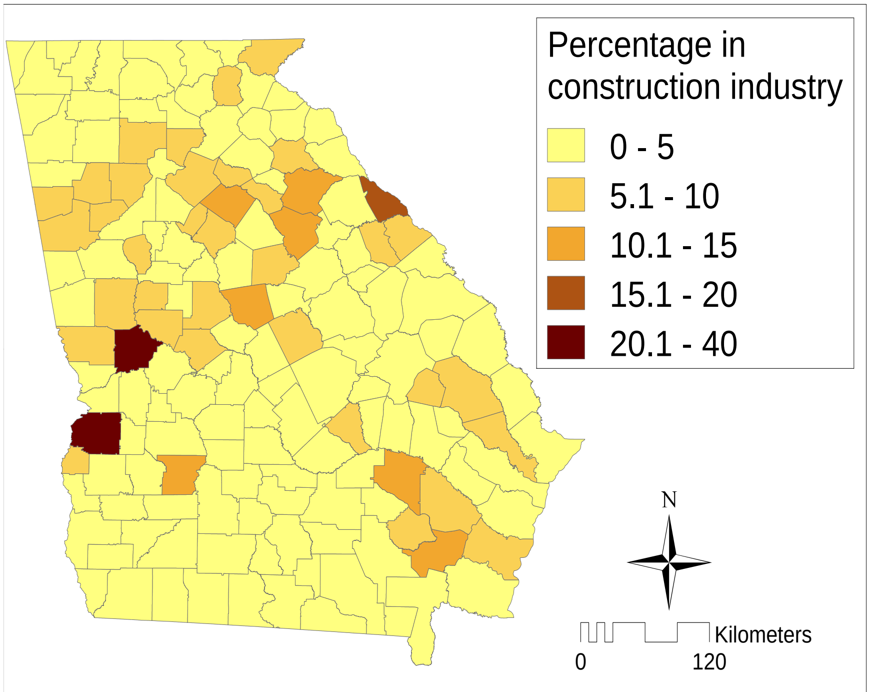

Figure 3.6: Percentage population involved in construction industry.

Social vulnerability (Figure 3.7) represents high-risk population such African American population, Hispanic, elderly population, population involved in forestry, fishery and hunting and construction, and infant population. High social vulnerability is projected to be clustered in suburban counties in Atlanta metro area, Southwest Georgia and counties south and east of the Atlanta metro area. High Social vulnerability clustered in Charlton, Ware and Clinch counties is due to the growth of the Hispanic population. High social vulnerability is projected in suburban counties in Atlanta metro area due to concentration of African American population. However, we should keep in mind the better environmental quality and social services of the suburban areas.

Recently there has been a lot of African American migration out of inner cities to much greener neighborhoods (Census Bureau 2002, Logan and Stults 2011). In Georgia, African

Americans are moving to the suburban Atlanta counties such as: Clayton, Henry, Rockdale, Newton, and Douglas in 2030. The out migration of African Americans from the inner urban counties towards more affluent suburb neighborhood will help to escape from constraints of the inner city. The migration to the suburb areas also helps these communities to avoid the pollution, elevated heat and hazardous environment of the inner cities. In these suburban spaces they can take advantage of the privileges of place, for example, access to better schools and health care facility, more housing space and the greener environmental conditions, hence lessening the social vulnerability to some extent.

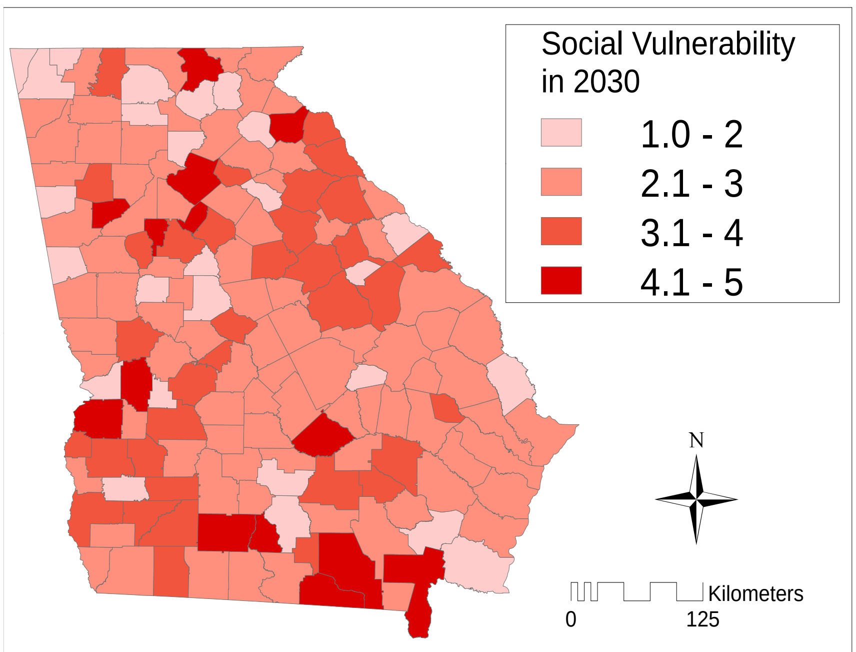

Figure 3.7: Social vulnerability as measured by summing up the elderly, African American, Hispanic, infant population and population involved in natural resource based industry and construction industry

Low social vulnerability is projected in North Georgia, which is due to low African American population and Hispanic population as well as low population dependent upon forestry and fishery. However, Union county will have high social vulnerability due to Hispanic population. Counties in east Georgia are vulnerable to sea level rise but exhibit low social vulnerability.

The anomalies in mean monthly temperature and precipitation in 2030s are increasing in the southwest Georgia. For example: Muscogee, Chattahoochee, Talbot, Upson, Meriwether, Randolph, Macon, Coweta, Crisp, Harris, Dooly, Taylor, Troup, and Ben Hill are projected to have standard deviations in temperature compared to the normal period 1971-2000 (figures 3.8 and 3.9). The counties in the west of the Atlanta metropolitan area have standard deviations as high as 4 which is very high compared to the standard deviation of 1 in recent decade (2010s). This indicates warming conditions in the 2030s. Similar warming conditions were observed in RCP 4.5 and RCP 8.5 conditions.

The counties with drier conditions are projected to be spatially clustered in southwest Georgia (figures 3.10 and 3.11). Some counties in north Georgia will also have drier condition (e.g., Catoosa, Whitefield, Gordon, Bartow, Cherokee, Stephens and Franklin). Similar conditions were observed for both RCP 8.5 and RCP 4.5 scenarios. Overall net drier conditions were projected over the state. Unlike temperature, precipitation projections suffer from uncertainties likely due to large natural variability in the southeast, and the southeast being in transition zone between projected wetter conditions to the north and drier conditions to the southwest (Kunkel *et al.* 2013, Melillo *et al.* 2014).

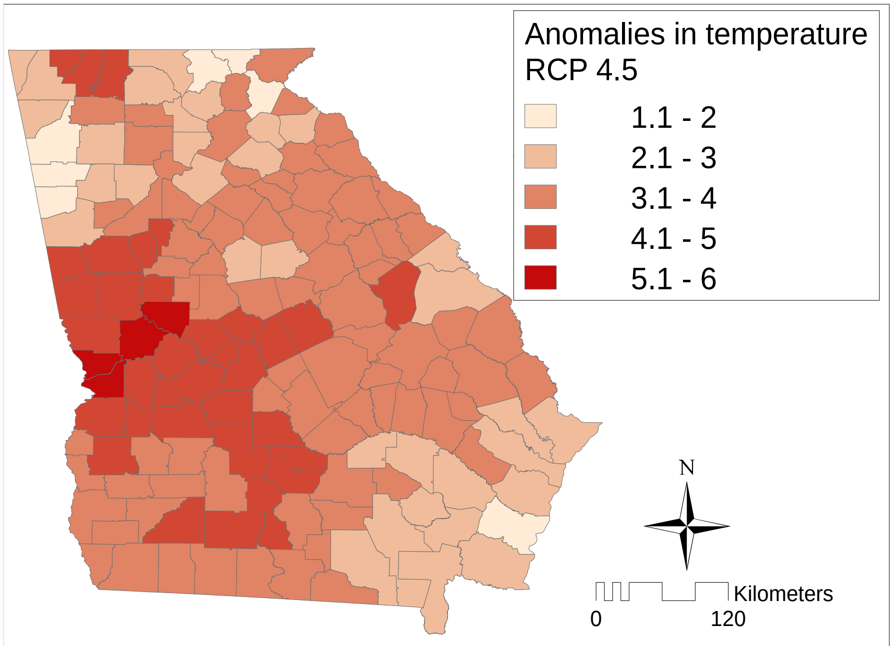

Figure 3.8: Anomalies in mean temperature in 2030s compared to baseline temperature in 1971-2001 indicated by z-score for RCP 4.5

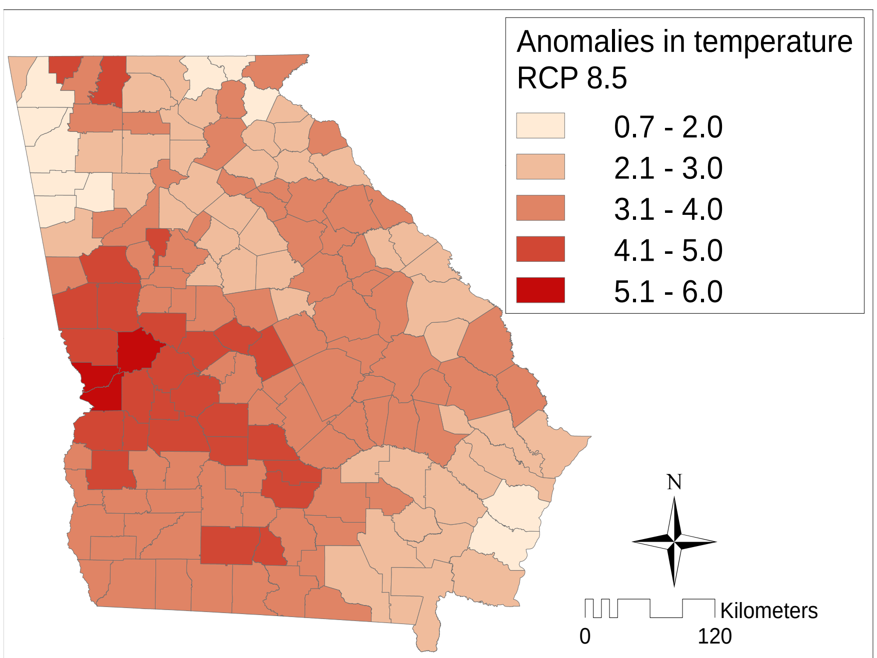

Figure 3.9: Anomalies in mean temperature in 2030s compared to baseline temperature in 1971-2001 indicated by z-score for RCP 8.5

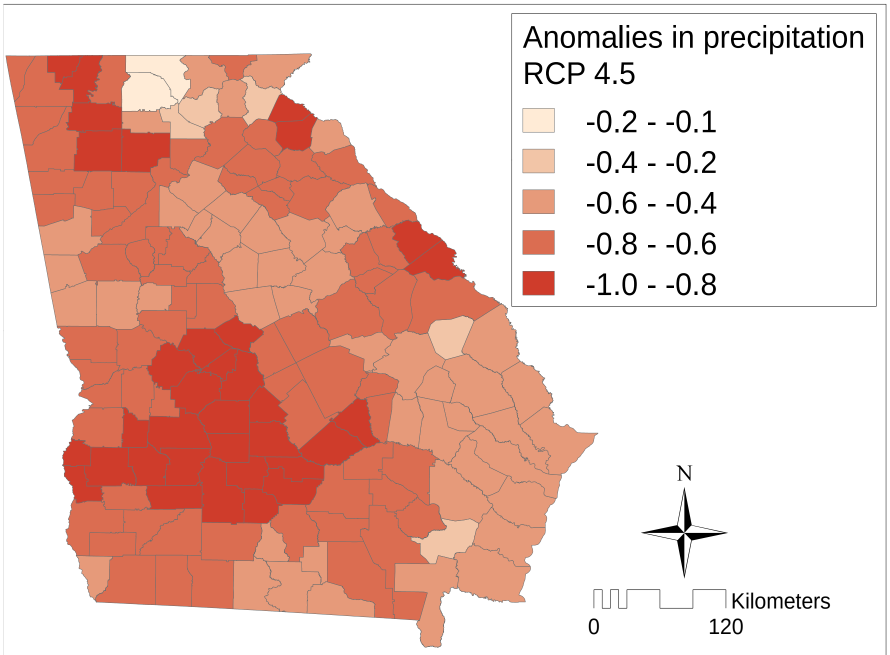

Figure 3.10: Anomalies in mean precipitation in 2030s compared to baseline precipitation in 1971-2001 indicated by z-score for RCP 4.5

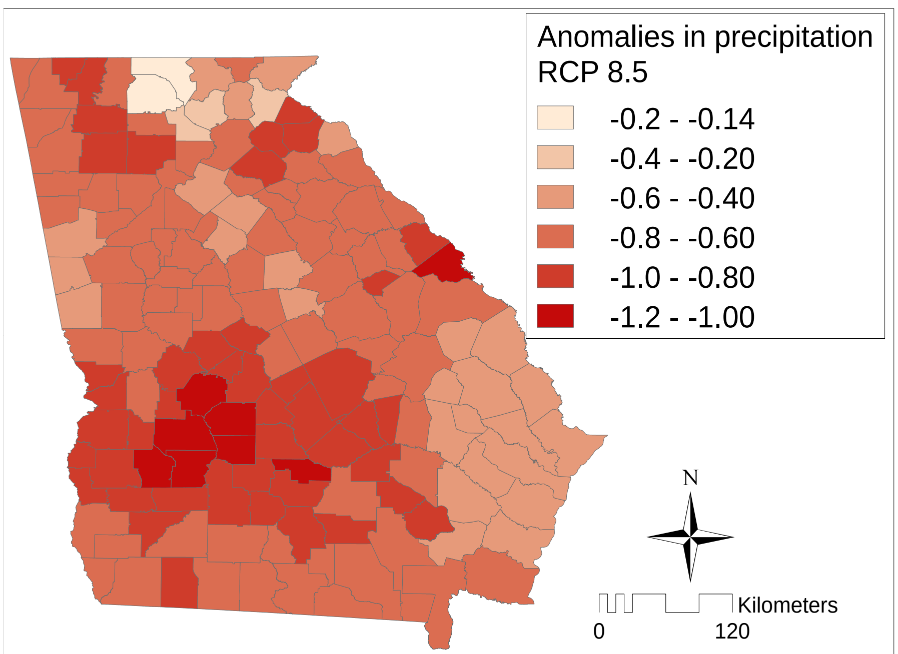

Figure 3.11: Anomalies in mean precipitation in 2030s compared to baseline precipitation in 1971-2001 indicated by z-score for RCP 8.5

Mean temperature and precipitation deviation were summed to indicate the counties, which will be affected by both change in temperature and precipitation. Looking at the mean temperature and precipitation projection (figures 3.12 and 3.13), overall heating and drying conditions will be observed in Southwest Georgia.

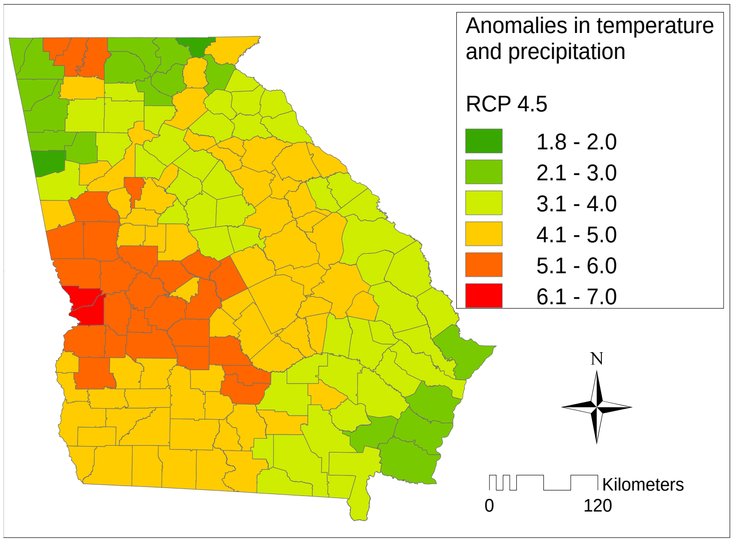

Figure 3.12: Anomalies in mean temperature and precipitation in 2030s compared to baseline temperature and precipitation in 1971-2001 indicated by z-score for RCP 4.5.

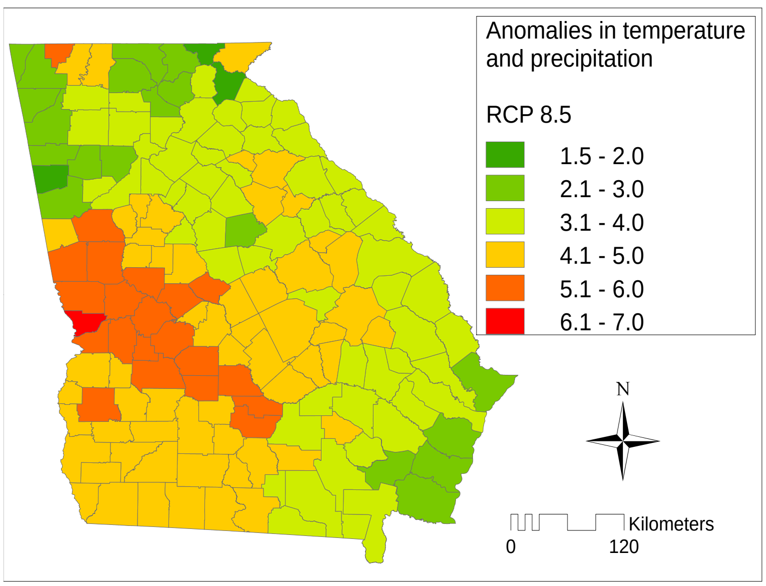

Figure 3.13: Anomalies in mean temperature and precipitation in 2030s compared to baseline temperature and precipitation in 1971-2001 indicated by z-score for RCP 8.5.

Similarly, projected daily temperature and precipitation over a 10-year period were analyzed to determine extreme temperature and precipitation events. The extreme precipitation event was calculated as the total number of days where the precipitation exceeds 25.4 mm is shown in red (figures 3.14 and 3.15). These counties are primarily in the northern part of Georgia. More counties will exceed this precipitation threshold in RCP 8.5 projection than in RCP 4.5. Similarly, however, southern Georgia seems to have less number of such events, roughly less than 50 events over a decade. The northern counties are mountainous and already receive significant rainfall. This finding is consistent with the notion of wet regions becoming wetter in a warmer climate system (Melillo *et al.* 2014).

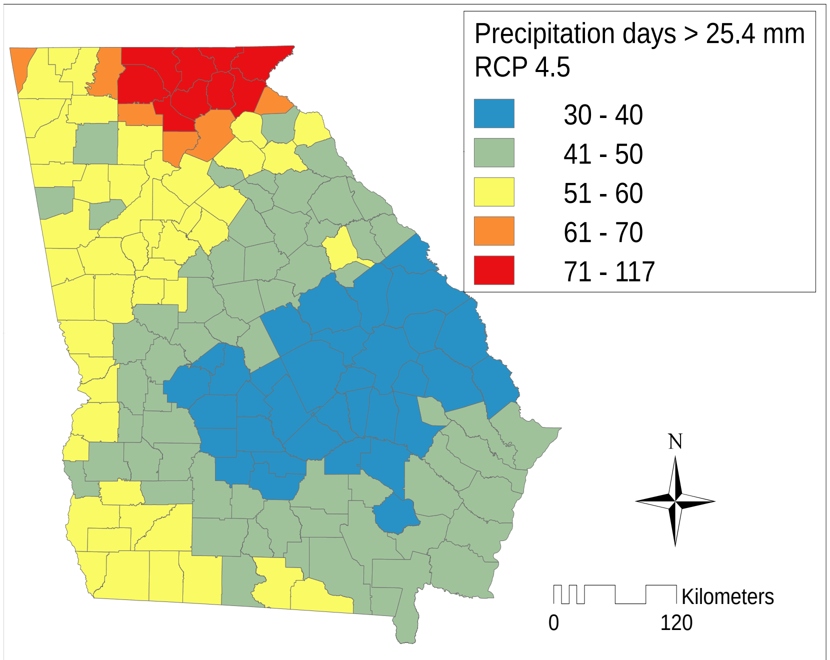

Figure 3.14: Heavy precipitation days exceeding 25.4 mm (1 inch) precipitation during 2030s for RCP 4.5

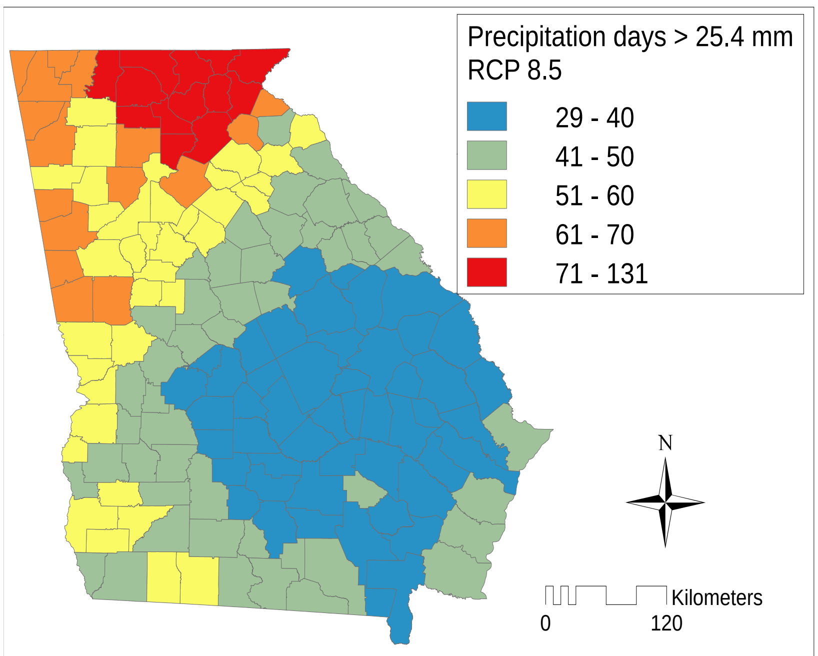

Figure 3.15: Heavy precipitation days exceeding 25.4 mm (1 inch) precipitation during 2030s for RCP 8.5

The total number of extreme heat events, where temperature exceeds the 97.5 percentile of the (2010 daily temperature) consecutively for three days, is highest in the metro Atlanta counties and some counties in northern Georgia. Approximately 17-20 magnitude heat wave events will be observed over 10 year period (figures 3.16 and 3.17). More Atlanta metro counties will experience these extreme heat events in RCP 8.5 than in RCP 4.5. The counties in north Georgia will also experience a significant number of 12-16 magnitude deviation events over the 10-year period.

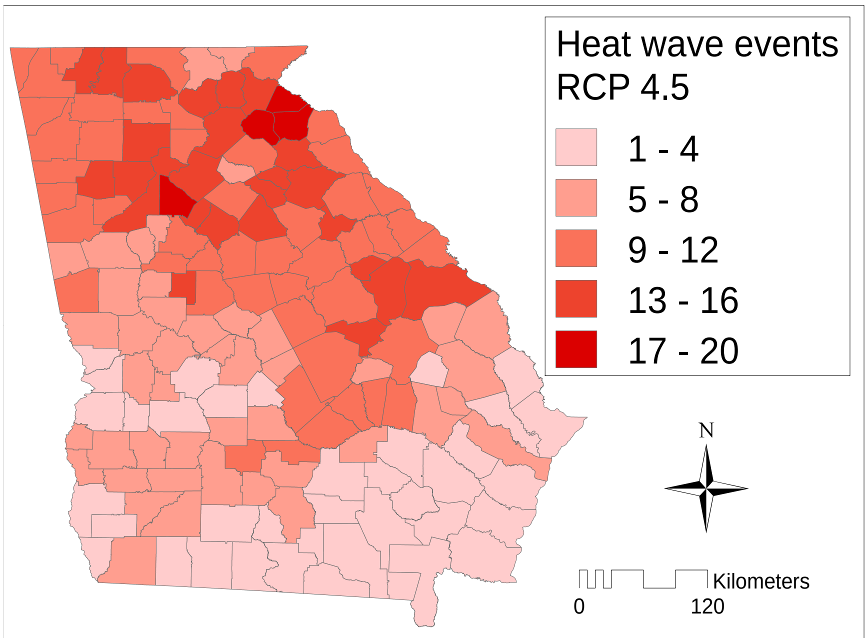

Figure 3.16: Extreme heat waves during 2030s for RCP scenarios 4.5. Extreme heat events exceeding the 97.5 percentile of the (2010 daily temperature) consecutively for three days

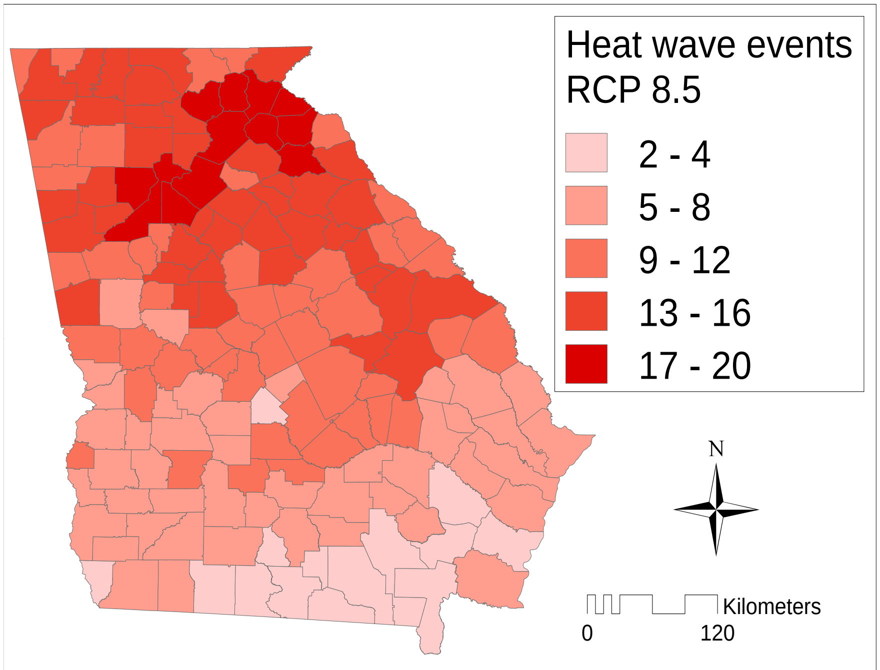

Figure 3.17: Extreme heat waves during 2030s for RCP scenarios 8.5. Extreme heat events exceeding the 97.5 percentile of the (2010 daily temperature) consecutively for three days

Figures 3.18 and 3.19 show the overall climate vulnerability index, which indicates the social vulnerability, mean change in temperature and precipitation, and frequency of extreme events together. Figure 8 shows the Atlanta metro as the most vulnerable part of the state in the future. There seems to be a constant pattern in vulnerability across Georgia. Southeast Georgia seems to be least vulnerable. Most vulnerable counties are clustered in the east of Atlanta metro in both RCP scenarios. Moreover, high vulnerability is seen in RCP 8.5 scenario.

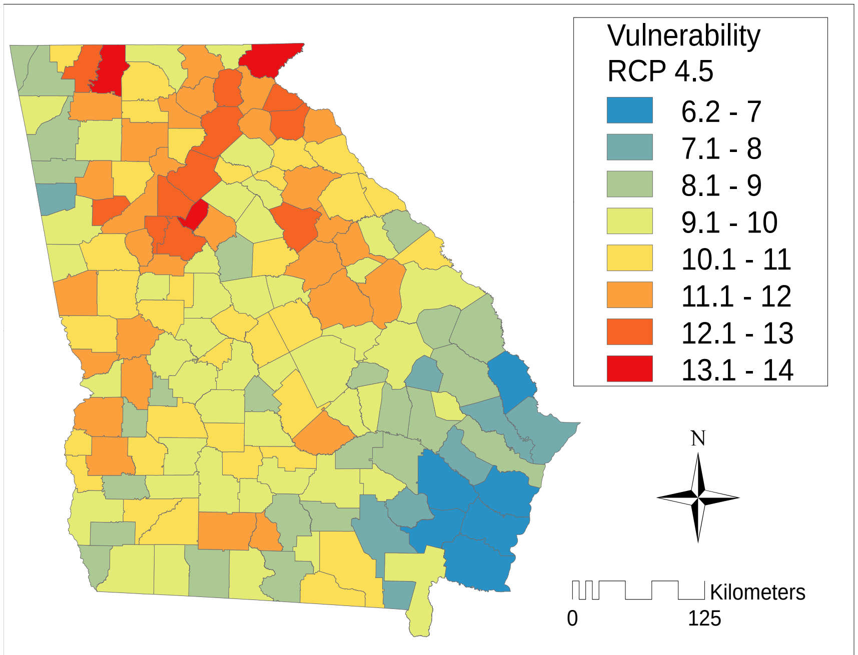

Figure 3.18: Climate vulnerability index by merging social and climatic exposure for RCP scenarios 4.5

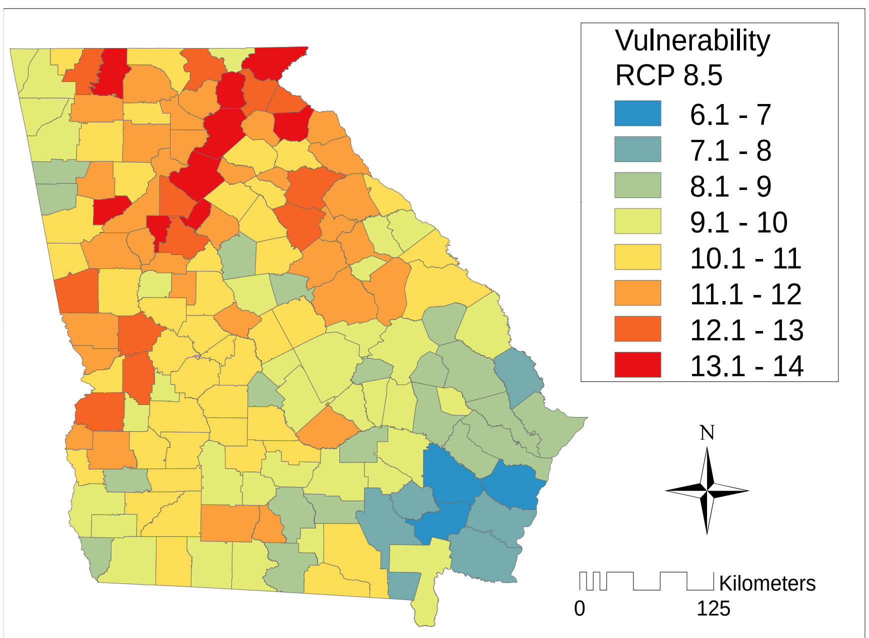

Figure 3.19: Climate vulnerability index by merging social and climatic exposure for RCP scenarios 8.5

Percentage of land exposed to 1 feet, 2 feet, 3 feet and 4 feet water levels adjusted to local MHHW is shown in figures 3.20, 3.21, 3.22 and 3.23, respectively. The highest percentage of land exposed to these water levels are in Chatham and McIntosh counties. Whereas the concentration of coastal property in less than 3 feet above MHHW (Strauss *et al.* 2014) and high population in 2030 make Chatham and Glynn County most vulnerable to future sea level rise and coastal inundation.

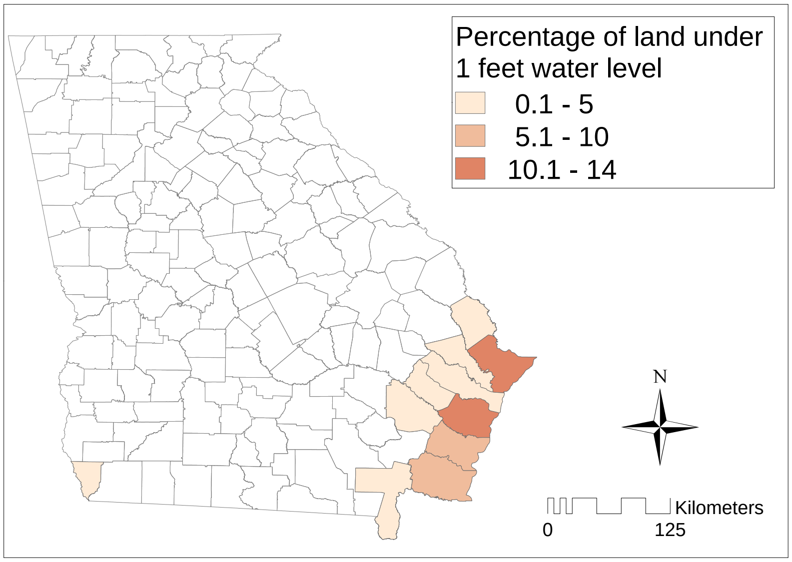

Figure 3.20: Percentage of land exposed below 1 foot water level (local Mean Higher High Water)

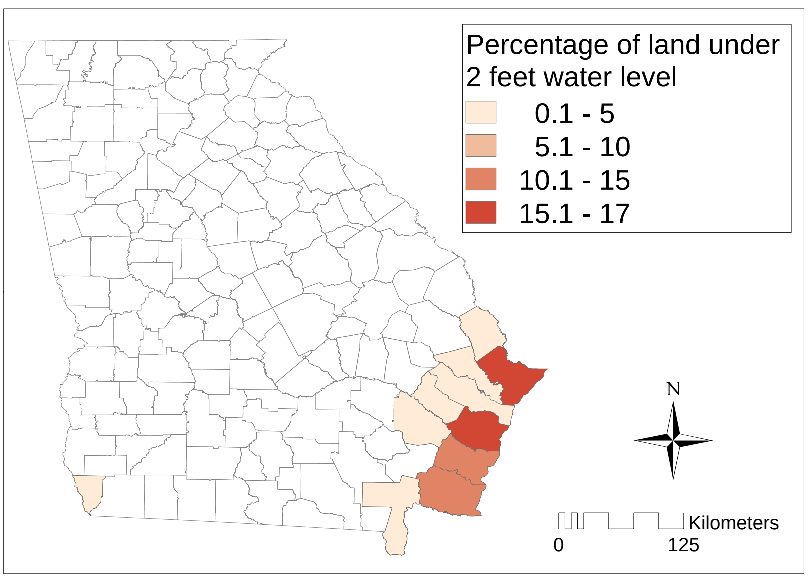

Figure 3.21: Percentage of land exposed below 2 feet water level (local Mean Higher High Water)

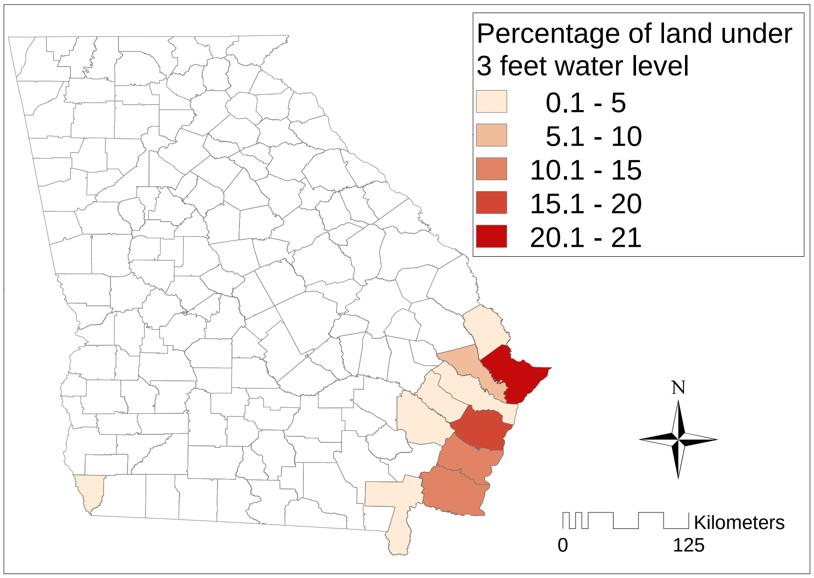

Figure 3.22: Percentage of land exposed below 3 feet water level (local Mean Higher High Water)

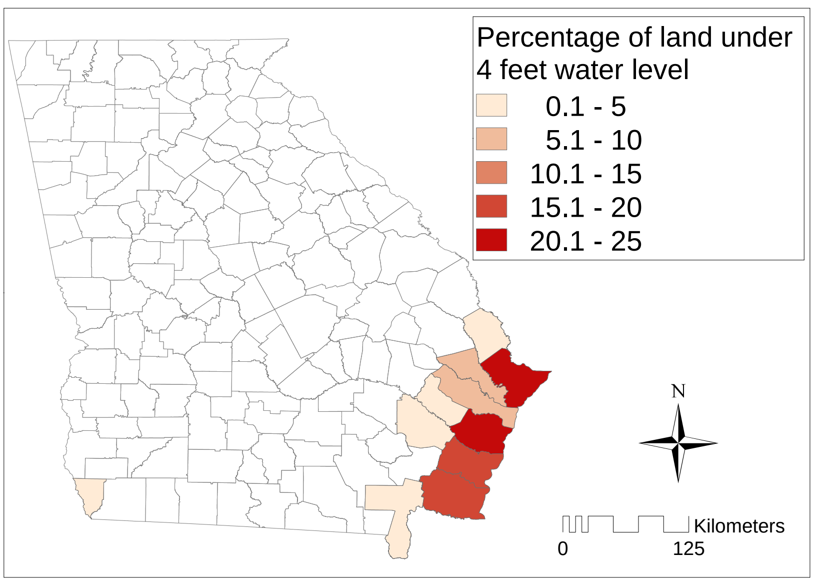

Figure 3.23: Percentage of land exposed below 4 feet water level (local Mean Higher High Water)

Figure 3.24 shows overall climate vulnerability by integrating the climate change vulnerability map under RCP 4.5 (figure 3.18) with areas exposed to 3 feet MHHW adjusted water level (figure 3.22). Similarly, figure 3.25 shows overall climate vulnerability under RCP 8.5 (figure 3.19) coupled with areas exposed to 4 feet water level (figure 3.23). Climate change vulnerability highlights socially and climatologically vulnerable counties and does not provide any indication of coastal vulnerability to potential sea level rise, and storm surges. Integration of flood risk areas with climatologically and socially driven vulnerability provides a better assessment of future climate vulnerability. Coastal counties specially, Chatham County, emerged as the most vulnerable after considering the geographic vulnerability with higher vulnerability under RCP 8.5 scenario.

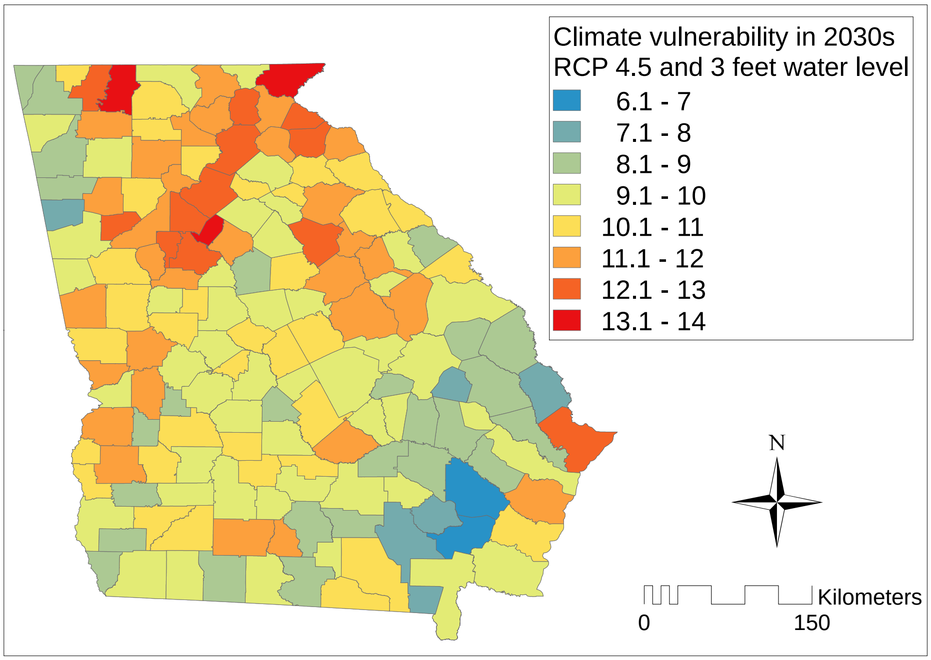

Figure 3.24: Climate vulnerability in 2030s under RCP 4.5 scenario merged with percentage of land below 3 feet water level (adjusted to local Mean Higher High Water)

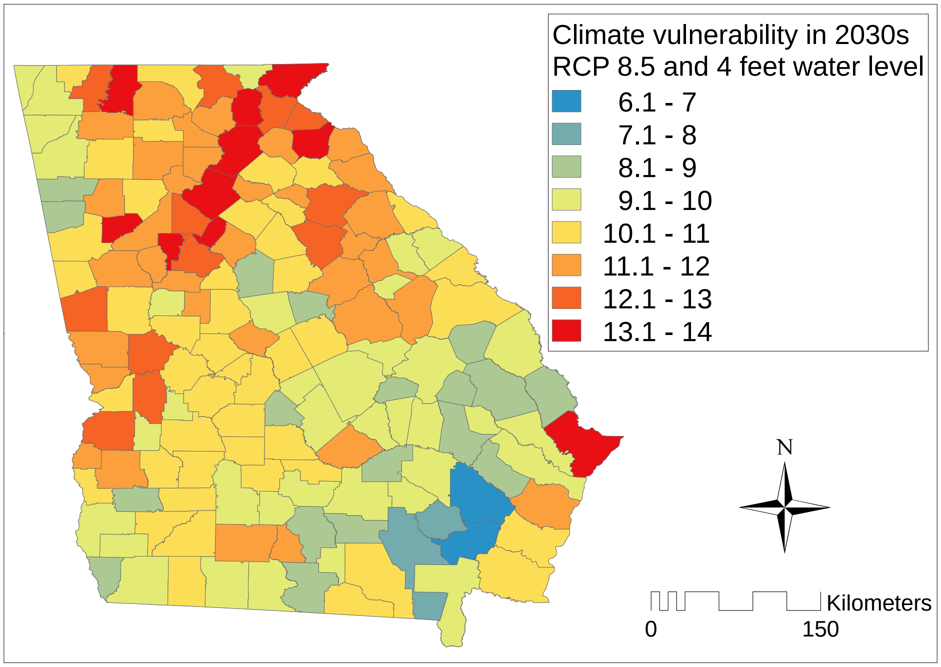

Figure 3.25: Climate vulnerability in 2030s under RCP 4.5 scenario merged with percentage of land below 4 feet water level (adjusted to local Mean Higher High Water)

Case studies

Climate vulnerability might be climatologically, socially or physiographically driven depending on the geographic location of a county. To explore various dimensions of vulnerability, a case study is performed in three counties in Georgia: a rural county, Stewart; a suburban county, Gwinnett; and a coastal county, Chatham.

The components of climate vulnerability in Gwinnett County is shown in figures 3.26. In Gwinnett County, climate change vulnerability is mainly driven by social vulnerability as well as extreme events such as frequent heat wave events. High social vulnerability in Gwinnett County is mainly due to concentration of ethnic minorities such as African American and Hispanic population (figure 3.27). However, social vulnerability in the suburban county depends upon other factors such as place of residence, access to social services, and income level which is not considered here due to limited socioeconomic projection. The better living condition in Gwinnett County can lessen the impacts of frequent heat wave events in the future.

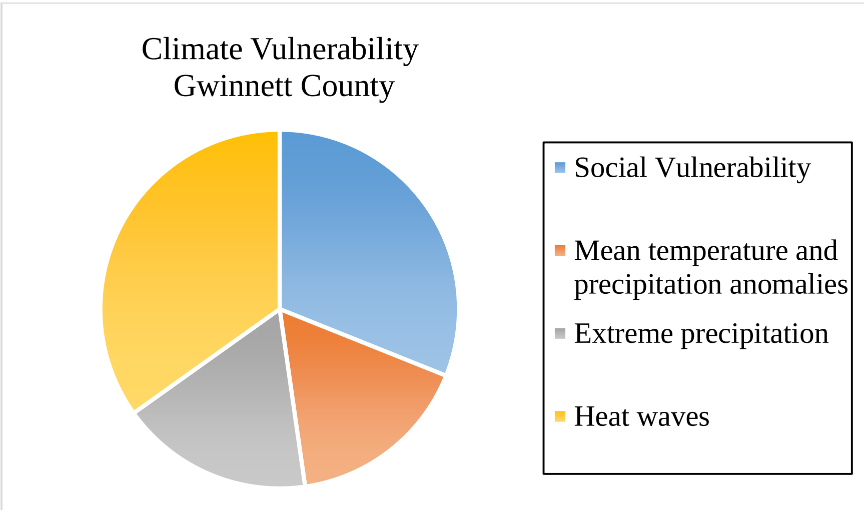

Figure 3.26: Components of climate vulnerability in Gwinnett (suburban county)

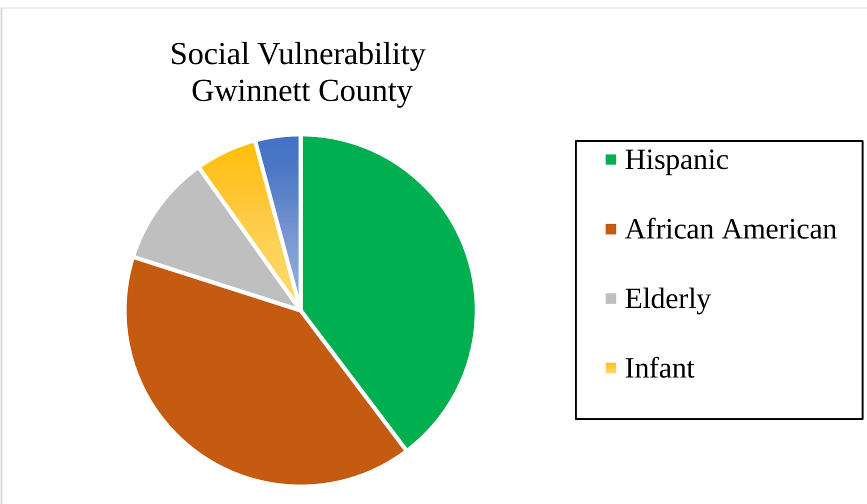

Figure 3.27: Factors driving social vulnerability in Gwinnett (suburban county)

Stewart, a rural county, is both climatologically and socially vulnerable (figure 3.28). High social vulnerability is mainly driven by high Hispanic population with agriculture as their main stay economy (figure 3.29). Greater anomalies in temperature and precipitation with warmer and drier conditions will have adverse effects on the agriculture industry affecting the livelihood of the farming community. Construction industry is another major source of income in this county. The warmer climate will affect health conditions of those heavily involved in construction industry. Hence, Stewart County is highly climate sensitive because of lack of resilience.

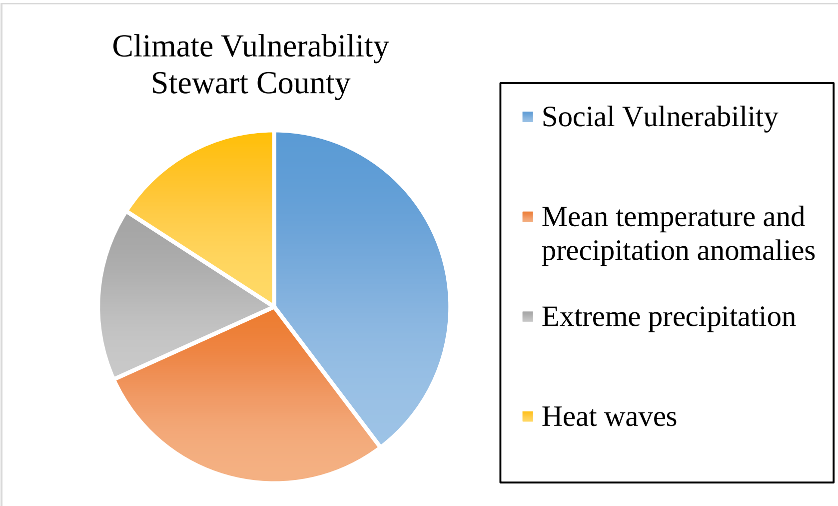

Figure 3.28: Components of climate vulnerability in Stewart County (rural county)

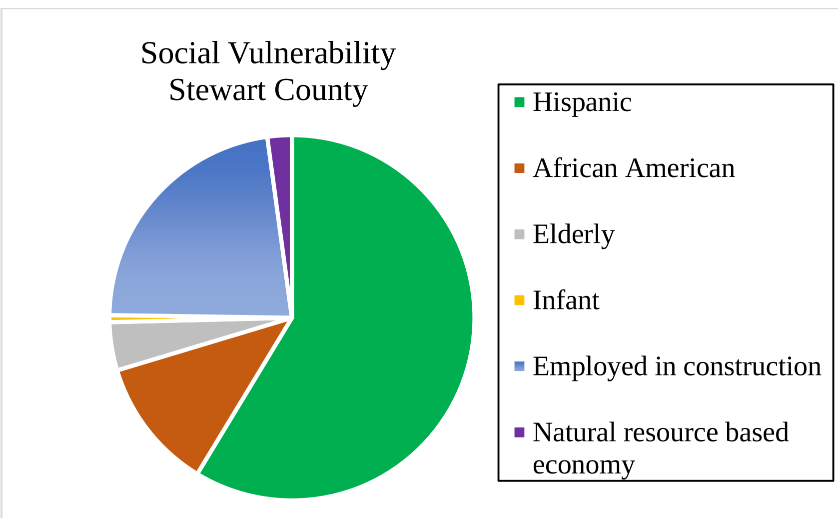

Figure 3.29: Components of social vulnerability in Stewart County (rural county)

If the low education attainment and low household income trend continues, higher social vulnerability than indicated by our social vulnerability index can be expected in 2030.

Chatham County has relatively low social vulnerability due to lower percentages of racial/ethnic minorities. Climate vulnerability in Chatham County is mainly driven by geographic vulnerability (Figure 3.30). Because of concentration of population and coastal property in less than 3 feet above MHHW (Strauss *et al.* 2014), Chatham County is at higher risk of flooding due to potential sea level rise and coastal inundation.

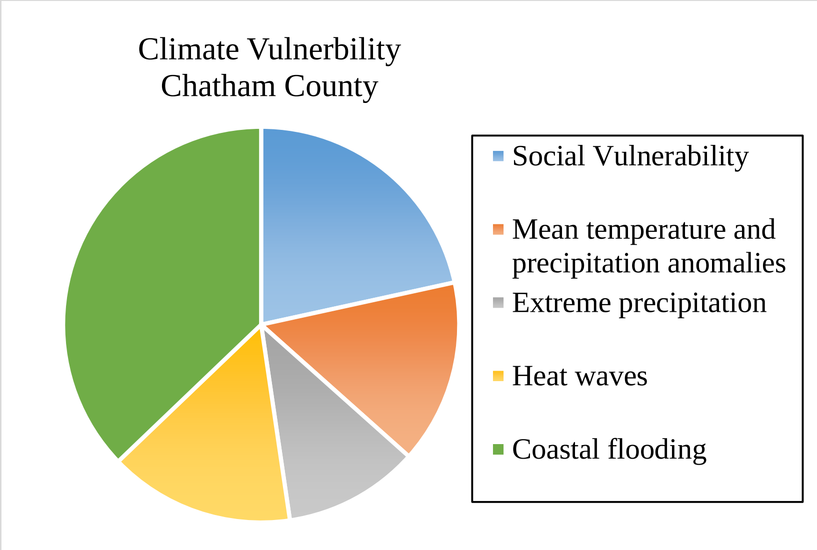

Figure 3.30: Components of social vulnerability in Chatham County (coastal county)

3.4 Conclusion

Increased heat wave events are projected in metro Atlanta counties. Moreover, heat wave events are more frequent in the RCP 8.5 scenario in these counties. Additionally, urbanization of Atlanta metro will increase climatic exposure due to increased risk of heat waves. More floods can be expected in the built environment because of increased runoff (Shepherd *et al.* 2011). Frequent heavy precipitation days are predicted in northern and southeastern counties whereas anomalies in mean temperature and precipitation compared to historical baseline climate are high in the western counties. Counties in southwest Georgia turned out to be socially vulnerable. Based on high concentration of ethic/racial minorities, Atlanta metro counties will be socially vulnerable, however, our analysis does not provide complete analysis of social vulnerability because of lack of adaptive capacity variables such as education attainment, access to healthcare facilities, and income level. Furthermore, the suburban Atlanta counties which are projected to have high social vulnerability could actually have lower social vulnerability in 2030 after considering better living conditions in suburbs such as better housing condition and green space. Despite the low social and climatological vulnerability, coastal counties are at flood risk from potential sea level rise and storm surges. Overall, climate vulnerability is high in Atlanta metro, some counties in the southwest Georgia, also known as "Black belt" counties, and coastal counties.

Climate change projection helps to identify climatologically hotspots. Climate change vulnerability studies often lack the social component because of difficulty in projecting future socioeconomic variables. In this study, climate change and variability is coupled with social and geographic component to derive climate change vulnerability in the 2030s. Most of the climate projections are performed at the end of or middle of the 21st century. This study focuses on short term projection of vulnerability in the state of Georgia by counties. Comprehensive assessment of future vulnerability is performed, which helps to target the adaptation strategies in an efficient manner.

Here, future climatic exposure and social components are given equal weights while deriving vulnerability index. However, weighting different components of vulnerability index could be a future research topic. The temperature and precipitation projections are based on statistically downscaled climate as opposed to dynamic downscaling. Also, the uncertainties in social vulnerability are mainly associated with cohort component projection.

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CHAPTER 4

4 HEAT AND COLD RELATED MORTALITY IN THE UNITED STATES BY RACE[3]

[3] KC, B., and J.M. Shepherd (2014). Heat and Cold related mortality in the United States by race. To be submitted to *Environmental Health Perspectives*

Abstract

This study test the hypothesis that African American suffer excess mortality due to extreme heat and cold compared to White Americans. Compressed mortality datasets from Center for Disease Control and Prevention (CDC) is utilized to test the hypothesis that African American bear the burden of extreme temperature conditions. T-test is performed at state level analysis in decadal span from 1969-2008 representing the decades of 1970s (1969-1978), 1980s (1979-1988), 1990s (1989-1998) and 2000s (1999-2008).

The test results showed that the normalized African American morality rate due to extreme heat and cold is significant higher than White mortality in throughout the decades except in 1970s during which the heat related morality in African American was not significantly higher than White. The elevated morality rate in African American population can be attributed to low socioeconomic status, poor housing condition and living in inner cities. There have been substantial decrease in both heat related and cold related morality in both races. Despite the increase in heat wave events in recent decade, the decrease in heat related morality is likely due to availability of air conditioning whereas the decrease in cold related mortality is due to decrease in cold related events.

4.1 Introduction

In addition to long-term increases in temperature and precipitation, studies suggest increased frequency and intensity of heat waves in recent decades and that heat related mortality could double by end of the century in major US cities (Easterling *et al.* 2000, Tebaldi *et al.* 2006, Zhou and Shepherd 2010, Stone *et al.* 2014). The Southeast United States, along with the Southwest and Midwest, are predicted to experience more intense heat waves in the future (Meehl and Tebaldi 2004, Meehl *et al.* 2009) due to increases in both maximum temperatures and minimum temperatures (Dole *et al.* 2011, Otto *et al.* 2012, Coumou and Rahmstorf 2012). With the increase in frequency and intensity of extreme temperature, vulnerability to heat waves is increasing. The negative effects of heat on human cardiovascular, cerebral, and respiratory systems are well established (Changnon and Kunkel 1996, Kovats and Ebi 2006, Kovats and Hajat 2008, O'Neill and Ebi 2009, Sherwood and Huber 2010) as people with severe heat stroke symptoms have little time to seek treatment in emergency departments (EDs) or hospitals (Naughton *et al.* 2002, Kovats *et al*. 2004, Kovats and Ebi 2006, Knowlton *et al.* 2009).

The prevalence of both morbidity and mortality for cardiovascular diseases, diabetes, and cancer are high in most racial/ethnic minorities, particularly African Americans and Hispanics (Hayward *et al.* 2000, O'Neill *et al.* 2003, Kaiser *et al.* 2007, Medina-Ramon *et al.* 2006). Infants and children are at risk of extreme temperatures as they cannot regulate their body temperature like adults and this trend is high among African American population (Zahran *et al.* 2008).

The 'human ecology of endangerment' by Hewitt (1997) states that poorer households tend to live around hazardous areas especially in urban settlements, which are at elevated risk of short term climate extremes as well as long term climatic changes. Racial/ethnic minorities with low socioeconomic status bear a disproportionately high health burden related to climate extremes, resulting from differences in housing characteristics (e.g. air conditioning), access to healthcare, differential prevalence of certain predisposing medical conditions and residential segregation (Hayward *et al.* 2000, Uejio *et al.* 2011, Jesdale *et al.* 2013). In past decades, African Americans were more likely than whites to live near industrial or manufacturing jobs in the inner cities because of housing discrimination, residential segregation and limited availability of public transportation to work in suburbs (Bullard 1990). Using contemporary Geographic Information Systems (GIS) analyses, Mohai and Saha (2007) found that African Americans were also more likely than others to live proximal to facilities the Environmental Protection Agency categoriezes as TSDFs or hazardous waste Treatment Storage and Disposal Facilities. Because of their marginalized positions in society, these groups often have the hardest time preparing for and responding to disasters; they receive less help coping with its effects, and thus suffer disproportionately large impacts when a disaster occurs (Zahran *et al*. 2008). The extreme weather and climate events interact with the social component before they convert into a disaster (IPCC 2012).

Heat related mortality and morbidity studies have been performed (Donoghue *et al*. 2003, Hajat *et al.* 2006, Kinney *et al.* 2008, Medina-Ramon *et al.* 2006, Vandentorren *et al.* 2004, Kovats *et al.* 2004, Mastrangelo *et al.* 2006, Nitschke *et al.* 2007, Knowlton *et al.* 2009), however, these studies have been focused on a single heat wave event and limited study areas. Maier *et al.* (2014) suggest poverty and population of non-white residents as the driving factors of heat vulnerability in urban counties while in rural counties, social isolation and prevalence of elderly with poor health conditions were the most prominent factors.

Additionally, hazards research in the United States focuses more on economic losses rather than examining injuries and deaths (Cutter *et al.* 2008, Borden and Cutter 2008). Thacker *et al.* (2008) examined spatial distributions of deaths associated with natural events from 1979-2004 using the compressed mortality files from Centers for Disease Control and Prevention (CDC). They found that 75 percent of the total number of deaths attributed to natural events were due to extreme cold or heat, which is more than all deaths resulting from lightning, storms, floods, earthquakes, and landslides. Heat wave is the number one weather related killer in the United States (National Weather Service 2012, Borden and Cutter 2008). Given the centrality of heat-related deaths in the U.S., the present analysis focuses on mortality due to extreme temperatures. Specifically, we examine whether a subset of the minority population, African Americans, are more likely than (who) to bear the brunt of climate extremes. For instance, Whitman *et al.* (1997) reported higher mortality of African American than Whites during the 1995 heat wave in Chicago.

The hypothesis that socially marginalized populations are particularly vulnerable, the so-called Climate Gap is tested (Morello-Frosch *et al.* 2009). We analyze mortality data to assess whether African American populations suffered more deaths than the White population during a 40-year span using decadal datasets. We based our analysis on African American and White populations only because Hispanic mortality dataset were available only after 1999. More specifically, the aim is to descriptively analyze how African American mortality by excessive heat (hyperthermia) and cold (hypothermia) vary spatially and temporally at the state level compared to White mortality.

Section 4.2 describes data and methodology used to derive mortality rate of African American and White populations due to excessive heat and cold. Section 4.3 provides the results of t-test and regional variation in mortality rate. Conclusions are provided in section 4.4.

4.2 Data and Method

The mortality data were obtained from Centers for Disease Control and Prevention (CDC) compressed mortality files (http://wonder.cdc.gov/cmf-ICD10.html). CDC Wonder is comprised of Compressed Mortality Files (CMF) (CDC, 2004a) by age cohort, gender, race, urban status, and county. Underlying cause of death is selected from conditions indicated by a medical professional on the cause-of-death section of a death certificate. The external cause of mortality and morbidity classification is based on the International Classification of Diseases, edition 10 (ICD-10), ICD-9 and ICD-8 for years 1999 -2008, 1979-1998, 1976-1978, respectively. We focused our analysis at the state level since counties with less mortality counts were suppressed for privacy. Our analysis focuses only on the states where mortality data are available for both African American and White populations. Hence, heat and cold related mortality data were available in the Southeast, Midwest, Northeast and Southwest whereas very limited data was available in Northwest United States due to data suppression. The number of states varies in each decade depending on where mortality occurred during the decadal span.

State level mortality count for both African American and White populations were obtained at decadal span. The 10-year mortality rates of African American and White population during each decadal span, 1969-1978 (1970s), 1979-1988 (1980s), 1989-1998 (1990s), and 1999 -2008 (2000s), were normalized by African American and White population in 1970, 1980, 1990, and 2000, respectively. The normalized population was multiplied by with 100000. For example, African American mortality rate of a state during 1970s was calculated as total African American mortality during 1970s is expressed by equation (4.1). This helps to adjust for the differing percentage of African American and White population in any particular state.

$$\frac{\text{(African American mortality in 10 years) x 100,000}}{\text{(African American population in 1970)}} \qquad (4.1)$$

In order to test whether African American suffered more heat or cold related mortality than White population, t-tests were performed. We set the null hypothesis as African American mortality and White mortality are similar and the alternative hypothesis as African American heat or cold related mortality is greater than White mortality.

4.3 Results

Using heat related mortality rate for 10 years from 1969 to 1978 (1970s), t-test results show a p-value of 0.34 which is greater than a pre-specified significance level of 0.05 (95% confidence level) hence we fail to reject the null hypothesis. T-test for years 1979-1988 (1980s), 1989-1999 (1990s), and 1999-2008 (2000s) show p values of 0.003, 0.028, and 0.01, respectively, hence we reject the null hypothesis. Therefore, we conclude that, for these decades, heat related mortality of African American is greater than White population. Overall, there is no statistical evidence that heat related mortality in African American is greater than White Americans during the 1970s, but in the decades afterwards, statistical analysis provides confidence that African American suffered more heat related mortality compared to White population. Mortality rates during 1970s, 1980s, 1990s, and 2000s, respectively, can be compared in figures 4.1- 4.4.

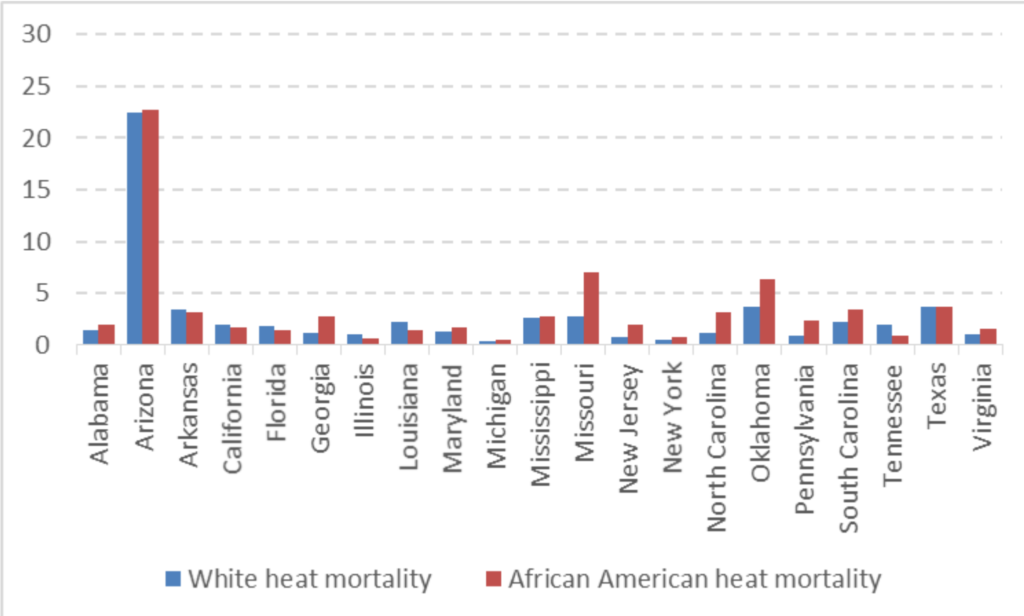

Figure 4.1: African American and White heat mortality per 100000 population during the 1970s

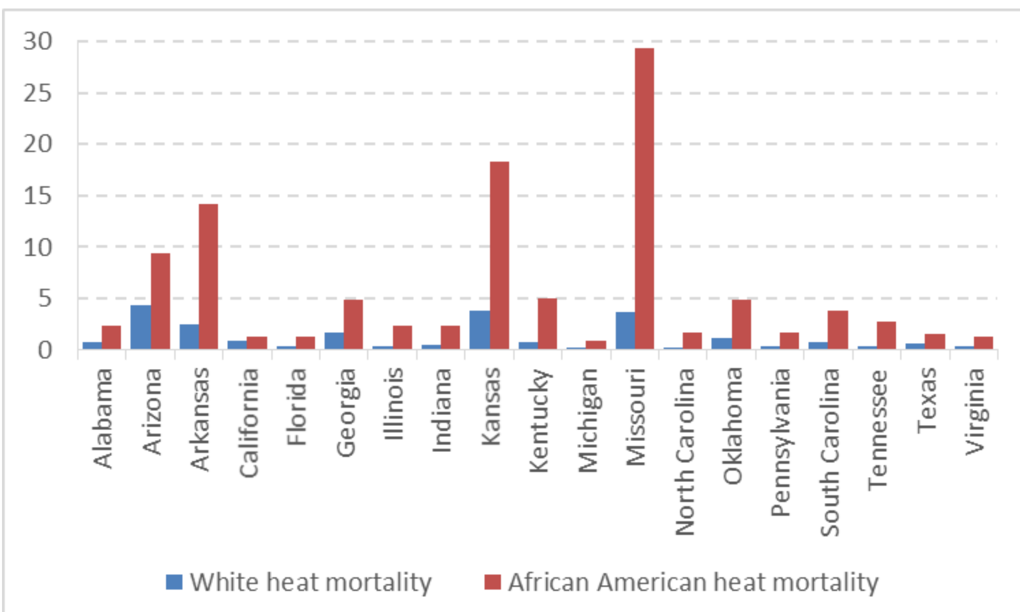

Figure 4.2: African American and White heat mortality per 100000 population during the 1980s

The return migration of African American towards the inner cities in the South during the mid-1970s and during 1980s may explain the elevated African American mortality rate during

1980s. The inner cities are prone to higher heat-related deaths because of more built environment and less green space which can further exacerbate a heat wave (Zhou and Shepherd 2010, Reid *et al.* 2009). Furthermore, the substantial decline in weekly wage and salary income in the African American population and deterioration of standard of living of the households during 1980s (Danziger and Gottschalk 1993, Williams and Collins 1995) could also be related to the higher heat related mortality in African American. Social isolation and elderly population could be other factors driving the vulnerability in rural areas (Maier et al. 2014). However, due to limited data availability at decadal scale our analysis does not allow us to control for the place of residence such as urban or rural environment.

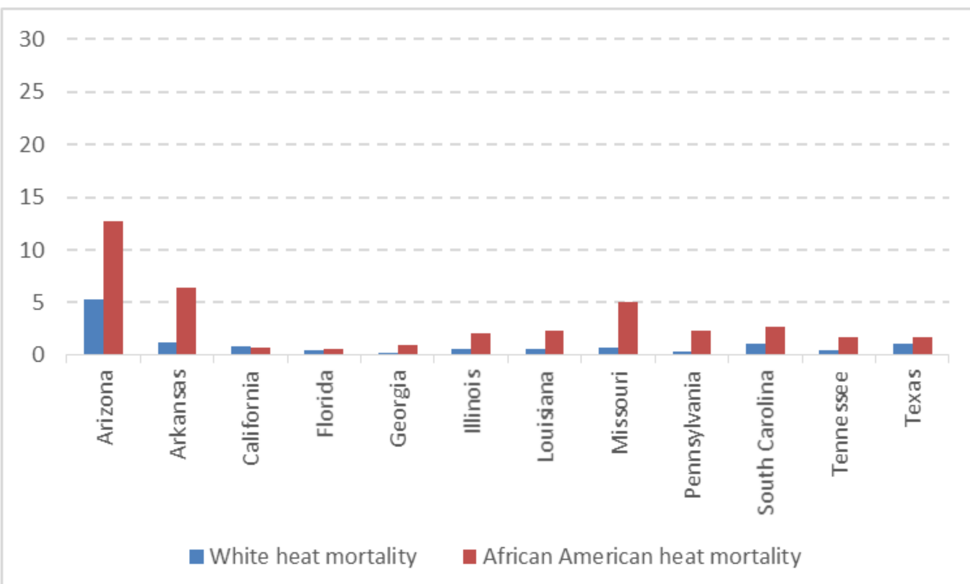

Figure 4.3: African American and White heat mortality per 100000 population during the 1990s

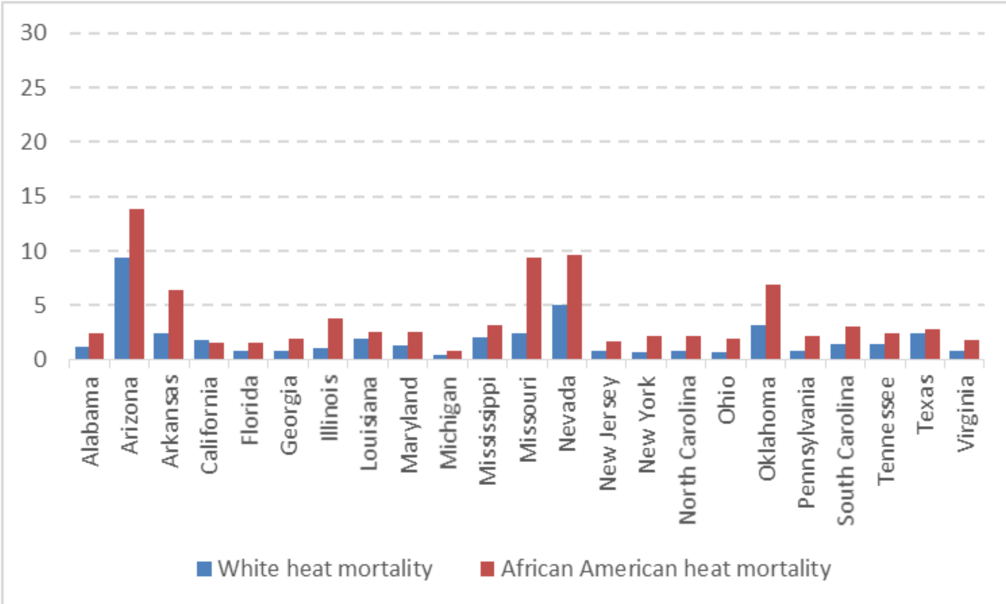

Figure 4.4: African American and White heat related mortality per 100000 population during the 2000s

The heat related mortality rate in African Americans peaked during the 1980s and declined during the 1990s and 2000s, respectively. Our results are in agreement with previous studies which show that overall heat related mortality lowered post 1990s in major cities in the United States (Davis *et al.* 2002, Davis *et al.* 2003) compared to the 1970s and 1980s. The limited availability of air conditioning in the earlier decades can be related to the higher heat mortality (Greenberg *et al.* 1983). Overall, socioeconomic status has been attributed to higher weather related mortality in African American populations (Greenberg *et al.* 1983, Kalkstein 1992).

Despite the frequent billion dollar heat events (Table 4.1), the decline in heat related mortality in the recent decade could be related to the prevalence of air conditioning (Naughton *et al.* 2002, Barnett 2007, Davis *et al.* 2003a, 2003b, Sheridan *et al.* 2009, O'Neill *et al*. 2005, Uejio *et al.* 2011) and extensive heat-related warming systems and public awareness implemented in several U.S. cities (Bobb *et al.* 2014). Positive associations have been found between the residential segregation of African American, which is characterized limited access to health care, education, employment and income opportunities, and mortality rate (Williams and Collins 2001, Jackson *et al.* 2000, Jesdale *et al.* 2013). A reduction in the residential segregation of African American post 1980 and 1990 (Census Bureau 2002) can be linked to decline in the mortality rate of African American population in the recent decades.

Table 4.1: Billion dollar disaster: heat wave and drought (source: NOAA)

Event	Begin date	End date	Affected areas
Heat Wave/ Drought	1980-06-01	1980-11-30	Central and eastern US
Heat Wave/ Drought	1986-06-01	1986-08-31	Southeast US
Heat Wave/ Drought	1988-06-01	1988-08-31	Across the US
Heat wave / drought	1993-06-01	1993-08-31	Southeast US
Heat Wave/ Drought	1998-06-01	1998-08-31	Texas/Oklahoma eastward to the Carolinas, Georgia, Florida
Heat Wave/ Drought	1999-06-01	1999-08-31	Drought in the east coast, extreme heat in the eastern and south central U.S.
Heat Wave/ Drought	2000-03-01	2000-11-30	Southeast, Central Plains, and Rocky Mountains
Heat Wave/ Drought	2003-03-01	2003-11-30	Drought across western and central portions of the U.S. with losses to agriculture
Heat Wave/ Drought	2007-06-01	2007-11-30	Southeast and portions of the Great Plains, Ohio Valley, and Great Lakes area
Heat Wave/ Drought	2011-03-01	2011-08-31	Texas, Oklahoma, New Mexico, Arizona, southern Kansas, and western Louisiana.
Heat Wave/ Drought	2012-01-01	2012-12-31	Across US
Heat Wave/ Drought	2013-03-01	2013-11-30	Western US

Cold Related Mortality

Apart from excessive heat, the African American population also suffers disproportionately from excessive extreme cold events. T-tests were performed to evaluate whether African Americans suffered higher cold related mortality rate than the White population. T-tests show very low p-values for the 1970s, 1980, 1990s and 2000s. These p-values are smaller than a significance level of 0.05 hence we reject the null hypothesis African American mortality from extreme cold events is similar to White Americans. This signifies, for all four decades, mortality due to excessive cold is high in the African American population compared to White. The cold related mortality in each decade is significantly higher in African American compared to the White population. Figures 4.5 - 4.8 compare African American and White mortality due to cold during 1970s, 1980s, 1990s, and 2000s, respectively.

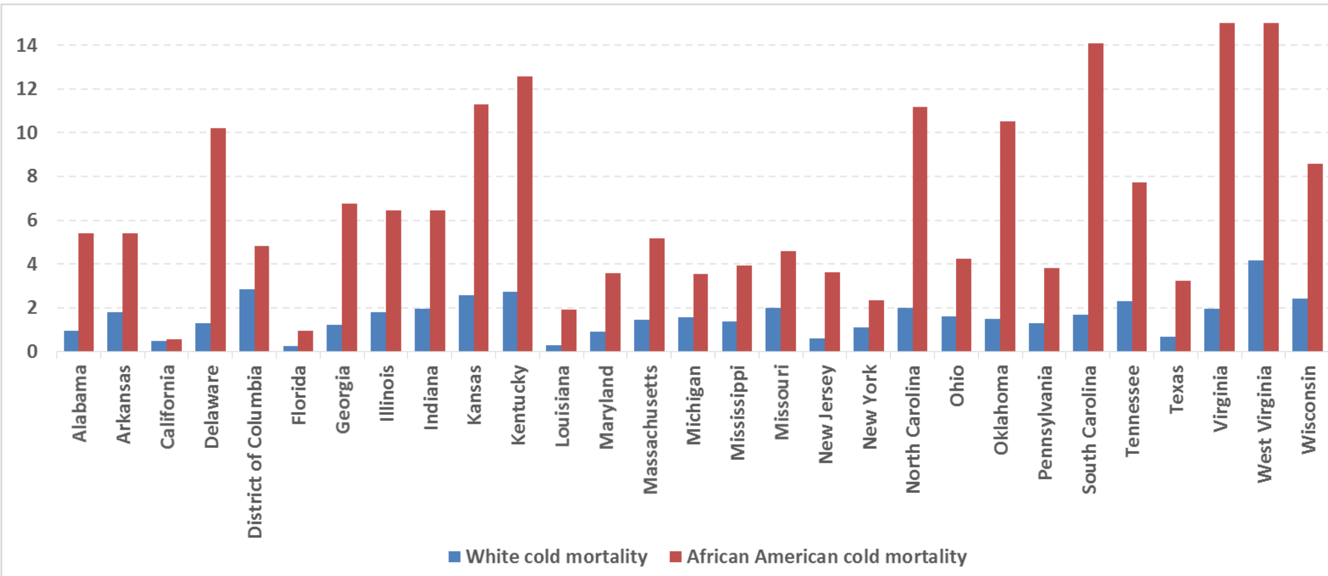

Figure 4.5: African American and White cold related mortality per 100000 population during the 1970s

African American mortality due to cold was significantly high during the 1970s and 1980s whereas during the 1990s and 2000s the mortality rate declined substantially. Cold related mortality among the White population was very low in all the decades compared to African American population. Peterson et al. (2013) also note lowest number of cold waves in recent decade.

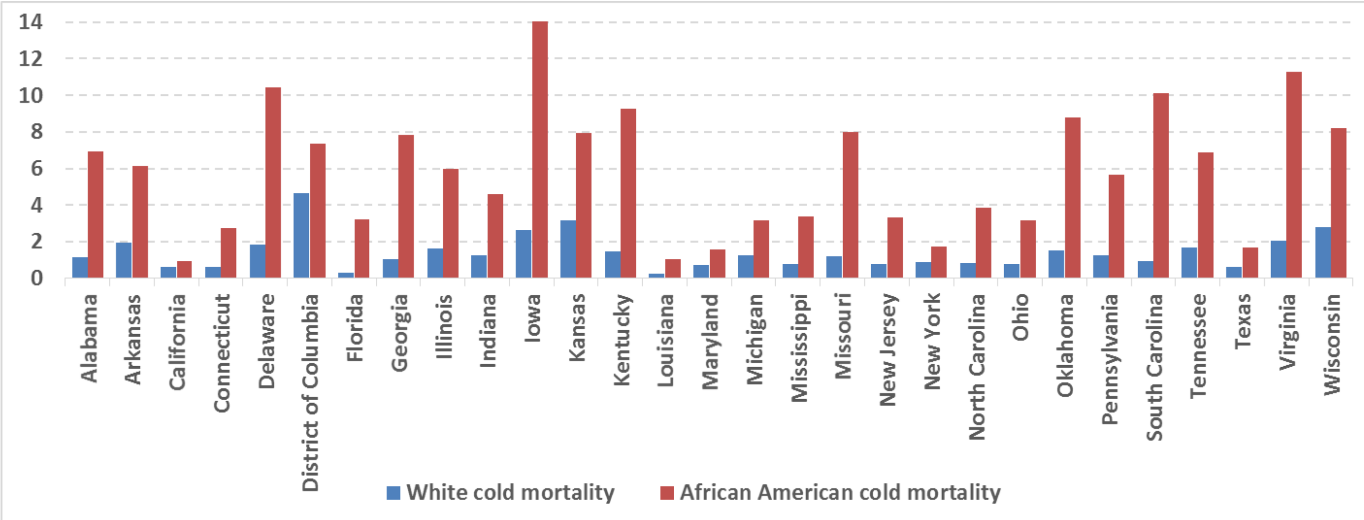

Figure 4.6: African American and White cold related mortality per 100000 population during the 1980s

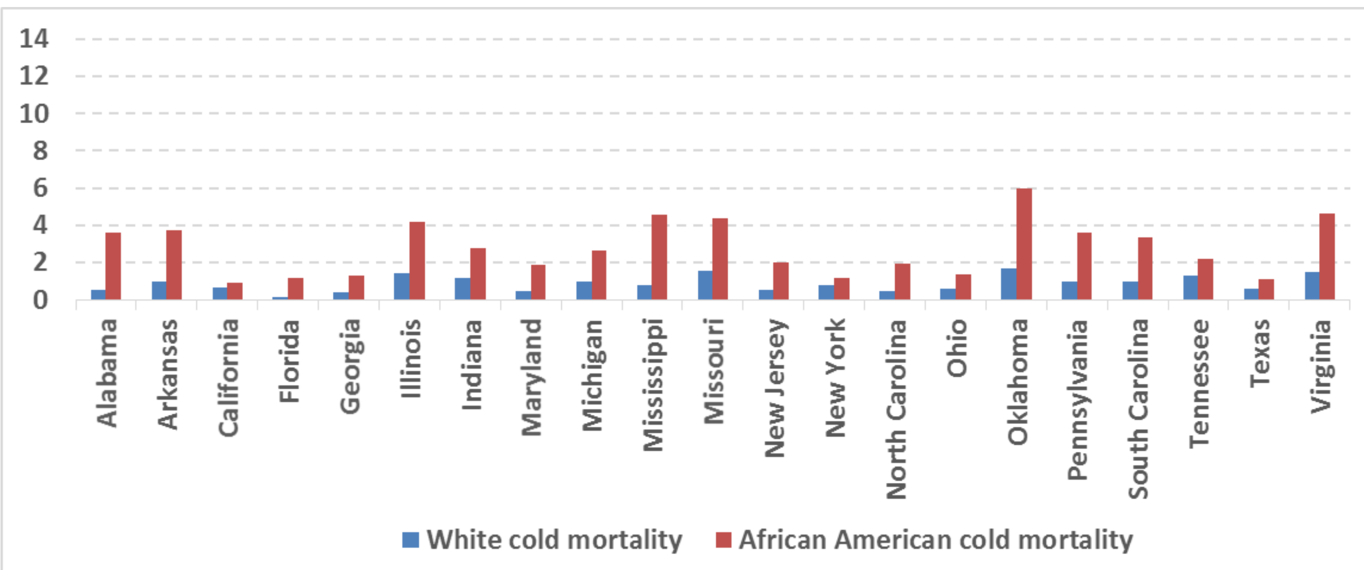

Figure 4.7: African American and White cold-related mortality per 100000 population during the 1990s

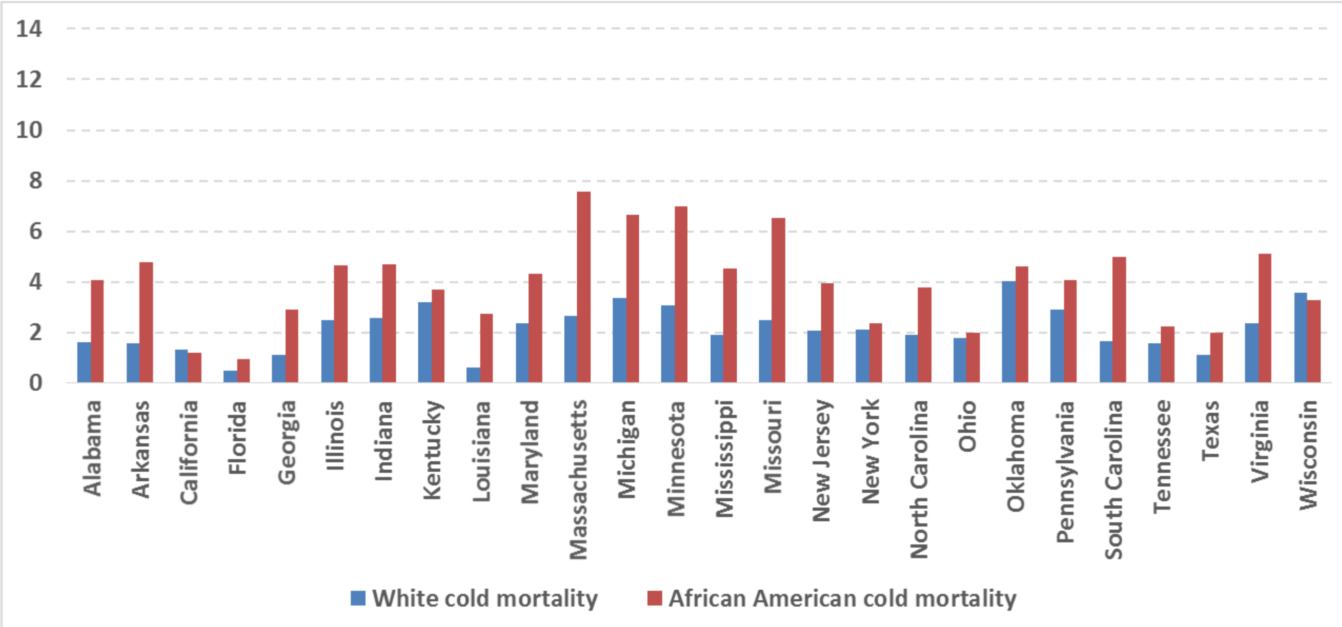

Figure 4.8: African American and White cold related mortality per 100000 population during the 2000s

Table 4.2 shows that billion dollar cold events are less frequent in recent decades. We also found that mortality due to cold events in both races have decreased in the recent decades as indicated by the smooth curve in the 1990s and 2000s compared to the 1970s and 1980s. This decline in mortality rate is indicative of warming or decline in cold events in recent decades.

Table 4.2: Billion dollar disaster: excessive cold events (source: NOAA)

Event	Begin date	End date	Affected areas
Winter Storm/Cold wave	1982-01-08	1982-01-16	Midwest, Southeast and Northeast
Winter Damage, Cold Wave	1985-01-19	1985-01-22	Southeast, South, Southwest, Northeast, Midwest, and North
Winter Damage, Cold Wave	1989-12-21	1989-12-26	Northeast, and Southeast
Nor'easter	1992-12-10	1992-12-13	Northeast U.S. coast, New England
Storm/Blizzard	1993-03-11	1993-03-14	Florida
Winter Damage, Cold Wave	1994-01-17	1994-01-20	Southeast and Northeast
Southeast Ice Storm	1994-02-08	1994-02-13	Southeast US
Blizzard/Floods	1996-01-01	1996-01-31	Appalachians, Mid-Atlantic, and Northeast
Northeast Ice Storm	1998-01-05	1998-01-09	Maine, New Hampshire, Vermont, New York
Winter Storm	1999-01-01	1999-01-04	South, Southeast, Midwest, Northeast
Winter Storm	1999-01-13	1999-01-16	Central and Eastern states
Groundhog Day Blizzard	2011-02-01	2011-02-03	Central, Eastern and Northeastern states

Regional Variations in Mortality

The spatial distribution of heat related mortality in African American and White population is shown in figures 4.9 and 4.10, respectively. Heat related mortality is mainly concentrated in the Midwestern and Southwestern United States. The spatial distribution of cold related mortality in African Americans and White Americans in each decade is shown in figures 4.11 and 4.12, respectively. Cold related mortality is concentrated in northern states, however, this study is limited in the states having both African American and White cold related deaths.

The South

The South suffered high mortality due to both heat wave and cold waves. In Arkansas, both races faced similar heat related mortality rate during the 1970s but after the 1980s, the mortality significantly increased in African American population compared to White Americans. Similarly, in Kansas, African American heat related mortality peaked during the 1980s and declined afterwards. The heat wave and drought of 1980, 1993, 1998, 2007, 2011, 2012 affected Texas and surrounding states. Mostly elderly, African American and those engaged in heavy labor were found to be the victim of the 1980 heat wave in Texas (Greenberg *et al*. 1983). Similarly, in Oklahoma African American mortality due to heat was higher than White population in all decades except in 1990s due to data suppression. The African American heat related mortality peaked in Georgia during the 1980s. The heat wave of 1993 also affected Georgia, Alabama, North Carolina, South Carolina, and Tennessee.

In the Southeast, cold waves of 1982, 1985, 1989, 1994, and 1999 are listed as billion dollar disasters by NOAA. Cold related mortality of African American population was high in Alabama, Arkansas, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Oklahoma, and Tennessee during 1970s and 1980s. The death due to excessive cold sharply declined in these states during 1990s and 2000s.

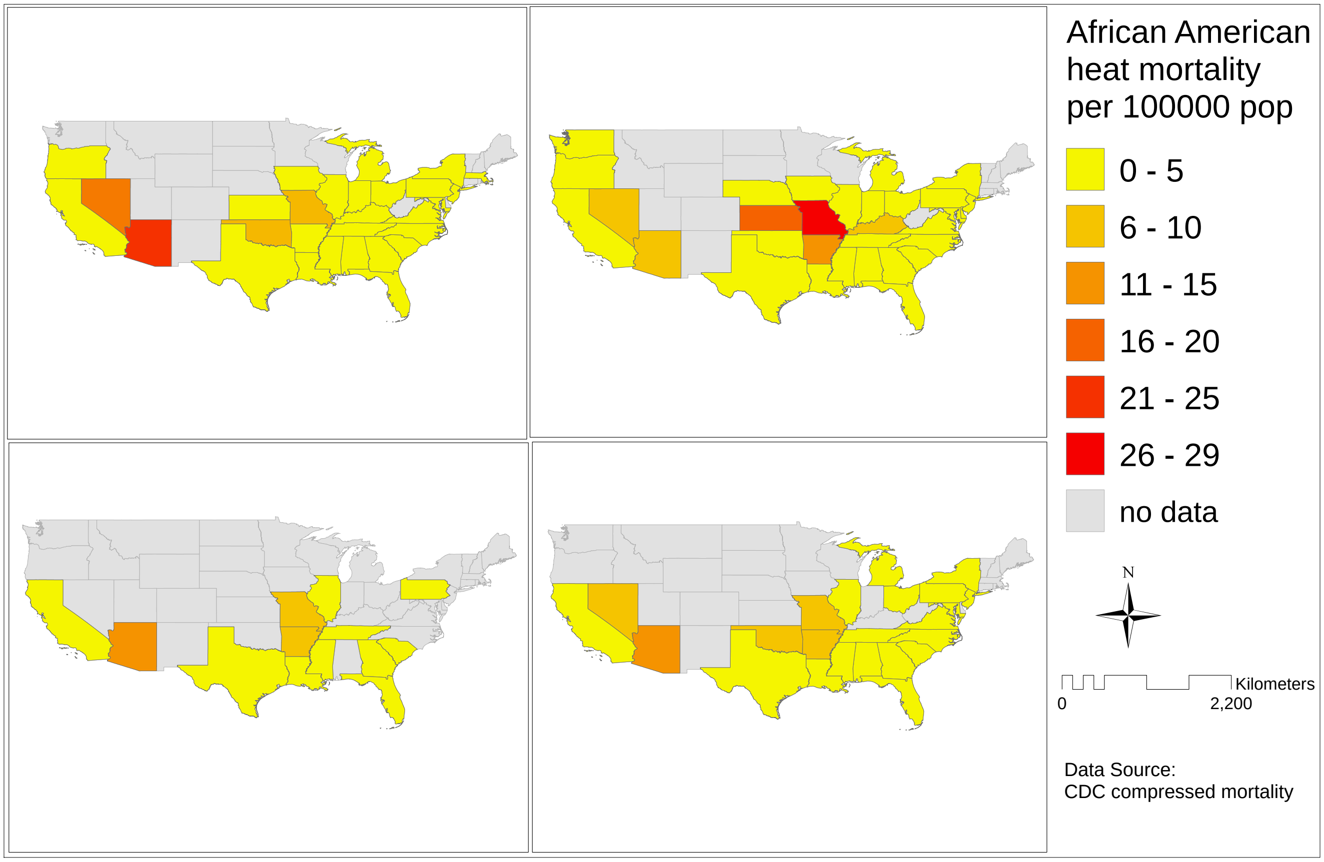

Figure 4.9: African American heat related mortality per 100000 population during the 1970s (top left), 1980s (top right), 1990s (bottom left), 2000s (bottom right)

The Northeast

Heat related death was not very prominent in the Northeast. However, in Philadelphia, Pennsylvania African American death toll was high during the 1995 heat wave. Billion dollar disastrous cold events were more frequent in the Northeast so were the cold related deaths (Table 4.2). Delaware, Virginia, Massachusetts, and West Virginia, had high cold related deaths for African Americans during the 1970s and 1980s, however this rate declined afterwards except in Massachusetts.

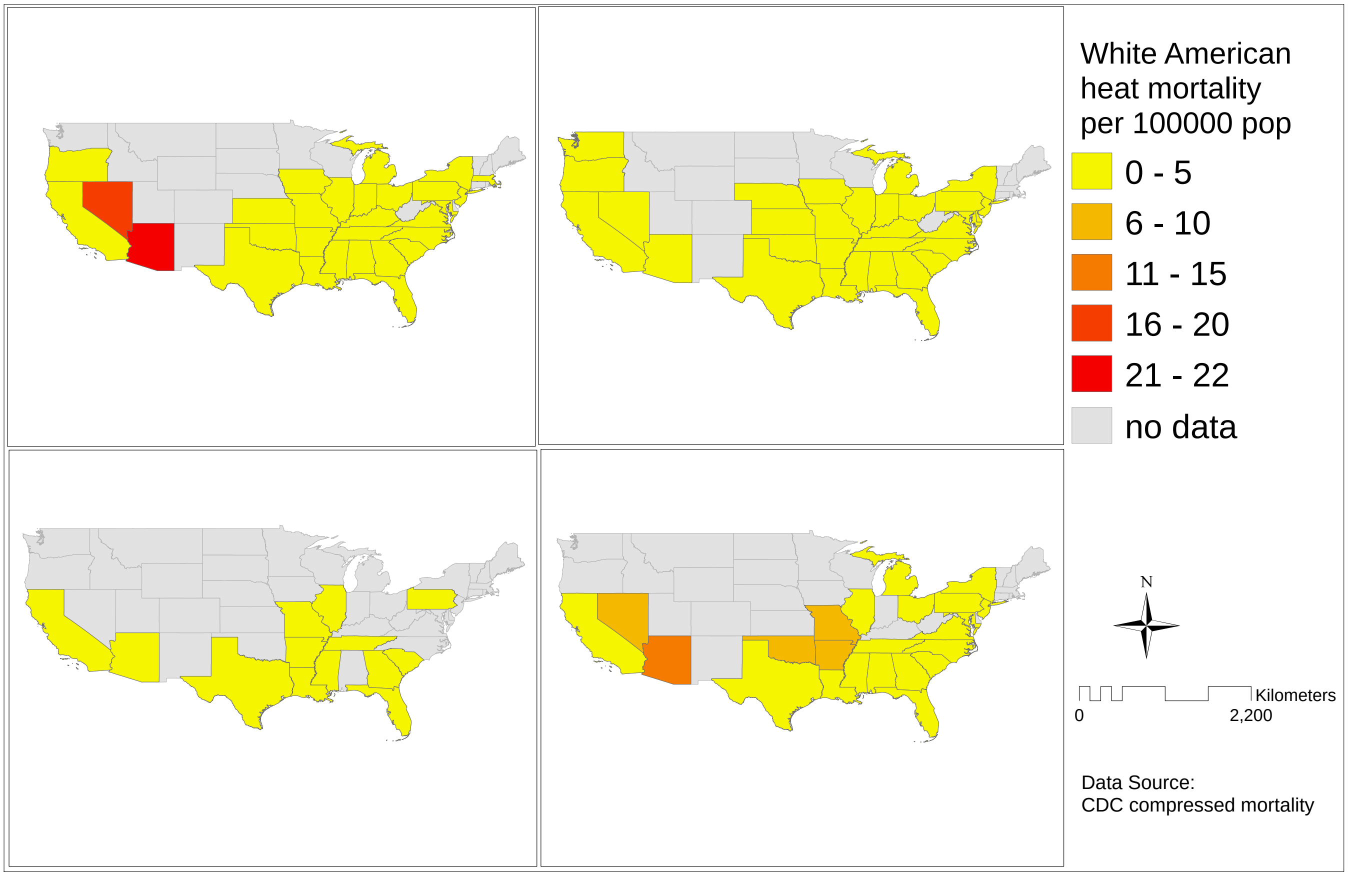

Figure 4.10: White heat related mortality per 100000 population during the 1970s (top left), 1980s (top right), 1990s (bottom left), 2000s (bottom right)

The Midwest

Midwest was the hotspot of the heat and cold related mortality of African American population. African American heat mortality peaked in Missouri during the 1980s, which can be attributed to the heat wave in 1980. The 1980 heat wave was the most severe heat wave since 1936. Throughout the 1970s to 2000s African American mortality in Missouri is higher than White mortality. Though mortality rate has declined over the years (post 1990s), African American heat related death is still significant in Missouri. The 1995 heat wave also claimed the lives of many elderly and African Americans in Chicago, Illinois (O'Neill et al. 2005), which is reflected in the high mortality rate of African Americans in Illinois relative to White population.

The elevated cold related mortality was observed in African American population in Midwestern states such as Nebraska and Wisconsin during 1970s and 1980s. In recent decades, as in any other states, the Midwest had decline in cold related mortality in African American as well as in White populations.

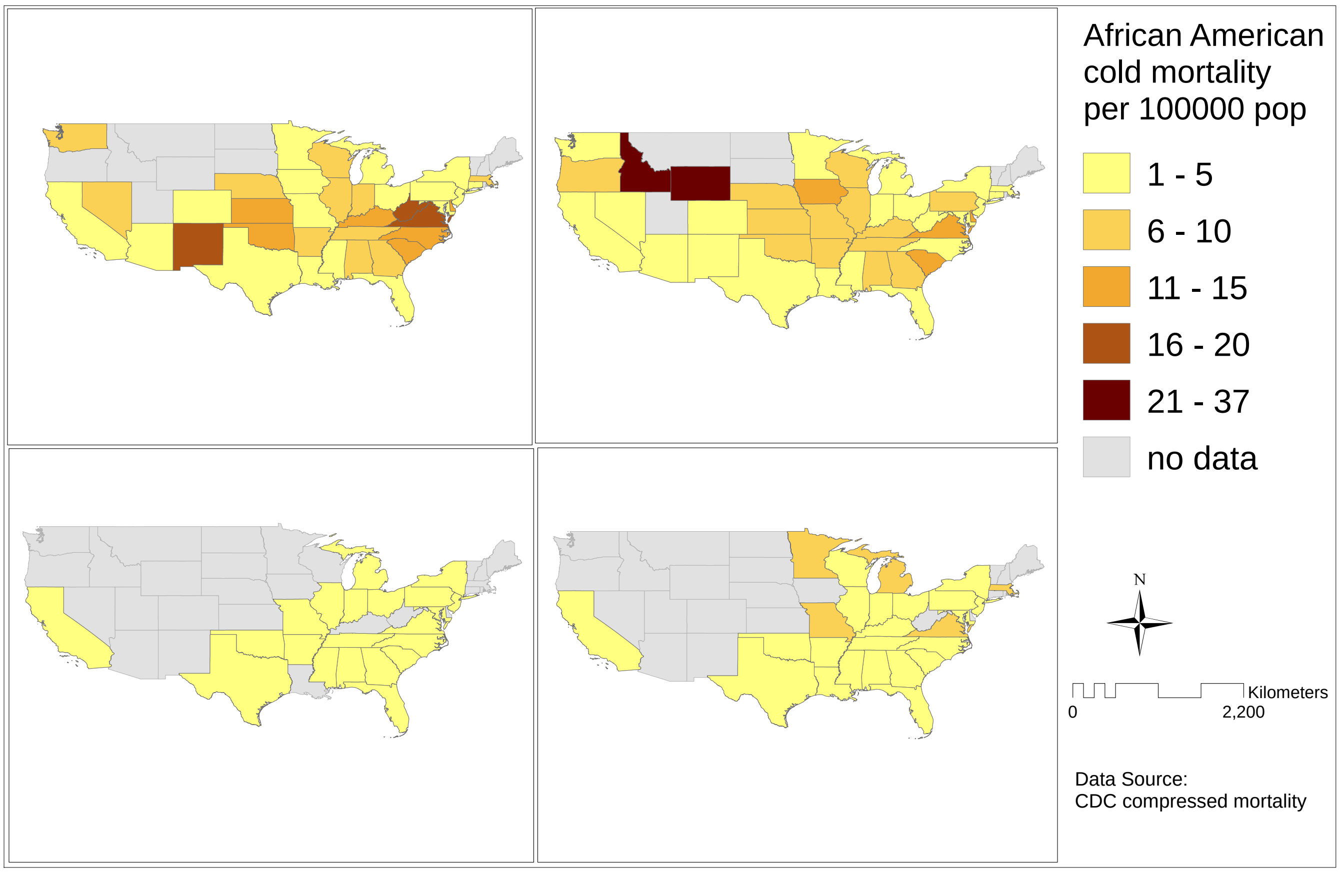

Figure 4.11: African American cold related mortality per 100000 population during the 1970s (top left), 1980s (top right), 1990s (bottom left), 2000s (bottom right)

The Southwest

The Southwest was also a relative maximum of the hotspot of heat related mortality during the 1970s and 1980s. Arizona has the highest normalized heat related mortality rate among African American and White population throughout 4 decades. Despite low African American population in Arizona, African American suffered more normalized heat related mortality rate compared to White Americans (figures 4.1-4.4). Similarly, Nevada had a high heat related mortality rate in the White American population during the 1970s, however, in the recent decade, African American heat related mortality rate exceeded White mortality. Recently the 2006 heat wave in California and Nevada claimed many lives (Gershunov et al. 2009). The cold related mortality of African American peaked in Nevada and New Mexico in the 1970s and declined afterwards which could be indicative of warming trend in the Southwest.

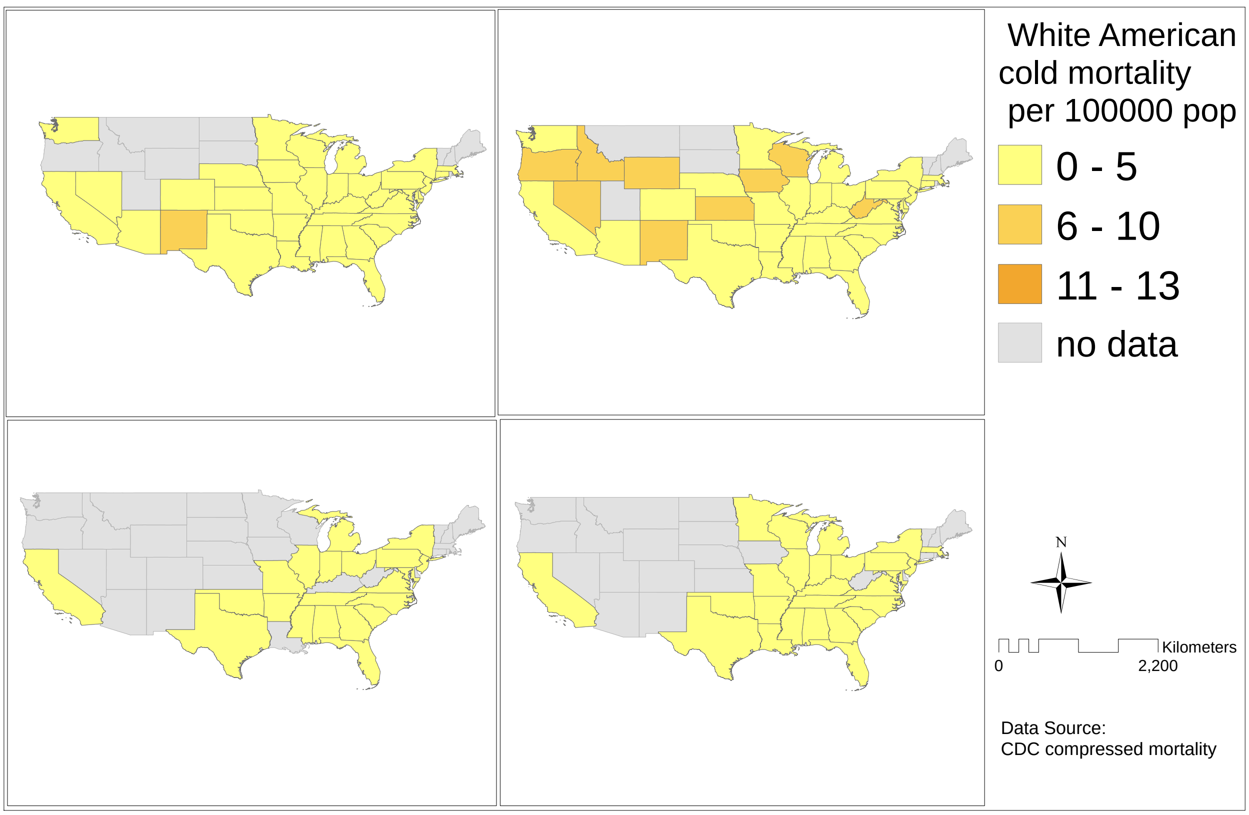

Figure 4.12: White cold related mortality per 100000 population in 1970s (top left), 1980s (top right), 1990s (bottom left), 2000s (bottom right). States with mortality rate of both races are analyzed

The Northwest

Heat related death are more prevalent in Oregon and Washington states. Despite very low African American population, normalized mortality rate remained high in African American population compared to the White population during the 1970s and 1980s. African American mortality rate was not available in the recent decade due to data suppression, however, the White mortality rate remained fairly consistent throughout the decades. Increasing trend in the frequency of the nighttime heat wave events is already occurring in the Northwest (Bumbaco *et al.* 2013). In the northwest cold related mortality peaked in Wyoming, and Idaho among African American during 1980s and declined afterwards.

Age Adjusted Cold-Related Mortality

Mortality rate due to extreme temperature condition is heavily dependent on population age structure. Studies have shown higher heat related mortality rate among elderly and infant populations (Zahran *et al.* 2008, Changnon *et al.* 1996). For meaningful comparisons across states with different underlying age structure, age adjusted mortality rate is required. Hence, we performed t-test analysis of age adjusted cold-related deaths to determine whether African American suffered higher mortality due to cold than White Americans. African American population suffered higher mortality rate due to cold than White Americans with the age adjusted mortality rate, which is consistent with the results we obtained without removing the age effect. Figure 4.13-4.16 shows the age adjusted mortality rate of African American and White American populations due to extreme cold during the 1970s, 1980s, 1990s and 2000s, respectively. Similar cold-related mortality trends are observed with the age adjusted rate and non-age adjusted rate.

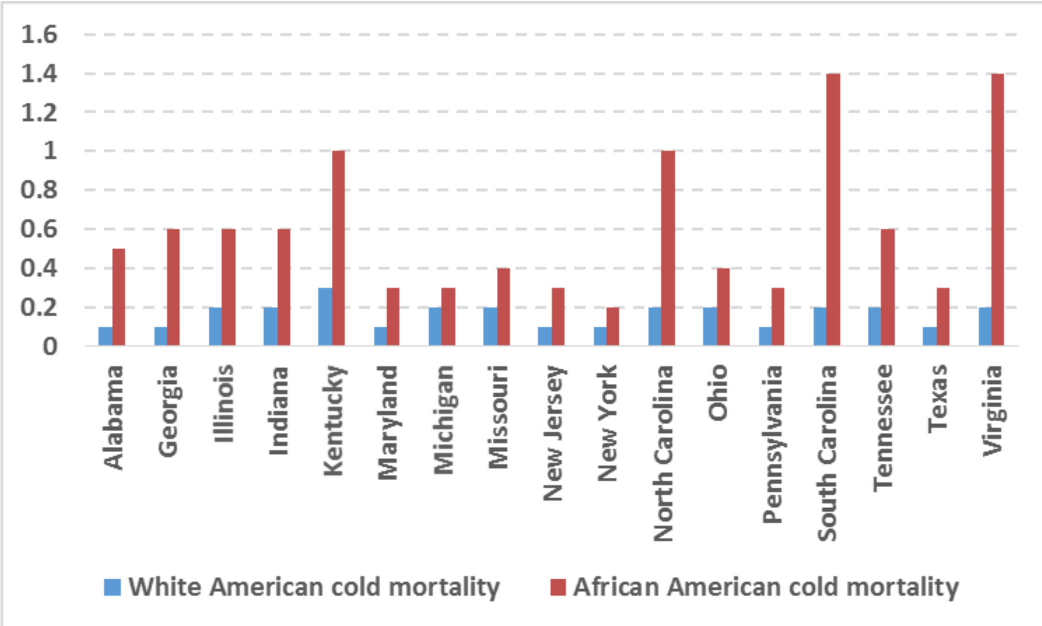

Figure 4.13: African American and White American cold-related age adjusted mortality rate during the 1970s

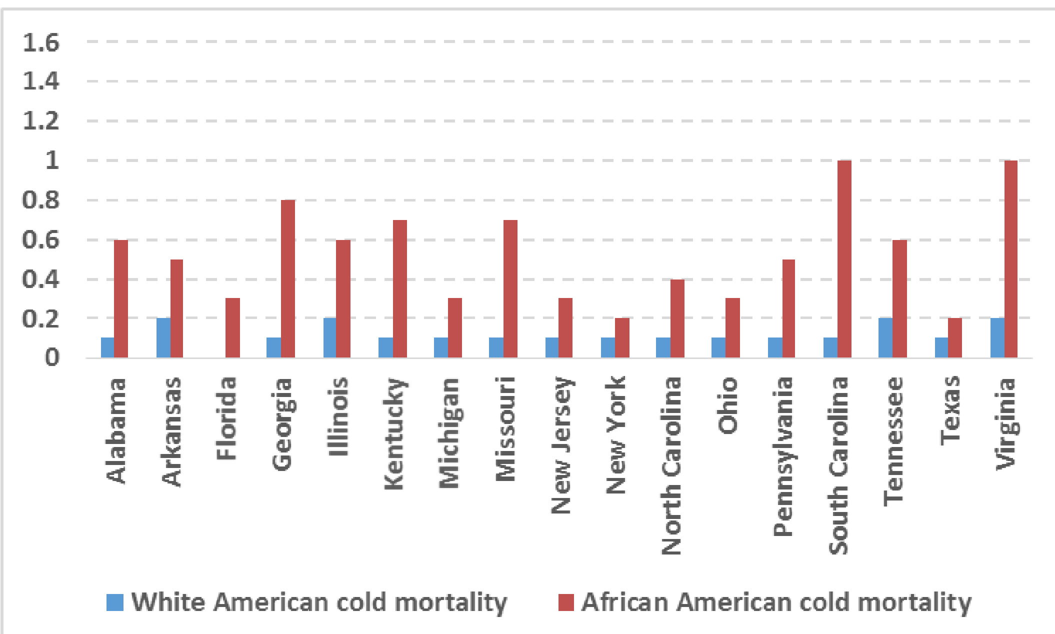

Figure 4.14: African American and White American cold-related age adjusted mortality rate during the 1980s

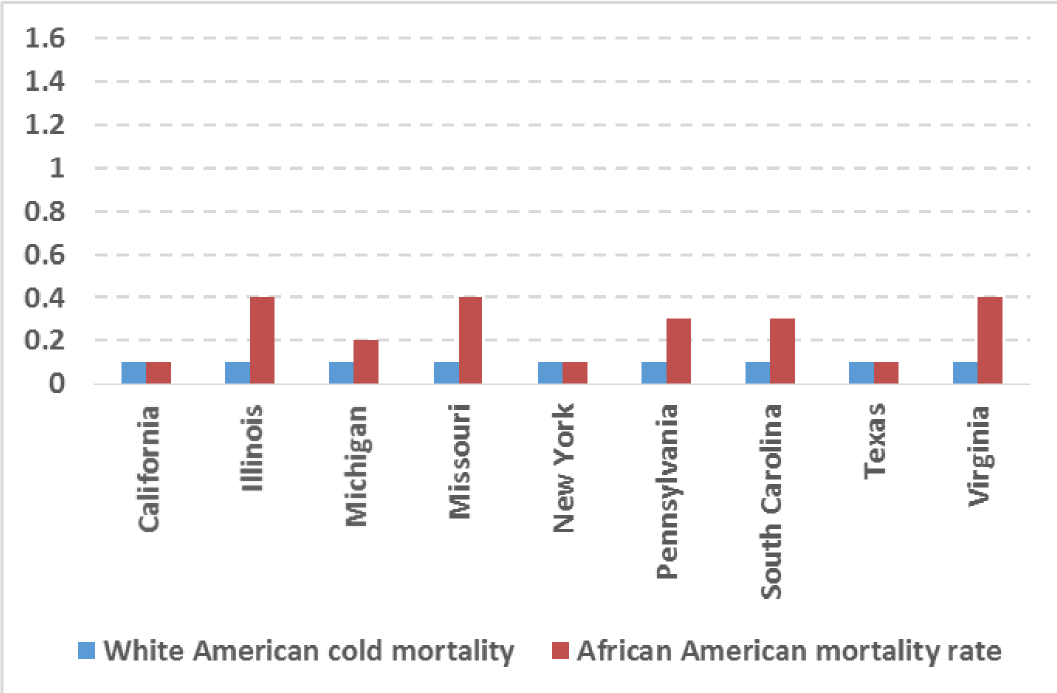

Figure 4.15: African American and White American cold-related age adjusted mortality rate during the 1990s

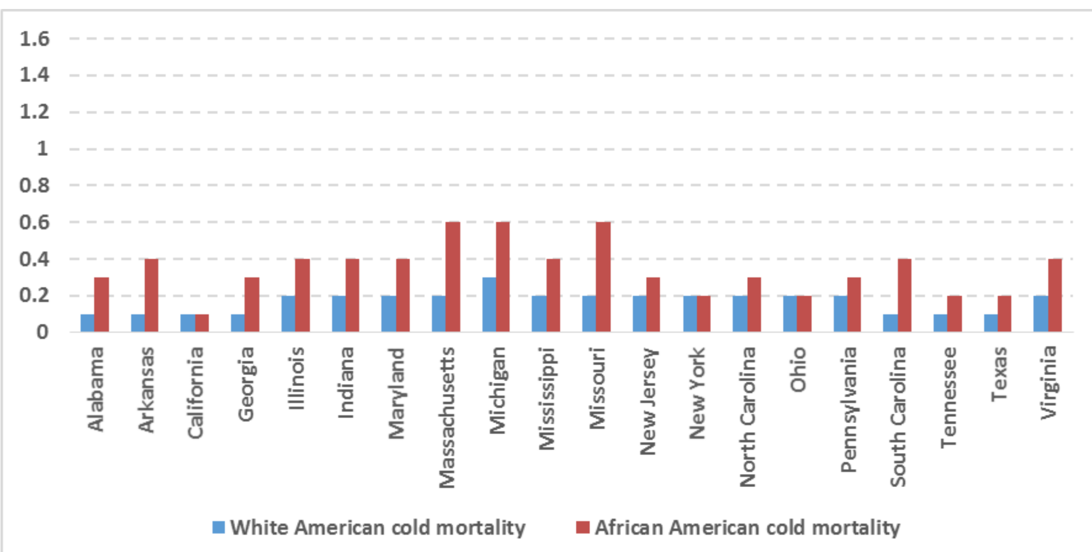

Figure 4.16: African American and White American cold-related age adjusted mortality rate during the 2000s

Age Adjusted Heat-Related Mortality

Using the age adjusted mortality rates, we performed t-test analysis to determine whether African Americans suffered higher heat related mortality than White Americans. Lack of sufficient age adjusted heat-related mortality rates at decadal span limits our analysis to the decade of 2000s only. With the age adjusted mortality rates, t-test analysis shows that African American suffered higher heat related mortality during the 2000s, which is similar to the conclusion drawn using non-age adjusted heat related mortality. However, during the 1970s, 1980s, and 1990s, we cannot draw similar conclusions regarding higher heat related mortality rate of African American compared to White American as the age effect is not removed during these decades. Figure 4.17 shows higher age adjusted mortality rate of African American due to extreme heat mortality compared to White American during the 2000s.

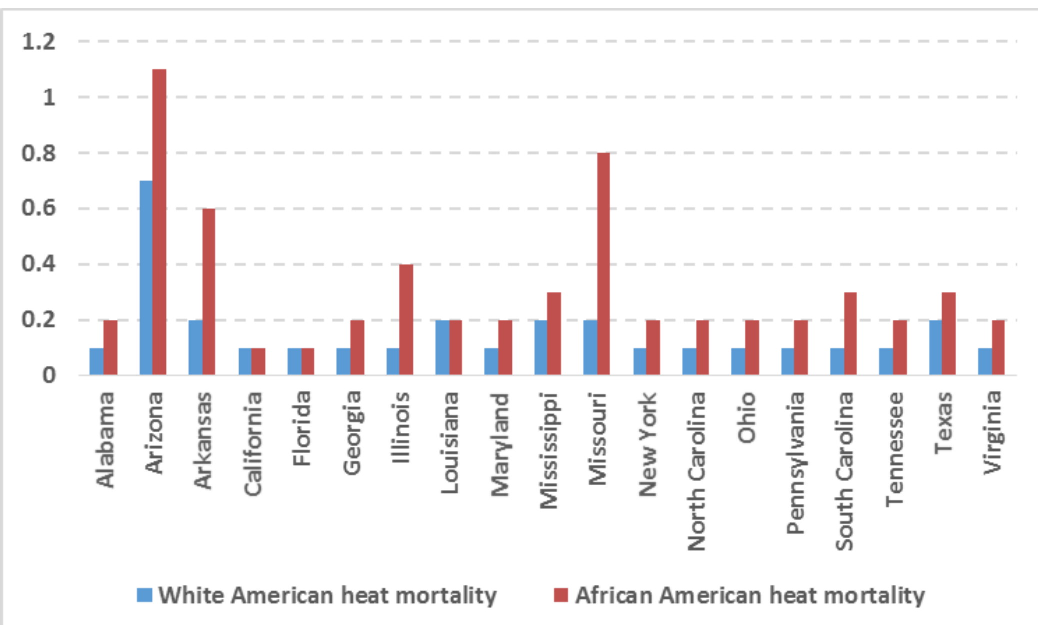

Figure 4.17: African American and White American age-adjusted heat related mortality rate during the 2000s.

4.4 Conclusions

Overall, African Americans suffer the most due to extreme temperatures in virtually every state in the United States over the period 1969 to 2008. Mortality of African Americans from excessive cold is relatively less than that from excessive heat, however, in both extreme temperature conditions African American mortality rate is significantly higher than White American mortality. Hence, we conclude that African Americans population bear the burden of climate change and variability. Poor housing conditions, low socioeconomic status, residential segregation, and social isolation have been associated with the high mortality rate, especially among the African Americans. However, due to limited availability of mortality datasets at decadal span, we could not control for variables such as urban or rural residence, tree canopy, or impervious surface.

Recently, more heat waves accompanied by droughts are listed under billion dollar disaster events. For example, heat wave and drought caused billion-dollar loss in years 2011, 2012 and 2013. Heat waves have increased while cold wave have decreased over the years. Despite, the increased number of heat waves, a decline in heat related mortality rate is observed in recent decades which can be directly linked to improved housing conditions with access to air condition, biophysical and infrastructural adaptations, decrease in minority residential segregation, and early heat warming systems.

Previous studies on severity of temperature extremes on racial minorities are mostly based on proxies such as cardiovascular disease, and upper respiratory tract infection. This study contributes beyond those studies because it provides quantitative assessment of direct mortality from these events. Besides, cold related morality which is less studied has been focused here. This study supports the hypothesis that racial minority bear the greatest burden of climate change and variability. Historical assessment of African American and White American mortality due to extreme temperature conditions also provide important insight into the changing relationship between mortality and extreme temperature conditions over time.

Although there have been conflicting views on whether heat-related mortality will increase or decrease in future (Davis et al 2002, Sheridan et al. 2008, Sheridan et al. 2012), given the increased frequency and intensity of heat waves, we conclude that heat wave will remain as a dominating cause of mortality in many years to come especially among African American population. African America heat related or cold morality will exceed White mortality as long as the gap in socioeconomic status exists.

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CHAPTER 5

5 SUMMARY AND CONCLUSIONS

5.1 Overview

With the long-term change in background climate, frequency and intensity of extremes weather and hydroclimatic events are increasing. The rapid urbanization has exacerbated the observed trends in extreme weather and climate events through urban heat island effects, increases in runoff, and decreases in vegetation cover. These extreme events have an impact on water resources, infrastructure, crop production, food security, and human health. Individuals and communities are differentially exposed as the severity of these events depends upon the coping and adaptive capacity of the society. Socially marginalized populations bear the greatest burden of climate change because they do not have enough resources to recover from the impacts. For example, the heat wave mortality rate of African American population was significantly higher than White Americans during the 1980s because of poor housing conditions lacking air conditioning. Populations with high sensitivity and low coping capacity (i.e., poor housing conditions, people with limited mobility, lack of health services, racial/ethnic minorities, low socioeconomic conditions, natural resource dependent (e.g., agriculture, forestry, fishery)) increase the sensitivity of the social system to climate change. On the other hand, education establishes a path for attaining upward occupational, economic, and social mobility and higher per capita income. These factors increase the adaptive capacity of the social system to recover from adverse effects of climate change. Due to lack of resources, vulnerable populations are forced to or choose to settle in hazardous environments, which further increases the risk from these extreme events. The socially vulnerability is the key determinant of whether these events will transform into disasters. Apart from social vulnerability, a place can exhibit vulnerability, for example, due to urban impervious surfaces, sea level rise and storms surges. Although coastal areas are inhabited mostly by affluent populations, the geographic location makes it highly vulnerable to future climate change.

This study provides a novel approach to characterize climate change vulnerability from long-term climate change as well as episodic hydroclimatic events. Social and placed based/geographic vulnerability is coupled with climatic exposure to determine overall climate change vulnerability in the state of Georgia (US). This dissertation performs a spatio-temporal assessment of climate change vulnerability and projects it into the future. Additionally, the hypothesis that socially marginalized populations are particularly vulnerable, the so-called Climate Gap (Morello-Frosch *et al.* 2009), is tested.

Climate change vulnerability was assessed by formulating three research objectives:

1) Determine climate change vulnerability in the state of Georgia at decadal spans from 1980 to 2010.
2) Project climate change vulnerability in the state of Georgia in the 2030s.
3) Determine whether socially marginalized groups, specifically African Americans, are more likely to bear the brunt of climate change and extremes.

5.2 Summary

For the first objective, a climate change vulnerability index was prepared by coupling social vulnerability with decadal anomalies in mean temperature and precipitation and frequency of extreme events. The composite vulnerability index was formed based on IPCC (2007) framework of vulnerability, which defines vulnerability as a function of exposure, sensitivity, and adaptive capacity. Exposure is measured as social vulnerability, which incorporates the notion of sensitivity and adaptive capacity. Exposure is measured as decadal anomalies in temperature and precipitation compared to baseline climate in 1971-2000 as well as the frequency of extreme hydroclimatic events such as heat wave, drought, and flood. Additionally, geographic vulnerability is incorporated into the climate change vulnerability to determine the composite climate vulnerability index. Metro Atlanta counties and Black belt counties in Georgia emerged as climatologically and socially vulnerable in recent decades. Based on geographic location, the coastal counties are at greatest risk because of potential sea level rise and storm surge flooding.

For the second objective, statistically downscaled CMIP5 climate projections were used to determine the anomalies in mean temperature and precipitation in 2030s (2025-2034) compared to the baseline climate of 1971-2000. The frequency of extreme events such as heat wave and heavy precipitation days were projected using daily temperature and precipitation projections over 10 year period from 2025 to 2034). Social vulnerability in 2030 was determined using socioeconomic variables using cohort component projection. The social vulnerability was combined with climatic exposure to derive the composite climate change vulnerability index in the 2030s. Atlanta metro counties turned out to be vulnerable both climatologically and socially. The highest heat wave events were projected in metro Atlanta counties. There is a notable out migration of African American population into the suburb counties in Atlanta. The privileges of the suburbs helps African American communities better prepare themselves from climatological stressors and lessen the climate vulnerability in future. Hence, overall climate vulnerability was high in Atlanta metropolitan counties and some counties in the southwest Georgia, also known as

“Black belt” counties. The coastal counties were at the elevated risk of flood due to potential sea level rise and storm surges.

For the third objective, African American mortality due to extreme heat and cold was compared to White American mortality. State level analysis is performed across the United States from 1969-2008 at decadal spans. Statistical analyses are performed to test whether African Americans suffered more deaths due to extreme heat and cold. The results support the hypothesis that African American mortality is significantly higher than White American mortality.

The vulnerability frameworks used in our first and second objective provide equal weights to the climatological, social, and geographic components of vulnerability. However, the diverse physical, climatological, and social composition of coastal, rural, and urban counties and their unique interactions demand for three different vulnerability weighting schemes. In addition, our future social vulnerability index lacks an adaptive capacity component such as access to school, healthcare facilities, and housing condition which could potentially have lowered the social vulnerability of Atlanta metro counties. Furthermore, our vulnerability index does not incorporate, vegetation cover of urban residential area which is a good indicator of environmental quality of the place. Finally, the vulnerability assessment would have been more integrative if we were to include the environmental and ecosystem services in coastal counties.

5.3 Conclusions

This dissertation provides a unique approach to determine climate vulnerability by coupling of climatic exposure and social vulnerability. The urban counties in metro Atlanta as well as the rural counties in southwest Georgia emerged as socially and climatologically vulnerable in the recent decades with similar trend in 2030s. Urbanization modifies the temperature through the urban heat island effect and effects the hydrological processes through excess runoff because of which the city residents of Atlanta metropolitan counties are at elevated risk. The out migration of African America population into the suburban counties captured in our study will help to decrease climate vulnerability in future.

Despite rapid urbanization, agricultural remains as an important source of income in many rural counties in Georgia. However, the agricultural sector is highly climate sensitive and increasing frequency and intensity of extreme events, for example, droughts, heat waves, and floods increase the vulnerability of poor rural communities. The low agricultural productivity accompanied by a lack of resources to adapt themselves increases the vulnerability of these rural counties. In coming decades, warmer and drier conditions are predicted in these rural counties in the southwest Georgia, which is detrimental to agricultural industry. Despite low social and climatological vulnerability, low lying coastal counties are at greater risk of flood because of potential sea level rise and storm surges in future.

Most of the climate change impact studies are aimed at mid-century or towards the end of the century. However, people respond to the short-term hazards and climate extremes rather than long-term climatic changes. This dissertation provides short-term projection of vulnerability in the 2030s that can be utilized by individuals, communities and planners and to prepare themselves in the near future. It is necessary to build resilience in these communities to better prepare for the future climate change and variability. Increasing urban tree cover, and better housing conditions can improve living conditions in metro Atlanta counties. In addition, increasing resilience of the farming community through better irrigation facilities helps to cope with the frequent droughts. Building climate resistant infrastructures and protection of coastal land from erosion, and inundation can help to reduce impacts of coastal community.