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Climate change vulnerability assessment in Georgia

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ABSTRACT

Climate change is occurring in the Southeastern 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. Climate change vulnerability is typically measured as a function of exposure to physical phenomena (e.g., droughts, floods), sensitivity to factors affecting the social milieu, and the capacity of a given unit to adapt to changing physical conditions. The paper builds on previous assessments and offers a unique approach to vulnerability analyses by combining climatic, social, land cover, and hydrological components together into a unified vulnerability assessment, which captures both long-term *and* hydroclimatic events. Climate change vulnerability indices are derived for the 1980s, 1990s, 2000s, and 2010s. Climate change exposure is measured as: 1) departure of decadal mean temperature and precipitation from baseline temperature and precipitation (1971–2000) using the United States Historical Climatology Network version 2.5 and 2) extreme hydroclimatic hazards indicated by flood, heat wave and drought events. Sensitivity and adaptive capacity are measured by well-established conceptualizations and methods built derived from socioeconomic variables. Impervious surface and flood susceptibility area are also incorporated to account for place-based vulnerability.

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 with a clearly established increase in extreme hydroclimatic events in recent decades. Climate vulnerability is highest in some metropolitan Atlanta and coastal counties. However, the southwestern region of Georgia, and part of the rural Black belt region are found to be especially vulnerable to climate change.

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, Richmond, & Yohe, 2014). According to Karl, Melillo, and Peterson (2009), the average temperature has risen by 1.1 °C in the southeastern United States since the 1970s, with a significant temperature rise during winter and a decline in number of frost days per year. Despite reported increases in precipitation, areas experiencing moderate to severe drought have also increased in recent decades in the region. Similarly, Tebaldi, Adams-Smith, and Heller (2012) report that a warming hole, which is the slow warming of parts of the Southeastern United States including Georgia, has disappeared in recent decade, which is consistent with the warming trend in the Southeast. The Southeast, along with the Southwest and Midwest U.S. could experience more intense heat waves in the future (Kunkel, Liang, & Zhu, 2010; Meehl & Tebaldi, 2004), which would be intensified by urban heat islands at the local scale (Zhou & Shepherd, 2010). Such changes result in decreased crop production and increased heat-related mortality and morbidity (Changnon, Kunkel, & Reinke, 1996). Shepherd and Knutson (2007) also suggest possible increased intensity of hurricanes.

This study focuses on climate change in Georgia, considering both biophysical and socio-demographic indicators of vulnerability.

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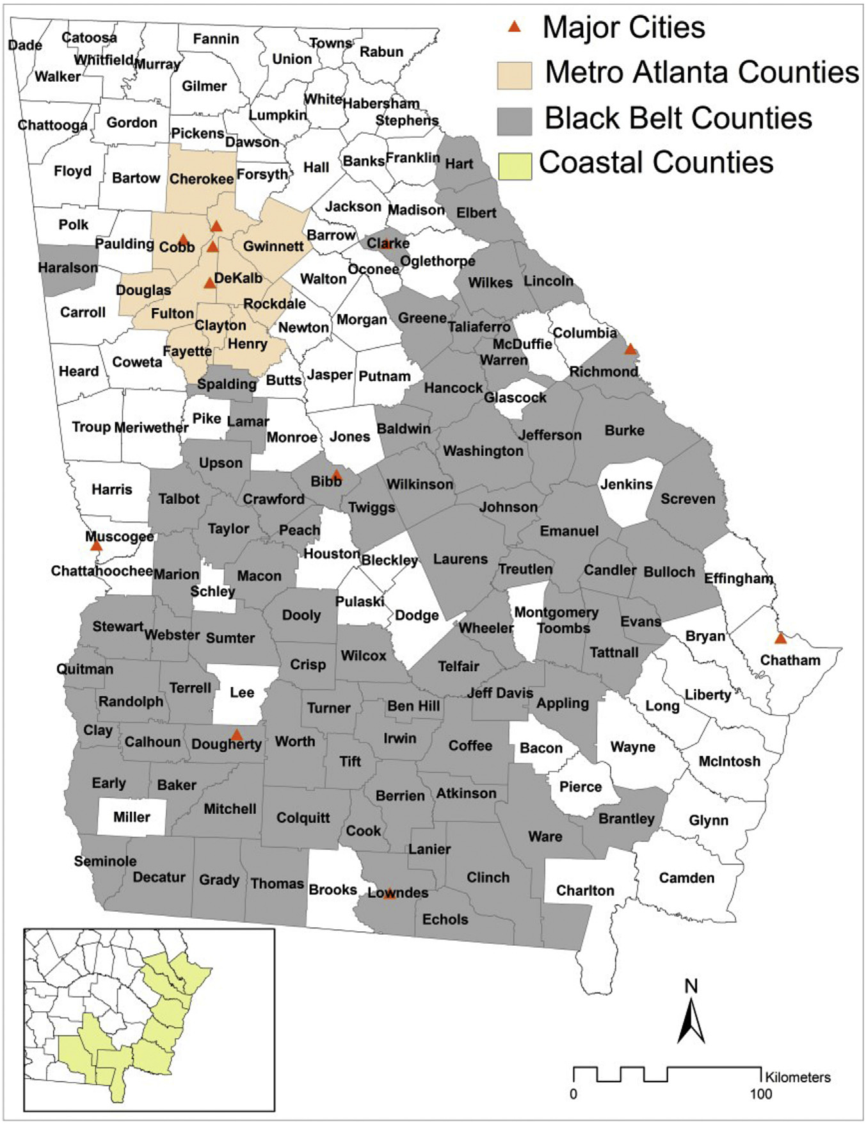

Fig. 1. State of Georgia with 10 Metro Atlanta counties, Black Belt counties (shown here as counties with poverty >20%), and coastal counties (>40% of land in Federal Emergency Management Agency (FEMA) designated flood zones).

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 those background or longer-term indicators of climate change with measures of episodic events (Azar & Rain, 2007; Emrich & Cutter, 2011; Gbetibouo & Ringler, 2009).

Georgia is one of the fastest growing states in the nation. 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). 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 & Ihlanfeldt, 2000); but Georgia still contains a substantial number of rural, "Black Belt" counties (Fig. 1), mostly in the southern part of the state, with resource-based industries as an economic mainstay (Wimberly & Morris, 1997).[3] 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 (Yarbrough, 2007; Zúñiga & Hernández-León, 2001). 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).

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[3] 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 which have higher than average percentages of African-American residents (McDaniel & Casanova, 2003; Wimberly & Morris, 1997). African Americans residing in this region have relatively higher poverty compared to the rest of the United States (Falk & Rankin, 1992; Falk, Talley, & Rankin, 1993; Hoppe, 1985); and a notable gap persists in social well-being of African Americans in this region compared to Whites and African Americans outside this region (Doherty & McKissick, 2002; Webster & Bowman, 2008).

These 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 exposure to extreme weather, conceptualizations of climate change vulnerability and its measurement, the development of a climate change vulnerability index, and the implications for hazard assessment.

Hazards and vulnerability

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)). Climatic variations measure exposure of the system; sensitivity is the effect of variations on 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 captured in terms of sensitivity and adaptive capacity (IPCC, 2007). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) report (IPCC, 2012) provides 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 likelihood.

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

Vulnerable population

Both urban and rural populations are confronted by climate change through complex feedback mechanisms affecting infrastructure, economic, social, and political systems. For example, extreme precipitation increases flood risks (likelihood) 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, Burian, Shepherd, & Manyin, 2008). The impact is more severe in poor households without insurance coverage to rebuild homes and recover quickly from damages (Coninx & 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 (Uejio, Wilhelmi, Golden, & Mills, 2011; Zhou & Shepherd, 2010). 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 1984–2007, and the average duration was roughly two weeks. Urban Heat Islands, together with heat waves, have a more detrimental effect on low income populations because of the higher likelihood that in urban areas, these communities tend to have fewer trees and shrubs to regulate temperature; and these residents are less likely to be able to afford health insurance or air conditioning (Morello-Frosch, Pastor, Sadd, & Shonkoff, 2009; Schultz, Williams, Israel, & Lempert, 2002; Williams & Collins, 2004).

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 (Malcolm et al., 2012; Wolfram & Roberts, 2009) 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 a “socio-economic drought” (Wilhite & Buchanan-Smith, 2005). Hispanics, many of whom are undocumented and have limited English proficiency, have largely replaced African Americans as laborers in Georgia's various rural, low-skilled industries, including agriculture and timber (McDaniel & Casanova, 2003). The precariousness of these already vulnerable populations increases with their employment in climate-dependent industries (Arcury & Marín, 2009; Chow, Chuang, & Gober, 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.

Also, elderly populations suffering from poor medical conditions are physiologically susceptible to extreme weather conditions (O'Neill, Zanobetti, & Schwartz, 2005). Temperature extremes affect human health, especially elderly populations, and those with preexisting medical conditions such as cardiovascular and respiratory illnesses (Knowlton et al., 2009); this trend is expected to increase especially with the increase in projected heat waves and elderly populations in the United States (Karl et al., 2009; Melillo et al., 2014).

Finally, less educated populations have low socioeconomic status and are more sensitive to climate variability as they are less likely to have disaster management strategies such as health insurance. Hayward, Miles, Crimmins, and Yang (2000), Wendell, Poston, Jones, and Kraft (2006), Bullard (2008), and Wilson, Richard, Joseph, and Williams (2010) also stress that racial/ethnic minorities bear an unequal health burden resulting from weather and 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. Racial minority status can modify the effect of heat on mortality, with consistently higher deaths among African Americans in several studies (Kaiser et al., 2007; Medina-Ramon, Zanobetti, Cavanagh, & Schwartz, 2006; O'Neill, Zanobetti, & Schwartz, 2003).

Vulnerability frameworks

Vulnerability frameworks have emerged from different schools of thought, which emphasize different policy responses to climate change (Kelly & Adger, 2000). Vulnerability research stemming from the hazards literature accounts for the amount of potential damages from an unexpected climate-related event or hazard (Nicholls, Hoozemans, & Marchand, 1999; Patt et al., 2010). Vulnerability in relation to specific hazards, for example, floods (Baum, Horton, & Choy, 2008), drought (Nelson & Finan, 2009; Wilhelmi & Wilhite, 2002), heat waves (Reid et al., 2009), and hurricanes (Frazier, Wood, Yarnal, & Bauer, 2010) have been targeted to examine the effect of these events on services and functions such as water supply (Barnett et al., 2008; Dawadi & Ahmad, 2012), food security (Bohle, Downing, & Watts, 1994), or public health (English et al., 2009; Guan et al., 2009).

Vulnerability has been viewed both as biophysical vulnerability, which is the first order impact from natural hazards (Brooks, 2003) and as social vulnerability, which refers to social characteristics of a given system (Adger, 1999; Cutter, Boruff, & Shirley, 2003; Emrich & Cutter, 2011; Kelly & Adger, 2000). In terms of social vulnerabilities, scholars distinguish between "starting and end point vulnerability". The end point approach as reviewed by Füssel (2005) and O'Brien, Eriksen, Nygaard, and Schjolden (2007) measures the residual impacts of climate change after adaptation to a stressor is determined. In contrast, the starting point approach frames vulnerability as a pre-existing state generated by socio-economic processes that determine the ability of humans to respond to stress. These studies point to poverty as a driving factor in vulnerability. However, the dynamic interactions between human and physical environments have often been ignored in vulnerability studies. Polsky, Neff, and Yarnal (2007) urge vulnerability assessments to be carried out with "biophysical, cognitive, and social dimensions".

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.'s (2003) vulnerability frameworks. As such, our approach provides a novel methodology to characterize long-term climate vulnerability by integrating, on the one hand, incremental changes in climate along with extreme climate events (i.e., tails of the distribution) and pre-existing social vulnerability, on the other, into a climate change vulnerability assessment. However, in the SREX (IPCC, 2012) framework, vulnerability is considered independent of physical events, and social vulnerability is explicit. We are using the pre-SREX vulnerability framework but understand that in the context of the SREX framework our vulnerability metric would be partly considered disaster risk. Since we are characterizing long term climate changes coupled with extreme weather and climate events, and our goal is a first order estimate of vulnerability, the framework that we used here is still valid. The assessment is performed by decade, at the county level in Georgia from 1975 to 2012.

Data and methods

We operationalized the IPCC's climate vulnerability equation (1) using our vulnerability framework shown in Fig. 2. The vulnerability framework includes mean temperature, precipitation and extreme weather hazard events as the climatic exposure, social vulnerability as sensitivity and adaptive capacity. Vulnerability due to settlement, that is, geographic vulnerability (for example in flood zone and built up environment) is also included in the overall climate vulnerability.

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, Williams, & Vose, 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, a cooling preceded the rapid warming after the mid-1970s (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).

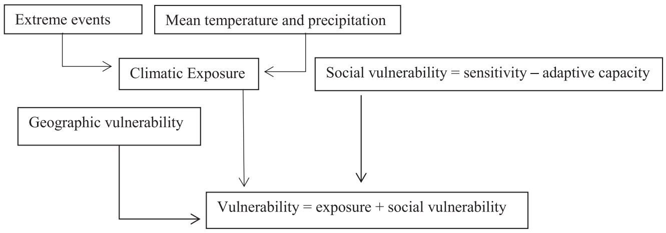


Fig. 2. Flow chart of vulnerability framework used in this study.

The extreme hydroclimate 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) measured 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 and climate change has been established in the literature (IPCC, 2007; Karl et al., 2009; Seneviratne et al., 2012; Wigley, 2009). Heat wave, flood and drought events in SHELDUS data were originally taken from the National Climatic Data Center, Asheville, NC, "Storm Data and Unusual Weather Phenomena" and are comprised of events with more than $50,000 in losses of either property or crop from 1990 to 1995 whereas from 1960 to 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; Cross, 2001; Cutter et al., 2003; Cutter & Finch, 2008; Kelly & Adger, 2000; Wood, Burton, & Cutter, 2010). These data were acquired from the United States Census Bureau, American Medical Association, United States Department of Agriculture-National Agricultural Statistics Service, and the United States Bureau of Economic Analysis. The data sets include: people with limited mobility, racial/ethnic minorities (African Americans and Hispanics, Asian), those with low socioeconomic conditions (US Census Bureau), and people who work in natural resource dependent occupations (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 physician availability (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 the 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 1.

Apart from socioeconomic vulnerability, geographic vulnerability is considered. This type of vulnerability is described as "hazard of place" by Cutter (1996), Cutter, Mitchell, and Scott

(2000), and Cutter et al. (2003). Geographical vulnerability is operationalized by flood risk and extent of impervious surface. 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 (Shepherd et al., 2011; Zhou & Shepherd, 2010). 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 FEMA's flood maps (Federal Emergency Management Agency, 2012). 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 (https://www.fema.gov/floodplain-management-old/flood-zones) 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 at the county level 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 & 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 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 frequency of extreme weather events per year indicates climate exposure in terms of extreme events. 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 component scores 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). Vulnerability has been modeled as a multiplicative or additive model depending on different conceptual frameworks (Adger & Vincent, 2005; Allison et al., 2009; Godber & Wall, 2014; Hajkowicz, 2006; IPCC, 2007, 2012). 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. Furthermore, the components of vulnerability are equally weighted in additive approach whereas multiplicative approach disproportionately captures these components. However, we acknowledge that the relationship

Table 1
Variables 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	
	Dwelling in mobile homes	

between vulnerability and some indicators of the index are not one-to-one and that this is a shortcoming of the index.

$$\text{Climate change vulnerability} = \text{exposure} + \text{social vulnerability} \tag{2}$$

$$\text{Overall climate vulnerability} = \text{climate change vulnerability} + \text{geographic vulnerability} \tag{3}$$

Geographic vulnerability is represented here by flood zones and impervious surface area. 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. The summed scores are transformed to a 0–4 scale in order to provide equal weights to other components of vulnerability and added to the climate change vulnerability index to identify an overall climate vulnerability index.

Results and discussion

Anomalies in temperature and precipitation

Greater anomalies in temperature have been observed in recent decades. Fig. 3 shows the transition from cooling (1975–1984) and warming thereafter. Our finding is consistent 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.

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 (Bonfils et al., 2008; Portmann, Solomon, & Hegerl, 2009), and thermal inertia of sea surface temperatures (Kunkel, Liang, Zhu, & Lin, 2006; Meehl, Arblaster, & Branstator, 2012; Meehl, Hu, & Santer, 2009; Robinson, Reudy, & Hansen, 2002; Wang et al., 2009).

Fig. 4 reveals drier conditions in Georgia in the most recent decades. This observation parallels Karl et al. (2009), which reported increases in areas of moderate to severe drought over the past three decades. It is also reflected in two significant droughts in 2007–2009 (Campana, Knox, Grundstein, & Dowd, 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). The drier conditions lead to higher temperature due to decrease in evaporation from the soil surface, which further increases the chances of droughts (Koster, Wang, Schubert, Suarez, & Mahanama, 2009).

Extreme climatic hazards

Among the three extreme hazard events, floods occurred most frequently whereas heat waves were 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, 4 floods were recorded in a 10-year period from 1975 to 1984 (1980s). 16 floods were recorded in an 8-year period from 2005 to 2012. Similarly, in Chatham, a coastal county, 2 floods were recorded in a 10-year period from 1975 to 1984 (1980s), 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 & Shepherd, 2013). Droughts were also frequent in recent decades. In west-

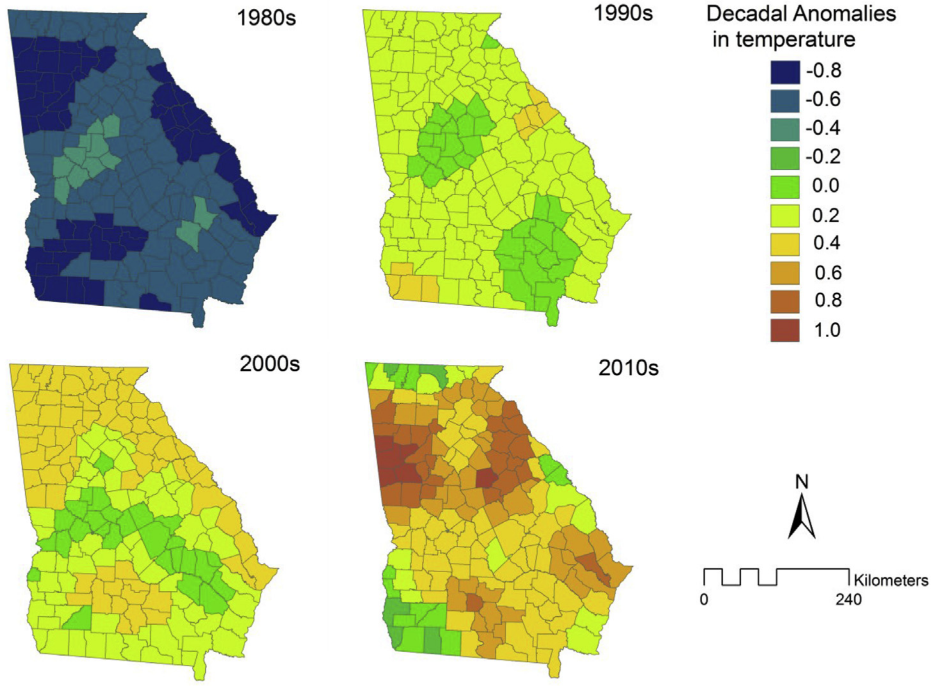


Fig. 3. Anomalies in decadal temperature in 1980s (1975–1984), 1990s (1985–1994), 2000s (1995–2004), and 2010s (2005–2012) compared to the 30-year climate normal (1971–2000). Gradation of brown color code indicates positive temperature anomaly while blue gradation indicates negative temperature anomaly. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

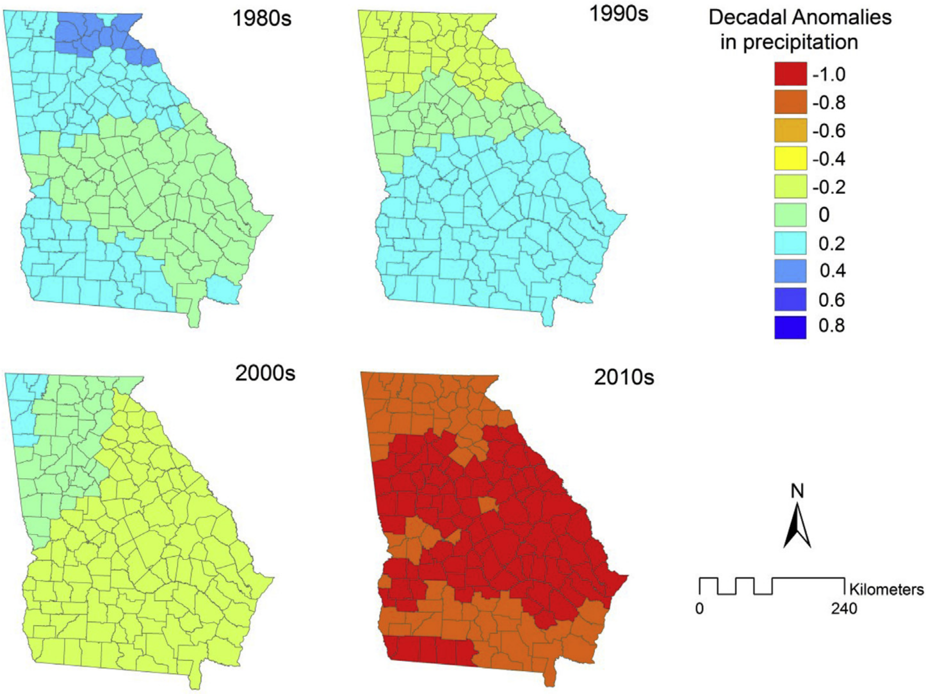


Fig. 4. Anomalies in decadal precipitation in 1980s (1975–1984), 1990s (1985–1994), 2000s (1995–2004), and 2010s (2005–2012) compared to the 30-year climate normal (1971–2000). Gradation of blue color code indicates positive precipitation anomaly, that is, increase in precipitation while red gradation indicates negative precipitation anomaly, that is, decrease in precipitation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 the 1980s, had 2–4 droughts from 2005 to 2012. Contrary to floods and droughts, 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.

The overall frequency of extreme hydroclimatic events are captured in Fig. 5 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, Smith, & Vecchi, 2013), frequent floods in Northeastern Illinois (Hejazi & Markus, 2009), record heat in the United States (Climate Central, 2012), and increases in extreme events globally (Goodness, 2013).

In general, though these extreme events have been linked to climate change it is beyond the scope of our study to assess whether each of these events are directly attributed to long term climate change or are due to the natural events. 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 2010s, which is reflected in Fig. 5. 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 is 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

Fig. 6 identifies metro Atlanta counties as more socially vulnerable, particularly Fulton County (where the City of Atlanta is located) and neighboring counties in each of the four decades. Counties in southwest Georgia and part of east Georgia are also socially vulnerable. 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, a greater proportion of residents in southwest Georgia, compared to the rest of the state, are dependent on natural resource-based industries such as agriculture and forestry for their livelihood.

According to the literature, language barriers and low education attainment also lessen a population's ability to recover from effects of climate disasters. Female-headed households are also concentrated in the Black belt region, especially in southwest Georgia. A study by Snyder, McLaughlin, and Findeis (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 fewer economic opportunities available to them. Between 2001 and 2007, 1

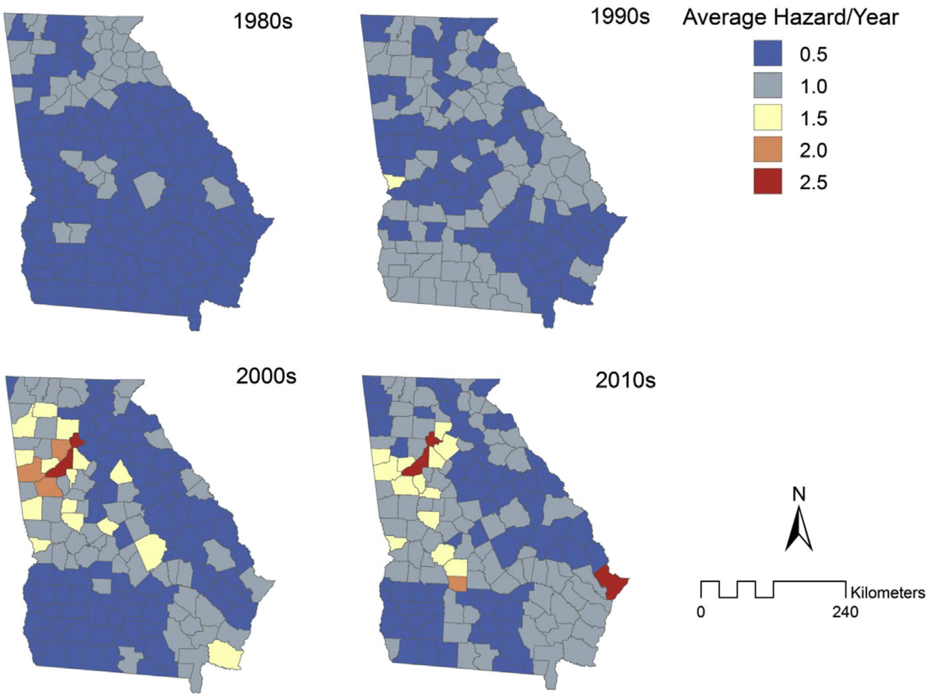


Fig. 5. Normalized frequency of climate hazard extremes (flood, drought, and heat wave) in the 1980s, 1990s, 2000s, and 2010s. Gradation of blue represents low average hazard frequency per year and yellow and red gradations represent high average hazard frequency per year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

million people moved from the Black Belt to other parts of the South, especially to suburban metropolitan counties in search of affordable housing and economic prosperity (Ambinakudige, Parisi, & Grice, 2012). Atlanta is an attractive destination with an affordable housing market for African Americans and Hispanics (Flippen, 2010). However, Driskell and Embry (2007) conclude that migration may not always serve as a means of escape from poverty. In recent years, there has also been a migration of Hispanic populations to suburban metro Atlanta in search of job opportunities. The flow of the Hispanic population peaked from 2007 to 2012,

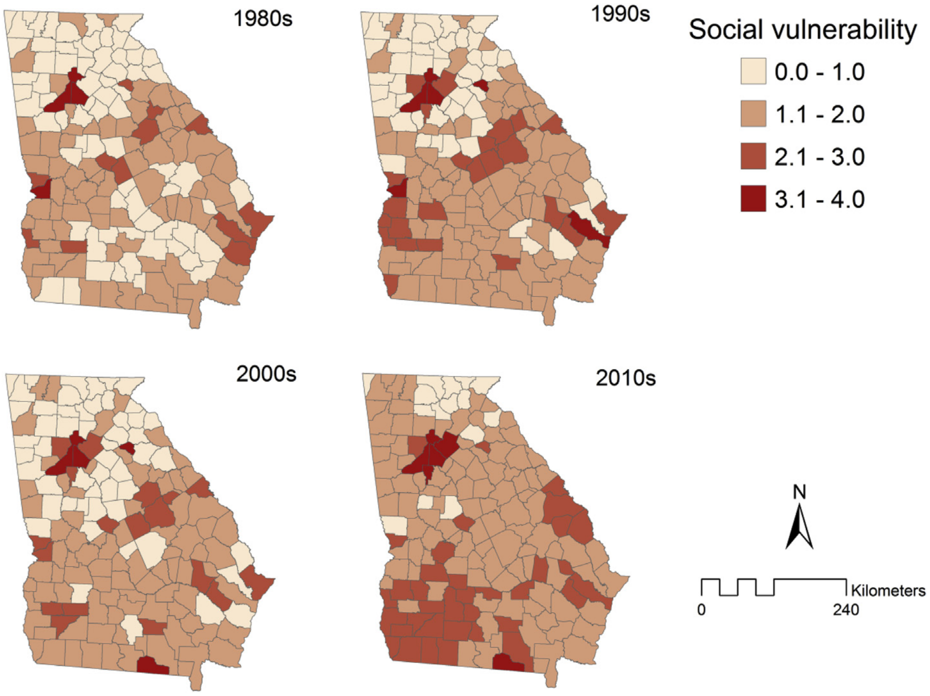


Fig. 6. Social vulnerability index in 1980s 1990s, 2000s, and 2010s. Light color indicates low social vulnerability and red indicates high social vulnerability. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

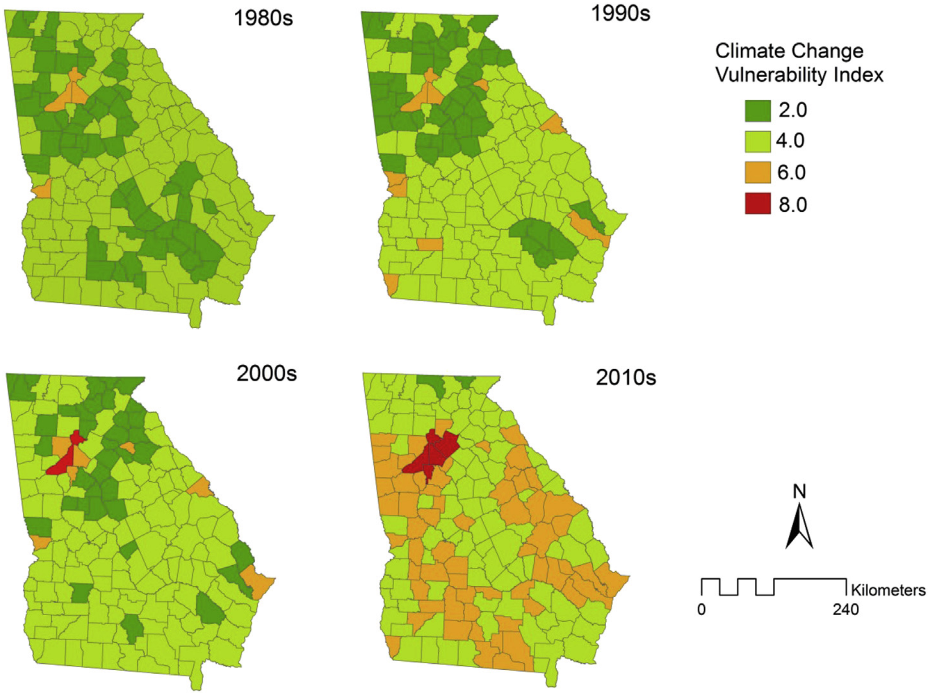


Fig. 7. Climate change vulnerability index that integrates change in temperature and precipitation, normalized hazard frequency per decade and social vulnerability score. Gradation of red indicates high climate change vulnerability. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

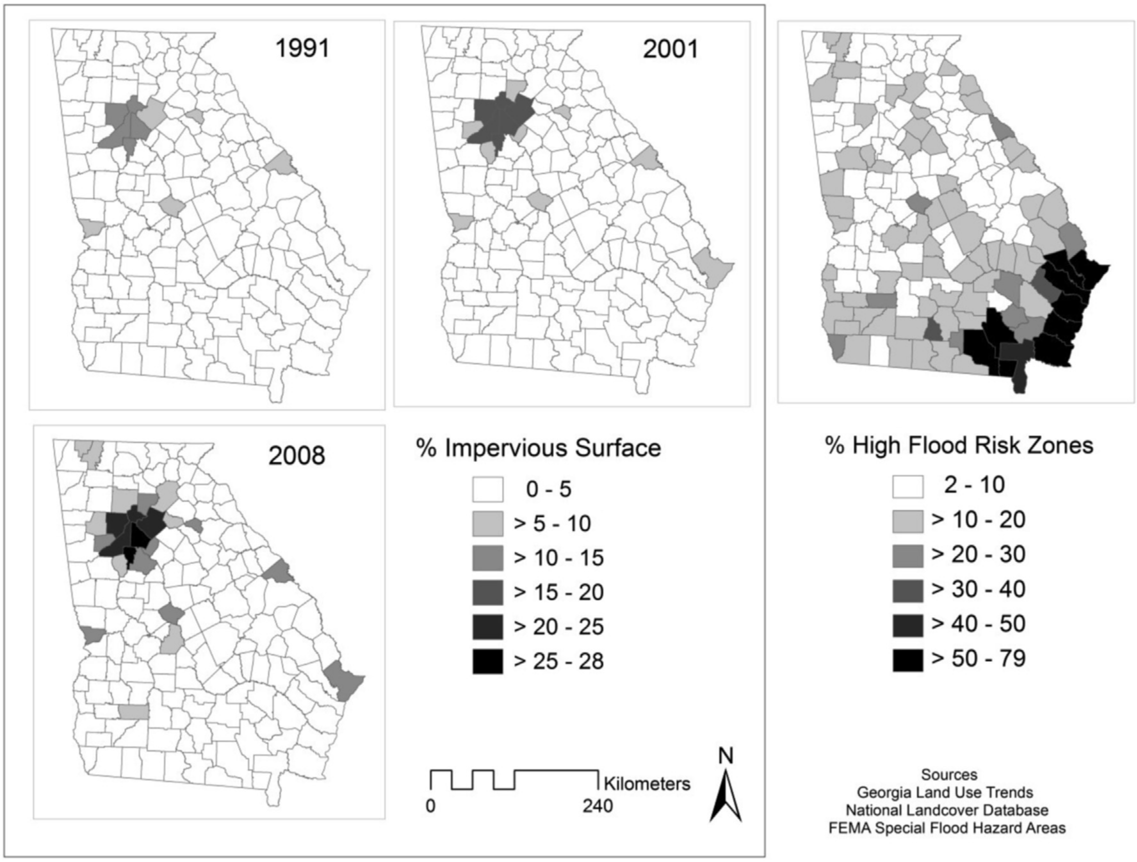


Fig. 8. Left. Three maps represent percent impervious surface coverage in 1991, 2001 and 2008, respectively. Right. Map represents percentage of county in high flood risk zones calculated from FEMA Special Flood Hazard Areas.

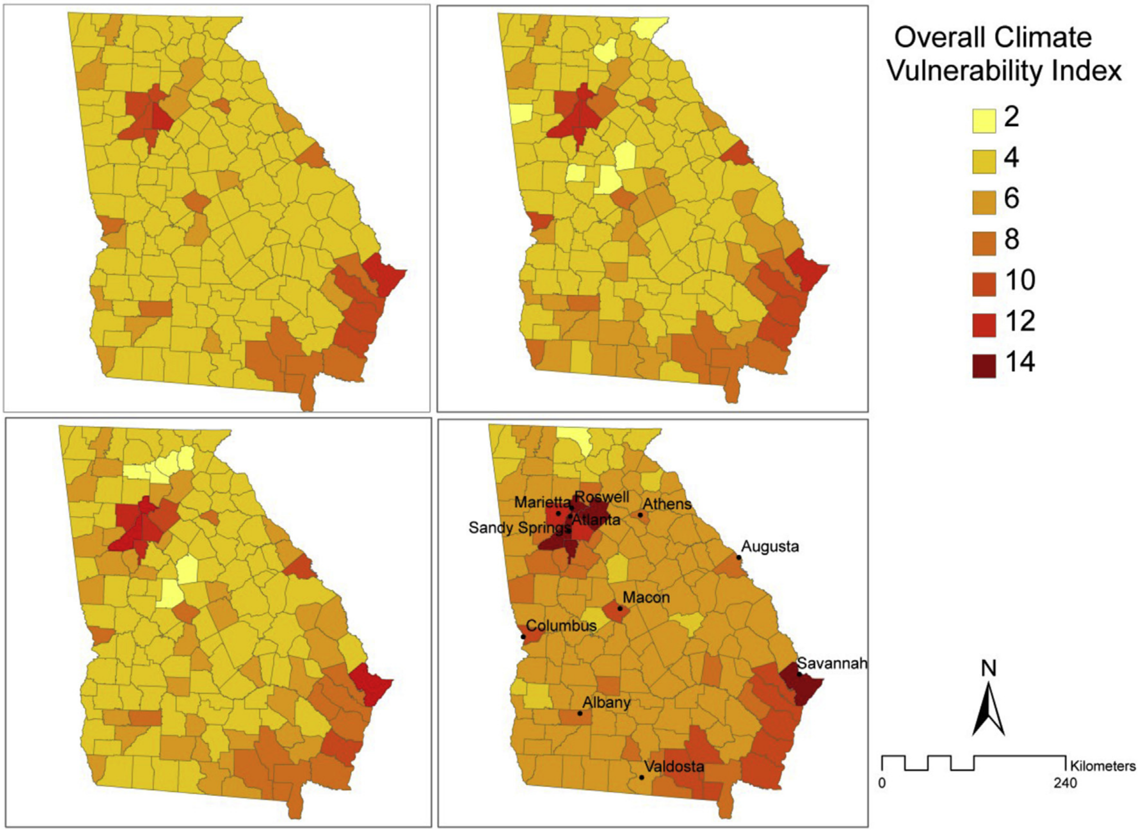


Fig. 9. Overall climate vulnerability index derived by combining the climate change vulnerability index and geographic vulnerability. Gradation of red indicates high overall climate vulnerability. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

especially in Gwinnett, Hall, Cobb, and Clayton counties. The migration of Hispanics and African Americans seems to have played a 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. However, the migration of ethnic/racial minorities to metropolitan areas of the state may have actually decreased social vulnerability for migrating populations because of their move to urban centers with more opportunities. The pursuance of such an analysis is beyond the scope of this paper. We assume that minority status and the other indicators of social vulnerability contribute to the vulnerability of that place.

The counties in east Georgia—Richmond, Burke, Jenkins, and Screven emerge as socially vulnerable counties in the 2010s. Hence, most of the counties in the Black Belt region of Georgia are found to be socially vulnerable, theoretically, because of the higher presence of groups considered to be socially marginal. Throughout the study period, racial/ethnic minorities, female headed households, age group, poverty and major occupation played dominant roles in increasing the sensitivity of a given 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 across all decades.

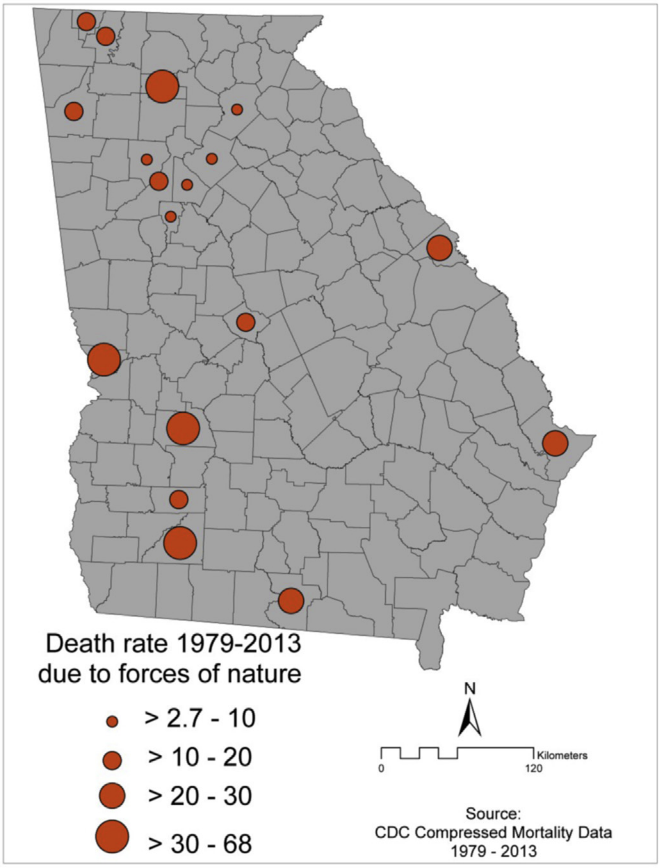
Climate change vulnerability

The interaction of social vulnerability with climatic exposures, that is, anomalies in temperature, precipitation and extreme events, resulted in high climate change vulnerability in recent decades (Fig. 7).

The emergence of metro Atlanta counties as vulnerable in recent decades is driven by land cover change, fueled by low adaptive capacity of the population. Similarly, a cluster of high vulnerability in southwest Georgia is driven by drier and warmer conditions in rural farming communities. Despite high social vulnerability, some counties in Southwest Georgia have low climate change vulnerability, which is reflected in Fig. 7 because of relatively low climatic exposures. The index is equally weighted so populations in urban and rural counties are similarly vulnerable; however, factors driving vulnerability are different. For example, heat and impervious surface (i.e., flooding) in the city contribute more to the climate vulnerability of urban Blacks/Hispanics in metro Atlanta, whereas drought and an agricultural-based economy in southwest Georgia contribute to vulnerability for otherwise socially vulnerable populations in that part of the state.

Vulnerability of place

The coastal counties, which are inhabited by both affluent and working class/poor populations, are at flood risk simply because of their geographic location. These counties are prone to flood due to storm surges 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 (Fig. 8). Similarly, in Fig. 8, inland counties with high built up or impervious surface area, especially metro Atlanta counties, are at risk of flood and heat island effects.



Source:
CDC Compressed Mortality Data
1979 - 2013

Fig. 10. Death rate caused by exposure to forces of nature which include excessive heat, cold, earthquake, storm and so on from 1979 to 2013. Only death counts > 10 are analyzed due to data unavailability. Death rate is measured as death per 100,000 population normalized by 2010 population.

Our vulnerability model discussed earlier does not consider potential vulnerable areas to future sea level rise and extreme events. 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 (Fig. 9). Atlanta metro counties and the southeastern part of Georgia, especially coastal counties, are most vulnerable to climate change and potential risk from future climate related stimuli.

Because social vulnerabilities can exist independent of climate exposure, social vulnerability by itself does not mean a population is also vulnerable to climate changes. To examine more closely the simultaneous *impacts* of social vulnerability and exposure on human communities, we compared our overall climate vulnerability index to the total number of deaths due to exposure to forces of nature (for example, excessive heat, cold, earthquake, flood, storms, volcanic eruption, and so on) at the county level. The aim here was to test the robustness of the overall climate vulnerability index in terms of its ability to influence impacts on human mortality. Center for Disease Control and Prevention (CDC) Compressed Mortality data from 1979 to 2013 are mapped in Fig. 10. As shown, the counties that suffer the highest number of deaths due to these events are also climatologically vulnerable counties as indicated by our overall climate vulnerability index. The greatest impacts are seen in metro Atlanta, southwest Georgia and coastal counties. Similarly, as reported by Hazards & Vulnerability Research Institute, metro Atlanta counties, southwest counties, and coastal counties in Georgia suffered the highest economic losses due to extreme events during 1960–2009.

Conclusions

This study quantifies vulnerability to climate change through a holistic approach by integrating biophysical and social vulnerability with geographic vulnerability. This vulnerability approach provides a broader perspective into vulnerability and provides a basis for projecting vulnerability to climate change into the future. Our results support prior research indicating that anomalies in temperature and precipitation have increased in recent decades, with warmer and drier conditions than during the 30-year period from 1971 to 2000. Extreme hydroclimate events like flood and drought have also increased in frequency in the study region, particularly in metropolitan Atlanta. We acknowledge that our period of study is rather short, but the tendencies are consistent with expectations previously published. Attribution studies are emerging as a challenging new field of study and beyond our scope. The metro Atlanta counties and Black Belt counties in Georgia emerged as potentially more socially and climatologically vulnerable. Based on geographic location, the coastal counties are at a higher 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.

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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