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Understanding the demographic implications of climate change: estimates of localized population predictions under future scenarios of sea-level rise

Katherine J. Curtis · Annemarie Schneider

Abstract Significant advances have been made to understand the interrelationship between humans and the environment in recent years, yet research has not produced useful localized estimates that link population forecasts to environmental change. Coarse, static population estimates that have little information on projected growth or spatial variability mask substantial impacts of environmental change on especially vulnerable populations. We estimate that 20 million people in the United States will be affected by sea-level rise by 2030 in selected regions that represent a range of sociodemographic characteristics and corresponding risks of vulnerability. Our results show that the impact of sea-level rise extends beyond the directly impacted counties due to migration networks that link inland and coastal areas and their populations. Substantial rates of population growth and migration are serious considerations for developing mitigation, adaptation, and planning strategies, and for future research on the social, demographic, and political dimensions of climate change.

Keywords Climate change · Sea-level rise · Population scenarios · Local estimates · Vulnerable populations · United States

The balance of scientific evidence now shows that anthropogenic emissions of greenhouse gases are having a discernible effect on the Earth's climate. We assert

K. J. Curtis (✉)
Department of Community & Environmental Sociology, University of Wisconsin-Madison, 1450 Linden Drive, Madison, WI 53706, USA
e-mail: kcurtis@ssc.wisc.edu

A. Schneider
Center for Sustainability and the Global Environment, 1710 University Avenue, Madison, WI 53726, USA
e-mail: aschneider4@wisc.edu

that anticipated climate changes such as rising sea levels will have important consequences for the human population given current settlement patterns. As temperatures increase and sea level rises at faster rates than previously observed, a substantial number of people currently living in coastal areas will become increasingly vulnerable to the impacts of sea-level rise, flooding, and storm surges (Small and Cohen 2004). Recent studies show that more than 10% of the world's population live in the world's low-elevation coastal zones (a contiguous zone along the coast less than 10 m above sea level), with a larger share of the population (14%) in developing countries living in this area compared to more developed regions (10%) (McGranahan et al. 2007; see also O'Neill et al. 2001).[1] Within the United States, some 23 million people live in the low-elevation coastal area (8% of the total population), and this estimate would be significantly higher if the population of the 20 major metropolitan areas at risk for inundation are considered.[2]

Research on climate often makes a case for the likely impacts of global warming on human populations, yet the resulting climate change scenarios are rarely, if ever, related to current or future population estimates (Lutz et al. 2007; Young et al. 2009; Plyer et al. 2010). Investigations in the geophysical sciences that include population rely only on static estimates of current population (Rowley et al. 2007), while demographic analyses have focused on coarse, brush-stroke models of population projections at the region or country level without regard for local or spatial variability (Grübler et al. 2007). While important in their own right, these approaches have yielded estimates that mask spatial variability in climate impacts on populations at the subnational scale and provide little to no information on future populations in these areas, their composition, migration patterns, or other population characteristics that shape human interactions (e.g., racial/ethnic relations) and population behavior (e.g., land use). Simply stated, spatially specific information on the vulnerability of specific population groups will be needed by local, regional, and even national government units for planning adaptation and mitigation strategies.[3]

Our research takes a foundational step in this direction by directly linking population and climate models at spatial (county-level) and temporal scales (5–30 year forecasts) that are meaningful for policy responses to anticipated environmental changes. We begin with a review of previous research linking population and environment research to motivate the technical approach we adopt in our study. Next, we describe the environmental data that we use to identify counties

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[1] The 10 m low elevation coastal zone defined by McGranahan et al. (2007) represents an upper bound for defining populations at risk for inundation. Throughout this paper, we take a more conservative approach by defining at-risk areas as those susceptible to a 1-4 m increase in sea level.

[2] The metropolitan areas susceptible to inundation include Portland, Maine; Boston, Massachusetts; Providence, Rhode Island; New York and the greater New York metro area, including Long Island; Wilmington, Delaware; Baltimore, Maryland; Norfolk-Hampton, Virginia; Charleston, South Carolina; Savannah, Georgia; Miami, Jacksonville, Fort Myers, St. Petersburg, and Pensacola, Florida; Mobile, Alabama; New Orleans, Louisiana; Oakland, San Francisco, and Sacramento, California; and Seattle, Washington.

[3] In its most general meaning, vulnerability implies ''susceptibility to loss or harm'' (Eakin and Luers 2006).

that are most vulnerable to sea-level rise and the case studies selected from among the most vulnerable counties. We then describe how we calculated the population projections for the selected cases, including alternative scenarios. Our results show that the impact of future sea-level rise will be significant and will extend beyond the inundated counties through migration networks that link inland and coastal areas and their populations. We discuss the implications of the study findings for research and policy in the concluding section.

Technical aspects to linking population and environment research

Current attention to global environmental change has begun to focus on the vulnerability of urban areas and individuals and the negative consequences of environmental changes on these groups (see, for example, a recent report by the National Science Foundation (2009) and Warner et al. (2009)). Research on this issue has taken one of two forms. The first aims to understand climate change and, specifically, sea-level rise from a geophysical perspective where climate models and projections are used to understand the "human impact," but humans are represented in their scenarios using static, spatially explicit population maps such as those available from LandScan (Dobson et al. 2000). While these are useful for understanding where populations are currently located, they contain no information on predicted population changes, its composition, or movement. Such information is vital for understanding, planning for, or mitigating impacts of climate change on human populations.

The second type of research is an impressive body of regional- and country-level demographic models and predictions (Lutz et al. 2007; Grübler et al. 2007) developed at the Institute of International Applied Systems Analysis (IIASA). These researchers have developed probabilistic projections of total population, age and life expectancy, and total fertility rates for 2008–2100 that bracket the upper and lower bound of future population developments. This research has provided useful projections, yet the estimates are limited to large-scale geographies and aggregate population groups. Thus, the challenge facing researchers today is how to effectively link these two methodologies to provide meaningful subnational, subregional projections of population that include detailed information on age, race, and sex. This information is critical for assessing the size of possible vulnerable populations, and for determining how best to respond to the needs of these groups.

Our objective is to illustrate the value of examining spatial variability in time-correlated climate and population projections at the subnational scale. We demonstrate the methodological approach by focusing on sea-level rise and population size and characteristics for a select sample of counties in the low-lying coastal zone within the continental United States. Our results show the value of this type of detailed demographic projection for local populations and, we conclude, demonstrate the need for investment in small-area population projections spatially and temporally linked with environmental projections.

Data and methods

Estimated sea-level rise

While it is often difficult to decouple the impacts of climate change on human populations from other driving forces (e.g., the impact of rising temperatures on human health), the potential effects of sea-level rise are unequivocal and will undoubtedly cause an immediate and important impact on population in terms of increased vulnerability to health risks, displacement, and migration in response to flooding. In this work, we use the concept of sea-level rise to define two separate, yet equally important, environmental impacts. The first is the potential sea-level rise due to changes in global temperature (Meehl et al. 2007) and subsequent widespread melting of ice and snow (Meier et al. 2007). These changes have resulted in sea-level rise at an average rate of 1.8 mm/yer since 1961, and 3.1 mm/year since 1993. The most recent Intergovernmental Panel on Climate Change (IPCC) scenarios show that global average sea level will continue to rise, with estimates ranging from 18–38 to 26–59 cm by 2100 depending on the emissions scenario (IPCC 2007). The impacts associated with this first type of sea-level rise are permanent, but it is likely that adequate infrastructure/planning responses could be made in time given the slow rate of change.

The second form of sea-level rise is potential flooding associated with major storms or hurricane events. This type of inundation is likely to be more extreme and affects a greater area than the case above and may be temporary or permanent in its impact. There is observational evidence of an increase in the severity of hurricanes and typhoons that impact coastal populations as a result of climate change, and it is likely that these storms will increase in intensity and frequency in coming decades (Webster et al. 2005). The storm surge from Hurricane Katrina that resulted in flooding from the levy breach on Lake Pontchartrain is estimated at 7.3–8.5 m (Knabb et al. 2006), providing a clear example of why extreme case scenarios should be taken into consideration during planning.

With these two issues in mind, we use sea-level rise scenarios to define "at-risk" locations within the continental United States. These locations are areas of potential inundation given two worst-case scenarios: 1 m inundation for worst-case sea-level rise (corresponding to the first definition above) and 4 m for worst-case storm surges/flooding (corresponding to the second definition). Two datasets were used to identify geographically vulnerable locations. First, we used Mulligan's (2007) sea-level rise scenarios, which were generated using 30–90 m resolution remote sensing data from the Shuttle Radar Topography Mission (specifically, SRTM V3 data with corrections applied by the Consortium for Spatial Information). We supplemented our analysis of these data with the detailed information available from the sea-level rise contours defined by Titus and Richman (2001). The main advantage of the Titus and Richman dataset is that it does not have the pixilation problem present in the Mulligan scenarios and thus provides a relatively clearer view of potential inundation. Unfortunately, the Titus and Richman data do not provide full spatial coverage of all coastlines (the contours cover up to ~70 km from the coast, while the Mulligan dataset provides information up to ~120 km inland), and they provide more conservative scenarios of 0.5 m and 3.5 m (i.e., a slight mismatch to the 1 m and 4 m scenarios), thus limiting their use in this study. Moreover, it is important to point out that neither dataset incorporates local variability that may affect the severity of flooding (e.g., the presence of wetlands, barrier islands, etc.) into their assessment of sea-level rise scenarios. Rather, these datasets provide a brush-stroke view of potential inundation across large areas based primarily on elevation, slope, and proximity to water bodies. Finally, the inundation scenarios derived from raw SRTM data may not fully characterize potential flooding in urban areas, since the satellite data may record the height of buildings rather than ground elevation. Thus, any potential inundation within dense metropolitan areas may be considered lower-bound estimates.

Because of the large area, the separate datasets were brought into a common map coordinate system (Albers equal-area projection) and stitched together to create one contiguous map of predicted inundation at 0 m (baseline map), 1 m, and 4 m. Finally, we added information on the physical extent of built-up areas by introducing Schneider et al.'s (2009) map of urban land extent, and land cover types by incorporating the 2001 National Land Cover Database (Homer et al. 2004).

Note there is no time scale associated with the inundation maps; rather, these maps depict coastal areas potentially at risk for inundation due to low elevation. To determine the time at which an area may become inundated due to sea-level rise (definition 1), we turn to the results of the predictive models as synthesized and reported in the 4th Assessment of the IPCC (2007). When bringing together the results of predictive numerical models and statistical models from disparate disciplines, an important consideration is the difference in the time horizon for forecasts. Climate change research is typically conducted on the order of centuries, with 2050, 2080, and 2100 often cited as time points for significant change and impacts. Because demographic research typically focuses on projections on much shorter periods of time (i.e., decades), we balance this trade-off by generating our predictions on a time scale to 2030. The 30-year period of prediction (using 2000 as the most recent observed base year for population counts) is within reach for planning and adaptation strategies, while also providing sufficient time for significant sea-level changes to occur. Moreover, population forecasts can only be reasonably calculated to the extent that past data are available (here, 30 years) (Shryock and Siegel 1980).

The IPCC scenario predictions for sea-level rise were adjusted to the 30-year time horizon using simple linear interpolation (current projections follow near-linear trends for all of the emissions scenarios) for five-year intervals for the period 2008–2030. The conservative results show that it is likely that global average sea level will rise from 4.2 to 13.9 cm during this time frame. Similar interpolation of recent sea-level rise trends (1961–2003) also falls within this range, supporting our results. Although these figures may appear low, sea-level rise of this magnitude is still worrisome in extremely flat, low-lying areas (e.g., much of Florida is < 1 m above sea level) and especially problematic in resource-poor areas with little capacity for mitigation or adaptation. Unfortunately, datasets depicting sea-level rise on the order of centimeters rather than meters have not yet been generated, so this research connects the 4- to 13-cm sea-level rise to the 1 m scenario to characterize sea-level changes attributable to climate change.

Admittedly, overestimating the degree of inundation in this manner may introduce error into our analysis, and the results should be considered in light of this bias. Further, these figures do not take into account known spatial variability in sea-level changes or, perhaps more importantly, the potential for extreme sea-level changes (on the order of meters) that will result from natural hazards, such as hurricanes and floods. These natural hazards are expected to increase in both frequency and intensity due to climate change (Goldenberg et al., 2001).

Case selection

To select case study areas with potentially significant impacts from sea-level rise, we intersected the maps of predicted sea-level rise (described above) with county political boundaries within a GIS; this process produced a total of more than 200 counties (of 254 counties located along a saltwater coastline) that experience some degree of flooding under either the 1 m or 4 m scenarios. We defined areas with the greatest impact (i.e., the most severe inundation) in two ways: (1) in absolute terms, by the greatest total area flooded (measured in square kilometers) and (2) in relative terms, by percentage of land affected within the county. Based on these results (Table 1), our study sample represents four areas that consistently appear at the top of the rankings as those most affected by either the 1-m or 4-m sea-level rise scenarios: California, Florida, New Jersey, and South Carolina. The selected areas (Fig. 1) are distributed across the United States and capture four compelling sociodemographic scenarios, as illustrated in Table 2. In addition, each case study has unique geographic characteristics that make it susceptible or vulnerable to inundation.

The reader will note the absence of New Orleans and other southern areas that were impacted by Hurricane Katrina. While these counties are expected to experience future significant damage from sea-level rise, methodological problems arise because of the timing of Katrina (2005) and the baseline population estimate (2000). Although the 2000 population estimates for areas hit by Katrina are accurate for this date, the region experienced dramatic outmigration that makes forecasting area population dubious at best. Rather than using Hurricane Katrina to demonstrate the technical advantages of the local approach, the human impact of the natural disaster makes obvious the importance of localized estimates.

California

The California cluster encompasses five densely populated counties (261 persons/km^2) comprised of primarily farmland, small city centers, and the greater Sacramento metropolitan area (> 2 million people). The area is known for its fertile lands and high agricultural production with over 69% of land used for pasture or cultivation, often with multiple crops per year (USDA 2008). A larger than average farm population (8.7% versus the national average of 5.1%) is required to maintain the high level of output in the region (e.g., the area produces nearly half of

Table 1 Rankings of US counties most affected by 1 m or 4-m sea-level rise scenarios (sea-level rise data are adapted from Titus and Richman 2001 and Mulligan 2007)

Rank	Predicted sea-level rise—1 m scenario		Predicted sea-level rise—4 m scenario	
	Greatest area inundated	Greatest percentage of county inundated	Greatest area inundated	Greatest percentage of county inundated
1	Cameron, Louisiana	Iberia, Louisiana	Walton, Florida	Cameron, Louisiana
2	Vermilion, Louisiana	Cameron, Louisiana	Cumberland, New Jersey	Walton, Florida
3	Terrebonne, Louisiana	Vermilion, Louisiana	Iberia, Louisiana	Terrebonne, Louisiana
4	Plaquemines, Louisiana	Plaquemines, Louisiana	Cameron, Louisiana	Vermilion, Louisiana
5	Lafourche, Louisiana	Lafourche, Louisiana	Nueces, Texas	Lafourche, Louisiana
6	Hyde, North Carolina	Jefferson, Louisiana	Vermilion, Louisiana	Plaquemines, Louisiana
7	St. Mary, Louisiana	Terrebonne, Louisiana	St. Mary, Louisiana	Cumberland, New Jersey
8	Beaufort, South Carolina	Hyde, North Carolina	St. Bernard, Louisiana	Palm Beach, Florida
9	St. Bernard, Louisiana	St. Bernard, Louisiana	Terrebonne, Louisiana	St. Mary, Louisiana
10	Jefferson, Louisiana	St. Charles, Louisiana	Lafourche, Louisiana	Jefferson, Texas
11	Charleston, South Carolina	Poquoson, Virginia	St. John, Louisiana	Hyde, North Carolina
12	Dorchester, Maryland	St. Mary, Louisiana	Iberia, Louisiana	St. Bernard, Louisiana
13	Carteret, North Carolina	Beaufort, South Carolina	St. Charles, Louisiana	Brazoria, Texas
14	St. Charles, Louisiana	Dorchester, Maryland	Hyde, North Carolina	Carteret, North Carolina
15	Solano, California	Cape May, New Jersey	Currituck, North Carolina	Iberia, Louisiana
16	San Joaquin, California	Carteret, North Carolina	Jefferson, Texas	Chambers, Texas
17	Camden, Georgia	St. John, Louisiana	Plaquemines, Louisiana	Charleston, South Carolina
18	Monroe, Florida	Currituck, North Carolina	Jefferson, Louisiana	St. Martin, Louisiana
19	Chatham, Georgia	Glynn, Georgia	Chambers, Texas	Beaufort, South Carolina
20	Glynn, Georgia	Chatham, Georgia	Carteret, North Carolina	Matagorda, Texas
21	King, Washington	Somerset, Maryland	Poquoson, Virginia	Collier, Florida
22	Accomack, Virginia	Hudson, New Jersey	Orleans, Louisiana	Dorchester, Maryland

Table 1 continued

Rank	Predicted sea-level rise—1 m scenario		Predicted sea-level rise—4 m scenario	
	Greatest area inundated	Greatest percentage of county inundated	Greatest area inundated	Greatest percentage of county inundated
23	Brazoria, Texas	McIntosh, Georgia	Chatham, Georgia	Jefferson, Louisiana
24	Jefferson, Texas	Iberia, Louisiana	Washington, North Carolina	St. Charles, Louisiana
25	Chambers, Texas	Accomack, Virginia	Bristol. Rhode Island	Brevard, Florida
26	Atlantic, New Jersey	Camden, Georgia	Tyrrell, North Carolina	Calcasieu, Louisiana
27	Iberia, Louisiana	Northampton, Virginia	Dorchester, Maryland	St. John, Louisiana
28	St. Martin, Louisiana	Orleans, Louisiana	Virginia Beach, Virginia	Camden, Georgia
29	McIntosh, Georgia	Cumberland, New Jersey	Beaufort, South Carolina	Chatham, Georgia
30	Calcasieu, Louisiana	Atlantic, New Jersey	St. James, Louisiana	Georgetown, South Carolina
31	Yolo, California	Chambers, Texas	Hudson, New Jersey	San Joaquin, California
32	St. John, Louisiana	Solano, California	Pamlico, North Carolina	Yolo, California
33	Cape May, New Jersey	Virginia Beach, Virginia	Galveston, Texas	Lee, Florida
34	Cumberland, New Jersey	Pamlico, North Carolina	Portsmouth, Virginia	Tyrrell, North Carolina
35	Colleton, South Carolina	Talbot, Maryland	Pasquotank, North Carolina	Jefferson Davis, Louisiana

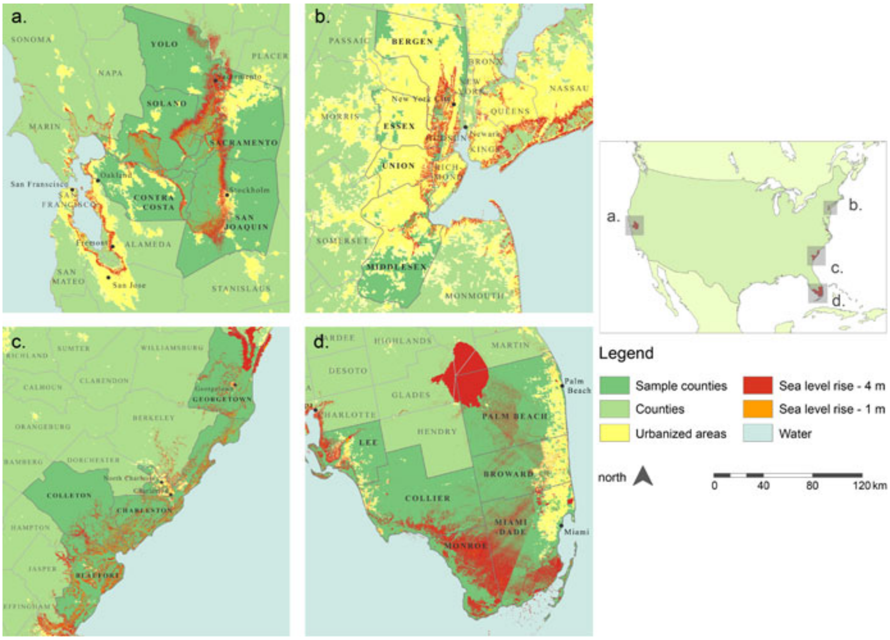

Fig. 1 Maps of the five study areas examined in this research: **a** Northern California, **b** New Jersey, **c** South Carolina, and **d** Southern Florida. The counties of each sample area are shown in *dark green*, while potential inundation is shown in *orange* (1-m sea-level rise) and *red* (4-m sea-level rise). For reference, urbanized areas are shown in *yellow*

California's corn crop), which borders the low delta lands between the Sacramento and San Joaquin rivers as well as the San Francisco Bay. Figure 1a reveals that inundation would likely affect valuable farmland, with extreme scenarios easily affecting small towns and settlement on the outskirts of Sacramento. Sacramento is the core cultural and economic center of the five selected counties, as well as the state capital. The city proper is not susceptible to sea-level rise, yet it faces a similar risk of flooding given the aging levee system on the American River and increased flow of snowmelt out of the Sierra Nevada mountains due to temperature rise.

As a whole, the population is also particularly susceptible to exogenous social and economic shocks that might result from climate change due to high rates of immigration to the area; the foreign-born population comprises just below 18% of the total population compared to the national average of 11%. California hosts one of the largest Hispanic immigrant populations and, thus, bears a huge cost to provide basic services to this sector of the growing population. While the percentage of the population living in poverty for the five-county sample is lower than the national average, poverty is disproportionately higher for the Hispanic population. For example, 8.8% of the total population and 7.7% of the non-Hispanic white population were living in poverty, whereas 18.5% of the Hispanic population in the same counties was living in poverty.

Table 2 Selected sociodemographic and environmental characteristics of the study areas with national comparisons (%), 2000 Census (SF3) and County and City Databook (2007)

	Study areas[a]				
	California	Florida	New Jersey	South Carolina	United States[b]
Land attributes					
Size of study area (km^2)[c]	12,761	23,481	2,085	8,745	7,664,014
Dominant land cover type (% of total area)[d]					
Urban areas	18.4	19.0	62.6	7.2	1.9
Agriculture, pasture, grasslands	69.0	13.9	5.1	13.2	40.9
Forests	3.7	1.8	22.2	32.7	26.8
Wetlands	4.4	65.0	9.5	42.2	5.9
% Inundated by land cove[e]					
Urban areas	12.2	60.9	8.5	38.7	–
Agriculture, pasture, grasslands	35.1	12.5	6.7	26.3	–
Forests	0.4	43.2	0.5	25.0	–
Wetlands	4.4	68.6	76.3	55.5	–
Urbanization					
Farm population (of rural)	8.7[f]	2.8	3.0	2.4	5.1
Urban population	95.8	97.9	99.7	75.2	79.0
Population density (persons/km^2)	261	178	1,474	60	36
Migration					
Out-of-state inmigration (past 5 years)	8.0	16.9	11.6	20.2	11.3
Foreign-born	17.8	32.1	23.8	3.9	11.1
Race/ethnicity					
Black/African American	9.0	16.3	17.9	32.6	12.0
Hispanic white	7.7	25.5	7.3	1.5	6.0
Non-hispanic white	54.9	48.7	57.1	61.9	69.1
Age					
<18 years old	27.7	23.0	24.2	24.0	25.6
65 + years old	10.8	17.4	13.3	13.2	12.4
Education					
<High School (no diploma)	17.7	22.9	18.1	18.6	19.6
Master's +	8.9	9.2	12.4	10.2	8.9
Industry/Class of Worker (civilian population)					
Agriculture	1.5	0.8	0.1	1.0	1.5
Professional[g]	18.4	18.7	21.0	14.1	15.3
Economic vulnerability					
Median income ($)	48,728	42,268	56,743	37,462	41,994
Poverty	8.8	10.2	6.5	11.8	9.2

Table 2 continued

	Study areas[a]				
	California	Florida	New Jersey	South Carolina	United States[b]
Local general revenue (2002, $per capita)	4,234	4,000	3,609	2,922	3,458

[a] Counties within California include Contra Costa, Sacramento, San Joaquin, Solano, and Yolo counties. Florida includes Broward, Collier, Lee, Miami-Dade, Monro, and Palm Beach counties. New Jersey includes Bergen, Essex, Middlesex, and Union counties. South Carolina includes Beaufort, Charleston, Colleton, and Georgetown counties. Virginia includes Hampton, Norfolk, Poquoson, Portsmouth, and Virginia Beach county equivalents

[b] For all land estimates, the United States category refers to the contiguous 48 states

[c] Land area reflects the total land area of all counties within the study area reported by county (official values) and excludes county water area. The land area values from the raster data are within 2% of these totals

[d] Land cover type was estimated using the National Land Cover Database (classified raster maps from Landsat remote sensing data). The values will not sum to 100% due to the presence of additional land cover types (e.g., barren, shrubland, etc.). Urban areas include open vegetated space contained within the city; agriculture includes cultivated crops, pasture, and grassland suitable for pasture; forests include all forest types; and wetlands include woody wetlands and emergent herbaceous wetlands

[e] Inundated land was estimated using 4-m sea-level rise scenario. Estimates are not reported for the United States since the number would not be meaningful because of the small areal extent of inundation relative to the total land area of the country

[f] The farm population was 12.3% and 8.1% of the rural population for Solano and Yolo counties (California)

[g] Category includes finance, insurance, real estate and leasing, and professional services

Florida

Few places in the United States are as vulnerable to sea-level rise as Southern Florida due to the low-lying elevation of nearly the entire state (on average less than 2 m above sea level). The six-county Florida cluster we have selected encompasses an area with significant risk to human populations (greater Miami-Dade area), vast economic assets, and natural resources of national and international significance (e.g., the Everglades). The area is one of the most densely settled and fastest growing in the country; Miami-Dade ranks sixth in terms of county population across the United States, while rates of net migration during the last five years are greater than 17% (compared to the national average of 11%). Incoming populations are comprised of retirees from across the United States (17% of the population is 65 +) as well as immigrants of distinct Latino origins (25% of the population, primarily of Cuban, Haitian, and Dominican origins). The majority of the 6 million people in the region live in the greater Miami metropolitan area, Fort Lauderdale, or Palm Beach. However, nearly 40% of the population lives in densely settled unincorporated areas along the coast that are particularly susceptible to erosion of beaches and bluffs caused by sea-level rise. While breach of infrastructure is a major concern, the real threat of sea-level rise in this area is the potential impact to the water supply caused by saltwater encroachment into freshwater surface water and aquifers.

The Florida study area supports fertile agriculture, with over 13% of its land cover devoted to production (predominantly orchards, USDA 2007), and similar to California, rising sea level puts a significant local food supply at risk. In addition, the cluster is home to the fragile ecosystem of the Everglades, a network of wetlands and forests with 36 threatened or protected species. This area includes the largest mangrove system in the western hemisphere and provides a wide range of critical ecosystem goods and services (e.g., ground water recharge, flood regulation, climate mitigation, tourism, and recreation). Although sea-level rise may be gradual, experts also fear the system may not be able to adapt to the higher saline content of inundation water (Gutierrez et al. 2007).

New Jersey

The four-county New Jersey cluster is distinct among our study areas because of its high level of urbanization (99.7%) and dense settlement (1,500 persons per km^2). The conurbation of Newark, Jersey City, and Elizabeth has a combined population of nearly 4 million and is officially part of the greater New York metropolitan area. The New Jersey cluster has a regionally based migration network that sets it apart from the other study areas (we discuss the potential consequences of such a geographically dense migration network in a later section). The area has a high percentage of foreign-born (23%, compared to the national average of 11%), given the proximity to New York City. In addition to its ethnic diversity, the area is socioeconomically mixed. The area houses some of the most severe pockets of poverty as well as the most exclusive suburbs in the United States. This dichotomy in wealth is masked in the high median income for the study area ($56,000), however.

Originally developed as suburbs, the area is now known for its transportation hub (it is the largest container port in the United States and houses a confluence of rail and a major airport) and the myriad of pharmaceutical, chemical, telecommunication, food processing, and publishing industries. The strategic location of New Jersey on the waterways has been a key reason for the region's economic development, but at the same time, puts the area at great risk in terms of sea-level rise due to climate change. The cluster of counties is not only on a low-lying tidal plain, but the geographic configuration of the coastline puts New Jersey at increased danger for hurricane and storm surges (Sugarman 1998). The coastline turns inland south of Manhattan Island, which can act to funnel hurricanes and their associated storm surges into Lower New York Bay and the New Jersey coast. While New York City would be buffered, the New Jersey coast would likely bear the full force of any storm and related flooding. The vulnerability of the area is further exacerbated by the dense nature of settlement; erosion, flooding, and salinity of surface and ground waters will have major impacts on the heavily developed communities and industry of this region, with potentially national-level repercussions on par with those witnessed in the aftermath of Hurricane Katrina (Goldenberg et al. 2001).

South Carolina

The final study area covers another geographically vulnerable area of the U.S. eastern coastline: South Carolina's low-elevation coastal zone, which includes Charleston, Hilton Head, the Santee River Delta, and the Barrier Islands. Although the region has the smallest total population of the four study areas, it serves as a unique case study because of its relatively large African American population (33% on average, compared to the national average of 12%) and its significant rural population (29%). This area is also home to the most economically vulnerable population of the study areas, with a median income of only $37,500, and nearly 12% of the population living below the poverty line. Despite these economic vulnerabilities, the region has experienced recent population growth as the result of a new wave of return migration (over a 20% increase in population) from the northern and western regions of the United States.

From an environmental perspective, South Carolina is susceptible to a number of adverse impacts from sea-level rise. Rates of coastal erosion have already increased (King et al. 2009), and South Carolina's eastern communities are starting to bear the economic burden of conservation measures to preserve coastal areas. As the barrier islands erode, storm impact and damage are also likely to increase as the full force of hurricanes and major storms is felt in the area. Similar to the Florida study area, the region's water supply is also at risk due to potential saltwater incursion into freshwater aquifers that serve the vast majority of drinking water needs in the area.

Case summary

It is reasonable to anticipate that the political responses to inundation would vary across the selected case studies given the differences in social and economic resources. That is, places with fewer resources may be less equipped to effectively respond compared to places with greater resources. Resource-dependent variation in the ability to respond or adapt is already evident in global studies of climate-related human migration and displacement (Warner et al. 2009). An example of resources in the U.S. context includes area tax base; a place with more wealth will have a greater ability, for example, to build a levy. The same pattern applies to the population; a population with less wealth or industry-specific skills will have more difficulty responding to environmentally induced dislocation than a more endowed population. For example, a population with low education and farming skills will be less competitive in a labor market dominated by professional services that requires a comparatively higher education and a different skill set. Moreover, a population with fewer assets will have fewer and different options for new destinations given the costs of relocation. Importantly, material assets, job skills, and formal education are unevenly distributed across race/ethnic groups in the United States. The human impacts of environmental change, therefore, will be differentially experienced according to race/ethnicity as well as geography—a lesson made clear in the case of Hurricane Katrina (Branshaw and Trainor 2007; Myers et al. 2008) as well as other climate-related disasters that have devastated communities across the globe (Warner et al. 2009).

The case study sample is a collection of counties. It is generally true that the human population is not evenly distributed across the county; thus, it may be difficult to determine which specific populations might be affected at a subcounty scale given sea-level rise or storm surge flooding. However, there are several reasons why a county-level analysis is a valid approach. First, although unevenly distributed within the county, populations tend to concentrate in coastal areas that are projected to be impacted by sea-level rise.

Second, while the economic characteristics of the population may not be evenly distributed across spatial units, the overall county will be impacted. Assuming the wealthier population tends to live closer to the coasts and, thus, is more environmentally vulnerable, the dislocation of this population may have far-reaching impacts in two different ways: (1) if the wealthier population was to be dislocated but stays within the county, they would likely dislocate the poorer population through a process like gentrification and (2) if the wealthier population were to be dislocated and move out of the county, the remaining local area population would be poorer; the county's economic vulnerability would increase through change in the population composition through selective outmigration. In either instance, the total county population will be affected.

Finally, we believe that the county is the appropriate geographic unit for the current study because it is commonly the county-level governing unit that responds to issues surrounding planning, including planning for climate change. Similarly, state and federal funds are often awarded to the county for distribution to subcounty units.

Population projections

We use a cohort-component method to calculate annual county population forecasts through 2030 and project forward the 2000 population baseline estimate according to county migration, fertility, and mortality rates reported by the U.S. Census Bureau (Census Bureau 2001a, b, c) and the U.S. Department of Health and Human Services (2001a, b). We use migration rates that have been adjusted to address census undercounts among specific age and race groups by a team of researchers headed by Dr. Paul Voss (Voss et al. 2004) at the Applied Population Laboratory, University of Wisconsin-Madison. In the current study, county estimates available through national organizations are compared with estimates reported by state organizations as well as 2005 population estimates. Adjustments were made by modifying the migration rate to correct for suspected over- or underestimated population counts. Although county-level population projections to 2040 are commercially available, we calculated our own projections to maintain model flexibility (e.g., explore migration flow scenarios).

The cohort-component method is perhaps the most common approach to project small-area populations (Siegel 2002). The strategy relies on age-specific data and, thus, permits us to report forecasted populations for specific age-groups. Our models also incorporate sex and race components. Therefore, we are able to report the total county population in 2030 as well as the forecasted population by age, sex, and race. Using the approach taken in Voss et al. (2004), we began with the Census 2000

Modified Race file (U.S. Census Bureau 2002) and distributed people reporting two or more races among the other race groups. The reported age-groups were allocated to single years using the age distribution of Summary File 1 (U.S. Census Bureau 2001a). County estimates of the Hispanic population and other subgroups (e.g., black women, black men, non-black women, and non-black men) were adjusted using the 2000 Redistricting File (U.S. Census Bureau 2001b) and demographic analysis by the Census (U.S. Census Bureau 2001c). Individual-level birth records with data on county and month of birth, sex, race, and Hispanic origin were obtained through a privileged data use agreement (U.S. Department of Health and Human Services 2001b). Similarly, death records from the Multiple Cause of Death Files were obtained through a privileged data use agreement (U.S. Department of Health and Human Services 2001a). Full details on model construction are available in Voss et al. (2004).

The resulting forecasts are based on trends believed to be valid for the projection horizon given our assumption of status quo population change; we assume that the current rates of natural increase and migration will generally persist for all counties through 2030. The projections are not intended to be perfect predictions of what will occur; rather, the projections are scenarios of what could happen given model assumptions. Because future growth may depart from historical patterns, we explored three alternative scenarios where we assume that the population will increase or decrease beyond the status quo due to potential changes in environmental and economic conditions, as elaborated below. Adjustment through migration is reasonable given its increasing influence on U.S. population redistribution and the uniformity in levels and decreasing impact of natural increase (Perry 2006).

Projected human impacts

We report two key findings: first, there is considerable spatial variability in the impacts of sea-level rise on population, and second, population impacts are not isolated to inundated counties but extend to geographically nearby and distant counties through migration streams. These patterns put certain segments of the population and places within the United States at risk of bearing a disproportionate burden of inundation.

Variability in impacts

We find roughly 19.3 million people will be affected by sea-level rise in 2030 within the four sample areas. This number evokes a different—and more realistic—sense of urgency than if we were to report the 2000 population figure of 12.5 million, about 35% fewer people, or the 2008 population estimate of 13.7 million, about 30% fewer people (U.S. Census Bureau 2008). As illustrated in Fig. 2, Florida is expected to experience the greatest population impact; in 2030, more than 9.9 million people could be dislocated by sea-level rise, storm surges, or inundation.

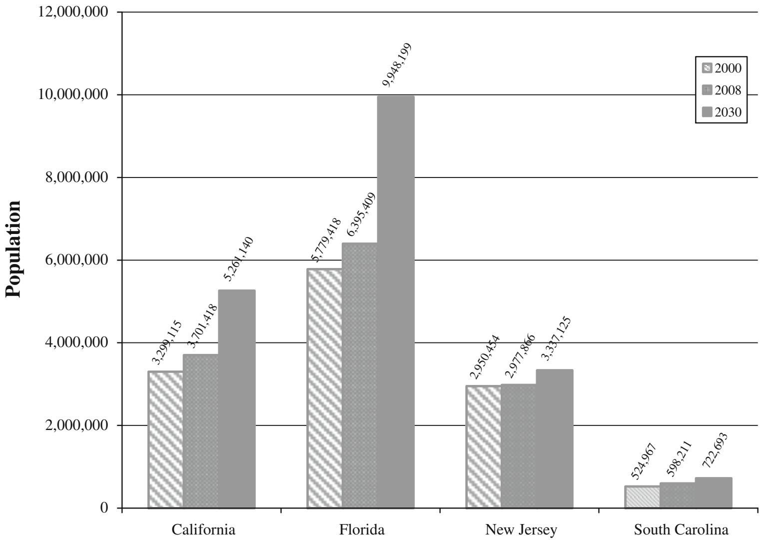

Fig. 2 Observed and estimated population in 2000, 2008, and 2030 for the five study areas impacted by sea-level rise in 2030

South Carolina has the slowest rates of population growth and smallest population and is, thus, the least impacted with “only” an estimated 722,693 affected residents.

Not all segments of the population will be impacted evenly due to the geographic distribution of the U.S. population and the link to risk of inundation. Because certain subgroups are more vulnerable, the magnitude of inundation will be more severe for some groups compared to others and, in turn, government units will have to confront associated social justice issues. Populations most susceptible to loss or harm include the youngest and oldest members of a society and, in the U.S. context, racial minorities. Vulnerability for these groups includes greater economic instability, poorer health conditions, and less access to social and political resources (Iceland 2006; Massey and Denton 1993; Williams and Collins 1995). Such vulnerable status puts these groups at a greater risk of experiencing hardships that accompany preparing for inundation or dealing with the aftermath of inundation, including the associated financial costs and physical demands of retrofitting homes and neighborhoods, and relocating to new areas either before or following inundation. We report projected population estimates for specific age, sex, and race groups in Table 3.

Florida will have not only the largest number of people impacted, but the at-risk counties are estimated to have 2.6 million people over the age of 65 and 1.9 million children. In terms of percentage of area population, South Carolina is estimated to have the largest proportion of elderly impacted (33% of the total projected population) while California will have the largest percentage of children impacted (26%). These populations are not as well equipped to respond to inundation compared to, for example, the working-age population who are less economically and physically encumbered. South Carolina is estimated to house the largest number

Table 3 Estimated population impacted by sea-level rise for selected counties experiencing an estimated 4-m rise, 2030

Area	Total population	Age			Sex		Race/ethnicity[a]		
		<18	18–64	65+	Females	Males	Black/ African	American Hispanic	Non-Hispanic White
California									
Contra Costa	1,357,964	328,196	794,937	234,831	699,415	658,549	149,146	314,298	723,067
Sacramento	1,824,416	470,251	1,067,781	286,384	932,168	892,248	223,149	369,271	958,326
San Joaquin	1,253,910	386,681	693,163	174,066	641,389	612,521	89,988	463,630	503,787
Solano	534,471	130,242	301,115	103,114	276,422	258,048	84,499	114,325	250,946
Yolo	290,379	71,435	190,405	28,539	153,844	136,535	6,172	105,204	148,999
Sub-total	5,261,140	1,386,804	3,047,401	826,934	2,703,238	2,557,902	552,953	1,366,729	2,585,125
% change (2000)	59	−11	7	45	61	58	87	111	43
% of sub-total		26	58	16	51	49	11	26	49
Florida									
Broward	2,600,197	528,899	1,608,601	462,698	1,330,882	1,269,315	755,341	488,502	1,293,905
Collier	684,494	124,859	318,279	241,356	327,858	356,636	52,151	199,976	426,159
Lee	3,325,802	690,877	2,035,908	599,018	1,679,474	1,646,328	868,404	1,772,617	664,184
Miami-Dade	1,203,175	163,555	478,822	560,798	558,004	645,171	107,624	152,619	925,934
Monroe	83,390	9,892	48,354	25,144	37,187	46,203	5,461	16,743	59,892
Palm Beach	2,051,141	345,217	1,023,699	682,224	1,046,338	1,004,803	400,884	336,907	1,262,603
Sub-total	9,948,199	1,863,299	5,513,663	2,571,237	4,979,743	4,968,456	2,189,865	2,967,365	4,632,677
% Change (2000)	72	−18	−7	48	67	78	133	64	65
% of sub-total		19	55	26	50	50	22	30	47
New Jersey									
Bergen	971,894	210,637	575,630	185,627	506,890	465,004	55,014	122,961	675,666
Essex	824,859	213,605	485,966	125,288	428,802	396,057	379,153	149,861	263,831

Table 3 continued

Area	Total population	Age			Sex		Race/ethnicity[a]		
		<18	18–64	65+	Females	Males	Black/ African	American Hispanic	Non-Hispanic White
Middlesex	965,644	225,447	590,455	149,742	494,531	471,113	100,633	173,659	556,655
Union	574,728	140,966	346,107	87,655	292,320	282,408	134,639	136,132	280,893
Sub-total	3,337,125	790,655	1,998,158	548,311	1,722,543	1,614,582	669,440	582,613	1,777,045
% change (2000)	13	−2	−4	23	13	14	26	39	6
% of sub − total		24	60	16	52	48	20	17	53
South Carolina									
Beaufort	207,760	29,044	84,755	93,961	97,234	110,527	52,004	14,704	138,187
Charleston	382,510	80,497	210,849	91,163	203,857	178,654	157,180	9,737	213,961
Colleton	47,875	10,224	24,605	13,046	23,619	24,256	83,342	679	24,535
Georgetown	84,548	9,105	34,872	42,115	43,026	41,522	34,019	1,570	47,979
Sub-total	722,693	128,870	355,081	240,285	367,735	354,959	326,545	26,690	424,661
% Change (2000)	38	−26	−22	152	37	39	91	55	31
% of sub-total		18	49	33	51	49	45	4	59
Total	19,269,157	4,169,629	10,914,303	4,186,768	9,773,258	9,495,899	3,738,801	4,943,396	9,419,508
% change (2000)	53	−16	−9	75	51	56	93	71	42
% of total		22	57	22	51	49	19	26	49

[a] Values reported for the race/ethnicity categories will not sum to 100% since they do not include all possible racial/ethnic groups. There is some overlap in the black/ African American and Hispanic populations because of the way race and ethnicity are reported in the data used to generate the population estimates

of blacks, and Florida is projected to house the biggest Hispanic population, followed by California. Given racial and ethnic trends in poverty in the United States, it might be particularly difficult for these groups to respond or adapt to inundation relative to the white population. South Carolina had the highest poverty rate among the study areas, and the California Hispanic population had a poverty rate 10% points higher than the white population in 2000.

The increasing vulnerability is demonstrated by the estimated percent change between 2000 and 2030 for the specific age- and race/ethnic groups. All areas combined, the elderly population is projected to grow by 75% whereas the working-age and child populations are expected to decline. The black and Hispanic populations are projected to increase by 93 and 71%, respectively. Among the study areas, the most dramatic growth is observed for Florida with a 72% increase in total population, where the elderly are expected to comprise one-quarter of the population and the non-white population is estimated to comprise the majority of the population (56%, 100–47). Overall, these figures demonstrate that we can expect the social justice challenges associated with inequality in vulnerability to increase by 2030.

Reach of impacts

The population implications, however, are not restricted to inundated counties because counties directly impacted by sea-level rise are connected to other places through migration streams. Inundation, therefore, will not only dislocate human populations, but will cause a restructuring of existing migration networks. Such restructuring will include increased inmigration to places that currently receive minimal inmigration from inundated counties, the formation of links to entirely new destinations, and the elimination of some current migration streams. The estimated 19.9 million people dislocated by sea-level rise will be forced to relocate to new areas, and potential inmigrants to inundated counties will have to move to alternative destinations. The effects of inundation will ripple across the U.S. population.

To demonstrate the ripple effect, we examined U.S. Census data on the top five destinations (outmigration) and sending counties (inmigration) in recent decades for a subsample of the selected counties that have the largest metropolitan area within the respective cluster (U.S. Census Bureau 2003). For example, as illustrated in Table 4, in 2000, about 180,000 people migrated into the metropolitan areas within the sample counties that are expected to be inundated. These nearly 200,000 people would need to find a new destination, either by establishing a new migration stream or by engaging an existing stream to alternative destinations.

The population implications of sea-level rise are further compounded by the connectedness of places that are potentially directly affected by inundation. Some of the top receiving and sending counties will also experience a loss of inhabitable land due to sea-level rise; among the top five destination counties for outmigrants that would be coming from inundated areas, 24% reported in 1990 and 2000 are counties also at risk for severe inundation in 2030. Migrant streams connecting two inundated counties will no longer be viable, thus compounding the impact of

Table 4 Top five counties sending (outmigration) and receiving (inmigration) populations for counties with large cities experiencing an estimated 4-m rise in sea level, 1990 and 2000

Outmigration (destination counties)				Inmigration (sending counties)			
1990		2000		1990		2000	
Sacramento, CA							
Yolo, CA	3,930	Placer, CA	22,430	Los Angeles, CA	5,027	Placer, CA	12,944
Los Angeles, CA	3,913	El Dorado, CA	7,706	Santa Clara, CA	4,756	Los Angeles, CA	12,260
Placer, CA	3,637	Yolo, CA	7,073	Alameda, CA	4,369	Santa Clara, CA	11,835
San Joaquin, CA	3,070	Los Angeles, CA	6,502	San Francisco, CA	3,726	Alameda, CA	9,336
Alameda, CA	3,050	San Diego, CA	5,747	Yolo, CA	3,624	Yolo, CA	8,961
Miami-Dade, FL							
Broward, FL	6,159	Broward, FL	89,915	Queens, NY	4,525	Broward, FL	18,136
Palm Beach, FL	4,232	Palm Beach, FL	14,448	Broward, FL	4,360	Queens, NY	7,467
Los Angeles, CA	3,462	Orange, FL	10,060	Kings, NY	4,333	New York, NY	6,154
Orange, FL	3,287	Hillsborough, FL	6,335	Los Angeles, CA	3,893	Los Angeles, CA	5,478
Hillsborough, FL	3,054	Leon, FL	5,390	New York, NY	3,647	Kings, NY	5,340
Essex, NJ							
Union, NJ	4,800	Union, NJ	19,831	Hudson, NJ	3,973	Hudson, NJ	10,831
Middlesex, NJ	4,033	Morris, NJ	11,925	Union, NJ	3,595	Union, NJ	8,619
Hudson, NJ	3,462	Middlesex, NJ	7,304	Kings, NY	3,264	Passaic, NJ	6,493
Morris, NJ	3,300	Hudson, NJ	6,312	Passaic, NJ	3,004	Bergen, NJ	5,979
Passaic, NJ	2,576	Ocean, NJ	5,161	Bergen, NJ	2,656	Kings, NY	5,488
Charleston, SC							
Berkeley, SC	2,879	Berkeley, SC	9,312	Berkeley, SC	2,516	Berkeley, SC	3,997
Dorchester, SC	2,576	Dorchester, SC	6,462	Dorchester, SC	2,111	Dorchester, SC	3,047
Richland, SC	1,760	Richland, SC	1,859	Richland, SC	1,652	Richland, SC	2,398
Virginia Beach, VA	1,375	Mecklenburg	1,388	San Diego, CA	1,152	Mecklenburg, NC	1,213
Duval, FL	1,312	Greenville, SC	957	Greenville, SC	1,011	Fulton, GA	1,124

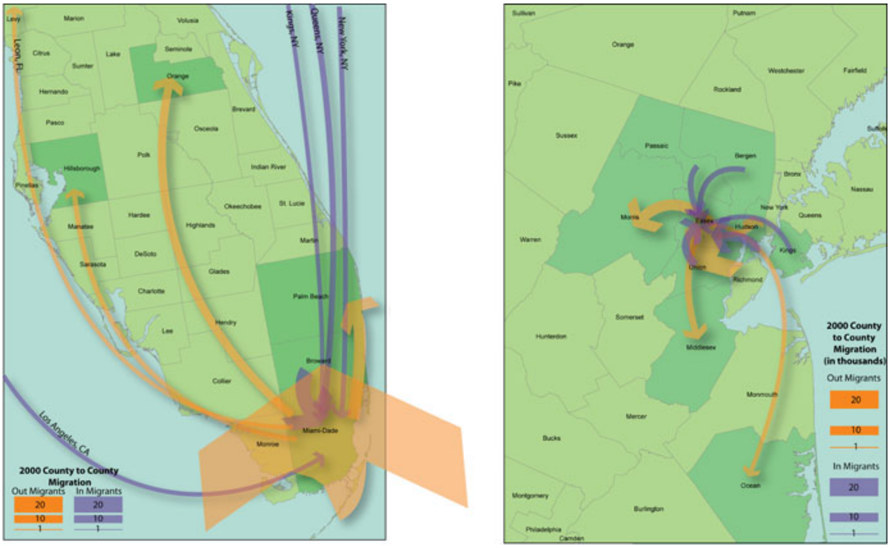

Fig. 3 Flow map illustrating the strength of observed inmigration and outmigration streams in 2000 for Miami-Dade County, Florida (*left*) and Essex County, New Jersey (*right*)

climate change-related inundation. For example, Miami-Dade sends a substantial population to neighboring Broward County (illustrated by the large orange arrow in Fig. 3), yet Broward County will no longer be a viable destination county since it, too, is estimated to be inundated. As a result, Orange and Hillsborough counties might absorb more Miami-Dade outmigrants, or alternatively, connections to new destinations might develop. Similarly, Miami-Dade inmigrants from New York state and Los Angeles will be rerouted to alternative destinations, perhaps outside of Florida state. More dramatic, the localized migration network exemplified by Essex County, NJ, would need to be almost entirely restructured in the face of inundation. None of the top destination counties for Essex outmigrants are anticipated to be viable, and similarly, none of the regionally centered inmigration streams will be possible.

Overall, our results show that while some migration streams will be eliminated, other streams will increase as a result of sea-level rise and new streams will emerge. An increase in migration will place numerous institutional and social pressures on receiving counties, including the availability and affordability of housing, seats in classrooms, and job opportunities as well as social interactions between different ethnic and socioeconomic groups. These challenges are further emphasized by revisiting the projections for specific age- and race/ethnic groups (Table 3).

Florida is estimated to have the largest total elderly and child populations, whereas South Carolina and California are expected to have the largest proportionate elderly and child populations, respectively. Specific service provisions are associated with these populations, most obviously health care and educational services. Service provisions will become the responsibility of the receiving communities and could negatively impact the quality of life for all community members if receiving communities do not have the necessary resources to absorb the costs.

New Jersey is estimated to have the largest proportionate working-age population (60%) followed by California (58%). The dislocation of this population has potentially negative consequences for both the receiving communities and the inundated communities. Inmigration of a large working-age population could lead to an oversupply of the local labor force in the receiving communities. At the same time, the outmigration of this population signals the loss of the most economically productive segment of the population in the inundated communities. Such a loss would negatively affect redevelopment of the inundated community, and such a rapid oversupply of labor could negatively impact wage structures for the receiving community. Overall, dislocation of each subpopulation, regardless of age or ethnicity, will require receiving communities to provide services to support a potentially larger and more diverse population.

Alternative scenarios

Up to this point, the migration component of our model draws on observed migration rates, yet it is reasonable to anticipate that migration flows may change based on adjustments in economic health or as a consequence of actual or anticipated inundation. We explore three migration scenarios to demonstrate alternative outcomes for the human population based on economic and environmental forces that have been shown to shape migration. These scenarios include (1) economic growth with positive net migration; (2) economic decline with negative net migration; and (3) environmental disaster with negative net migration.

The first scenario reflects a growing economy and is based on migration rates for Fulton County, Georgia. The county is home to the Atlanta metropolitan area and is located within the southern region which has expanded its economy in recent years and also has experienced positive net migration during the same period. The most recent estimates show that Fulton County had a net migration rate of 14.1 (per 1,000) in 2007–2008. The second scenario represents a declining economy and is based on observed migration rates for Wayne County, Michigan. The Detroit metropolitan area is located within Wayne County and has become the standard example of population loss due to outmigration accompanying prolonged economic hardship. In 2007–2008, Wayne County reported a net migration rate of −20.6. Finally, we use Orleans Parish, Louisiana, for our natural disaster scenario. This parish houses New Orleans and was most heavily impacted by Hurricane Katrina in 2005. The net migration rate for Orleans Parish in the 2005–2006 period was −669.4. This rate is far more dramatic than either of the economic scenarios. Although certain subgroups within Orleans Parish were more vulnerable and experienced a disproportionate burden of the catastrophe, environmental disasters have a more generalized impact on an area's population compared to economic hardship. Population projections according to the three scenarios are reported in Fig. 4.

The figure makes clear the more dramatic impact of natural disasters on the human population compared to the impact of economic growth and decline.

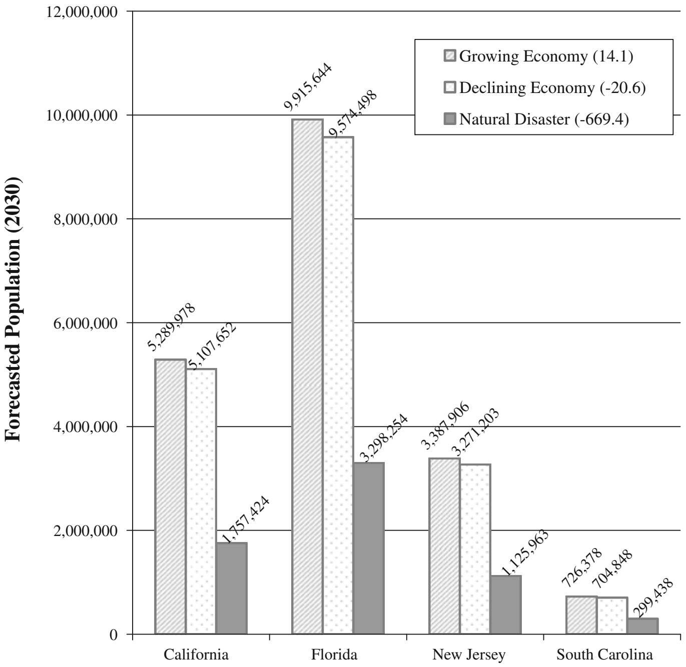

Fig. 4 Population projections in 2030 for the four study areas based on three net migration scenarios (growing economy, declining economy, and natural disaster)

Scenarios 1 and 2 based on economic typologies differ from the standard projections presented in Table 3 and Fig. 2 by between −4 and 2% across the study areas. While significant, these percentages are dwarfed by the magnitude of the population impact of scenario 3, the environmental disaster scenario. The projected populations based on the third scenario differ by −67 to −59% from the standard projections. To further contextualize the size of the environmental impact, the total population of all study areas is projected to grow by 53% between 2000 and 2030. One natural disaster such as Hurricane Katrina would undo more than 30 years of population growth. All study areas would have lower populations in 2030 than 2000 under this scenario. Among the most dramatic cases is New Jersey, which is projected to change by −66% under the environmental disaster scenario. Of the study areas, New Jersey most closely approximates New Orleans in terms of vulnerability; the area is on a low-lying tidal plain, and its position along the coastline increases its risk of hurricane and storm surges.

Discussion

Our findings highlight the need to initiate planning for climate change now and to understand which communities and populations are most vulnerable. This research demonstrates the importance of linking the temporal and spatial scales of the environmental event with the affected population and provides a model from which meaningful projections can be derived and applied to other geographic and environmental contexts. These projections are vital to local area governments and organizations that wish to plan for the human impacts of anticipated environmental shocks associated with climate change. Moreover, our results have implications for local area adaptive capacity. Most critically, our approach provides insight on the issue of vulnerability; we identify areas that have a potentially greater need to examine their adaptive capacity. Ultimately, adaptation in the United States is an issue revolving around how local governments respond to improve infrastructure and social services. Results show that local governments need to adjust population scenarios to correspond with the same temporal and spatial scale as environmental scenarios to gain a reasonable estimate of the magnitude of the impact of climate change. In addition, our analysis of the potential reach of impacts can inform efforts to coordinate local area responses to include areas not directly impacted by environmental shocks, but indirectly affected through social relationships as shown by migration streams.

Our investigation is motivated by the need to learn from the impacts of previous environmental disasters (e.g., Hurricane Katrina) on vulnerable populations and communities. Research has demonstrated that pre-existing social vulnerability affects the capacity for communities to recover. The resiliency of communities has also been shown to be directly impacted by the uneven distribution of resources post-environmental impact (Finch et al. 2010), as well as the likelihood and nature of community repopulation (Fussell et al. 2010). These studies further demonstrate the advantage of our research; understanding the distribution of vulnerability in terms of population characteristics *prior to* environmental impact is a critical aspect of the human–environment link and an essential element to effective planning.

This research is also prompted by recent population movement resulting from the impacts of environmental disasters. Our results show that there will be many "receiving" counties if catastrophic sea level rises, storm surges, or hurricane-induced flooding occurs. These places need to be prepared for dramatic and rapid population change in terms of the size of the population, the sociodemographic composition of the new population, and the associated effects on vulnerability. Although recent research demonstrates that "environmental calamities" such as Katrina have not had as broad of an impact on human migration as other environmental factors (including amenities) within an historical context (Gutmann and Field 2010), the immediate effect on the human population is undeniable and far from inconsequential for population dislocation and its social and economic implications (e.g., Hori and Schafer 2009).

In the case of Katrina, 10 counties and parishes of the 77 impacted counties experienced 82% of the total population increase (reflecting dislocated migrants in addition to other migrants and immigrants) in the year following the disaster (Frey and Singer 2006). This means that a relatively small number of places absorbed a large share of the dislocated population. Importantly, the evacuated population was from largely economically and socially disadvantaged places (Myers et al. 2008). In terms of public health concerns, many of the Katrina evacuees suffered physical and emotional stress, and a disproportionate number of the victims were uninsured and already in poor health (Brodie et al. 2006; Hori and Schafer 2009). Communities that receive inmigrants from future inundated counties can reasonably expect similar demands on economic and social resources.

We view this study as the beginning of a larger research agenda that will use discipline-specific methodologies to advance the study of human–environment interactions. Indeed, any research question on human–environment interactions ultimately requires an inter-disciplinary approach. Future research should extend the approach to new locations, such as the entire United States and other countries with sizeable coastlines and vulnerable populations (e.g., India and Bangladesh), to gain a global perspective on the potential impact of sea-level rise. A second potential step is to extend the forecasts to migration networks and to identify factors associated with changes in migration signals (e.g., insurance premium rates). The incorporation of post-2000 data (i.e., 2010 county-to-county flow data when available) is essential given environmentally induced migrations that have occurred since the 1990's. The resulting estimates will provide a more comprehensive assessment of the population impacts of climate change since, as our results demonstrate, the effects of sea-level rise will extend to places that will house the uprooted population and to places that would have sent migrants to the no longer inhabitable areas.

A third focus for future work is to model coastal inundation using the increased accuracy and precision offered by new data sources, such as digital terrain techniques. This will provide more detailed information on areas that might be inundated by sea-level rise on the order of centimeters and allow better correlation of population forecasts to future sea-level rise scenarios. Our study focuses on sea-level rise, although we also discuss the possibility of whether storm surges lead to temporary flooding like that resulting from Hurricane Katrina. As Katrina demonstrated, such temporary flooding may be as damaging as permanent sea-level rise. The permanency of inundation, due to sea-level rise or flooding, is unknown, and similarly, the impact on human migration is unknown. How migration patterns—including size, flows, and duration—differ according to temporary versus permanent inundation is a topic of future research, and one that requires additional data than what we analyze here. Moreover, future research should examine the population impacts of additional climate-change-related environmental outcomes beyond sea-level rise scenarios, including the impacts of increased heat waves and forest fires due to rising temperature, as well as the effects of drought on soil salinization and degradation, and more generally, water availability for human use. Within these ventures, researchers should articulate variation in the magnitude of the population impacts across the different types of environmental effects, especially in terms of land suitability and the permanency of resultant population dislocation.

We have come far in planning and preparing for climate change. Government organizations have created task forces and commissions at various scales, including the municipal and county levels (e.g., New York City Panel on Climate Change, Miami-Dade County Climate Change Advisory Task Force), and recent research has identified the most useful data sources to plan for resettlement post-disaster (Plyer et al. 2010). Our research has shown that if we are to prepare effectively for climate change, we need to consider the sociodemographic and geophysical dimensions of potential environmental change in tandem, with one informing the other in meaningful ways. Plans relying solely on current population estimates will be inadequate to address the needs of future populations.

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