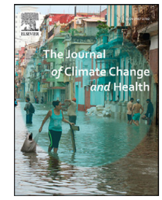
The Journal of Climate Change and Health 3 (2021) 100028

Contents lists available at ScienceDirect

The Journal of Climate Change and Health

journal homepage: www.elsevier.com/joclim



Research article

Present and future sea level rise at the intersection of race and poverty in the Carolinas: A geospatial analysis

Leah R. Handwerger[a], Margaret M. Sugg[a], Jennifer D. Runkle[b,*]

[a] *Department of Geography and Planning, Appalachian State University, P.O. Box 32066, Boone, NC 28608, United States*
[b] *North Carolina Institute for Climate Studies, North Carolina State University, 151 Patton Avenue, Asheville, NC 28801, United States*

A R T I C L E   I N F O

Article History:
Received 22 May 2021
Accepted 22 June 2021
Available online 14 July 2021

Keywords:
Sea level rise
Climate change
Racial segregation
Poverty
GIS
coast

A B S T R A C T

Sea level rise (SLR) has and will continue to impact coastal communities in the coming decades. Despite the widespread availability of data on SLR projections, little is known about the differential impact of SLR on minority or economically disadvantaged populations. In this study, we aim to identify the geographic areas in which low-income and communities of color along the North and South Carolina coastline in the United States will experience the most severe effects of SLR. Geospatial mapping was performed to estimate the total area impacted by 1) SLR, 2) tidal inundation, and 3) low-lying areas separately for three scenarios (0-, 2-, and 4-feet). Findings project that over 2.2 million people and at least 370,000 Black or economically disadvantaged individuals will be impacted by SLR by 2100. Results showed that the most economically deprived and racially segregated communities are already experiencing the effects of SLR, including more frequent tidal inundation and low-lying flooding. Inland flooding is seven times more likely to occur in low-income Black communities compared to high-income white communities. Findings highlight the urgent need for additional resources and adaptive measures that target low-income, black communities who will continue to be disproportionately impacted by SLR in coastal Carolina.

Background

Rising sea levels pose significant threats to coastal communities [1-3]. One of the most obvious effects of SLR is the increased spatial extent of flooding at high tide during normal conditions. For this analysis, we define tidal inundation as the continuous flooding along the receding shoreline, while inland flooding refers to the sporadic flooding of low-lying areas further inland. In the Carolinas, projections indicate that sea levels will rise an estimated 1.3 to 2.4 feet under a moderate emission scenario and up to 2.0 to 3.6 feet under a high emissions scenario by 2100 [2,5]. The combined effects of low-lying topography, subsidence (i.e., sinking of land), and a heavily developed coastline make North and South Carolina in the United States particularly vulnerable to tidal inundation and inland flooding. While the effects of sea-level rise (SLR) will be experienced differently along the coastline [2], few studies have explored the present and future impact on low-income and racially segregated non-Hispanic Black communities in the Carolinas.

Although coastal communities must make difficult decisions to mitigate, adapt, or retreat from receding shorelines [1], there are few state and federal resources that help measure the impacts of SLR and develop targeted adaptation plans. Decisions will be made based on localized impacts and available funds [5], and costs will not be evenly distributed across coastal populations. Developed beach-front property typically has higher property values and more affluent residents, while more disadvantaged populations tend to reside further inland and generally have fewer mitigation options due to poverty and political marginalization [7]. Therefore, SLR's effects are likely to be felt harder in low-income communities or communities of color because they typically don't have the financial means to employ expensive mitigation methods, relocate, or repair home-related damages.

Similar to other climate change threats, SLR acts as a “risk-amplifier” for health impacts by exacerbating existing environmental, socio-economic, and health disparities. Increased coastal flooding and storms from SLR create greater health-related challenges for low-income and minority communities including food security [4,6], availability of safe, reliable drinking water, loss of infrastructure and income, and adverse effects on mental health and disease transmission [8−10] Climate change in addition to race and poverty have been cited as important social determinants of population health that influence individual and community-level vulnerability to climate drivers (e.g., SLR) [11].

Although SLR has been widely studied, there has been considerably less research examining the societal impacts, particularly

* Corresponding author.
E-mail address: jrrunkle@ncsu.edu (J.D. Runkle).

https://doi.org/10.1016/j.joclim.2021.100028
2667-2782/

through the lens of poverty and race, at the regional level. The objective of this study was to quantify the present and future spatial extent of SLR in coastal North and South Carolina, while capturing the number of individuals living in extreme poverty and/or racially-segregated communities that will likely be impacted by future SLR throughout the century.

Methods

Study area

Our study area consisted of the entire coastline for both North and South Carolina in the United States (Fig. 1). The area was selected based on the region's susceptibility to tidal inundation and inland flooding, a heavily developed coastline, and stark contrasts of socioeconomic status among coastal communities. Like other southern states, NC and SC experience higher poverty rates than the national average (10.5%), with 13.6% of NC residents and 13.8% of SC residents living in poverty [19]. In NC the most common minorities are Black (22.2%) followed by Hispanic (9.8%), whereas SC has a higher Black population (27%) and smaller Hispanic population (6.0%) [19].

North Carolina's (NC) coastline can be divided into two provinces which exhibit distinct geology and very different coastal zones. The Northern province is classified by gentle gradients and low-lying slopes, a broad coastal plain and long barrier islands, while the Southern province exhibits rocky, steep slopes and short barrier islands [2].

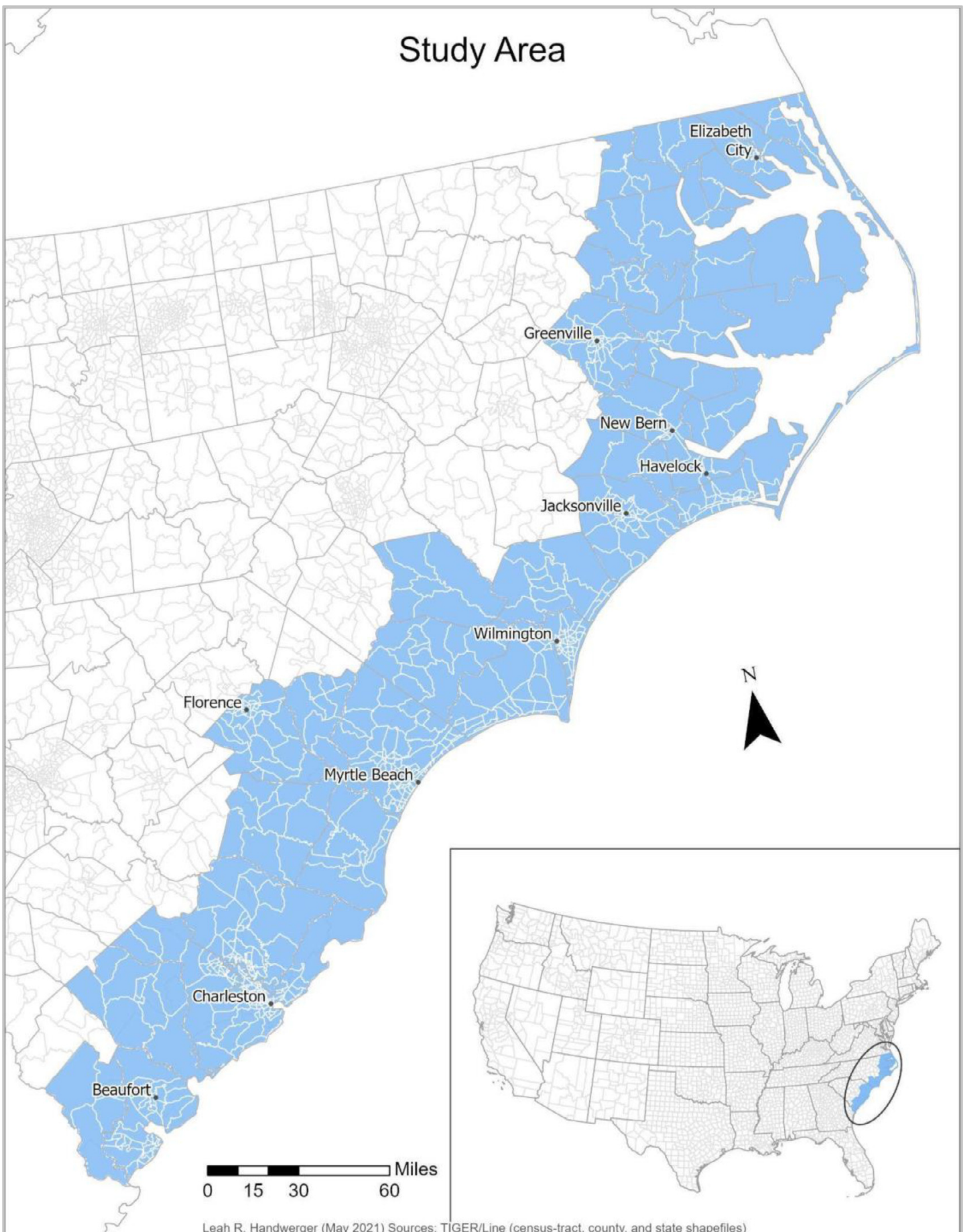


Fig. 1. Study area of the coastline of North and South Carolina.

The Northern province experiences subsidence of approximately 4 inches per century, and the Southern province exhibits an uplift of about 1 inch per century [2]. South Carolina's (SC) coastline gradually shifts from rocky topography to a large estuarine system with gentler slopes and short and thick barrier islands [14]. Particularly in the southern half of SC, which includes the heavily-developed metropolitan area of Charleston, exhibits subsidence as much as 1 inch every twenty years [15]. SC's sea level has risen 10 inches since 1950, and in the last ten years has risen 1 inch every two years [11].

Sea level rise

Inundation is the most expensive and deadly effect of SLR [16], and areas that are heavily developed with high population density are most vulnerable [17]. To measure the severity of inundation and inland flooding, we used the NOAA SLR Database [18], which contains shapefiles for current 0-ft SLR conditions and 1-foot increments of projected SLR above current Mean Higher High Water conditions. These files were constructed by NOAA utilizing Digital Elevation Models of the area and a tidal surface model that represents spatial tidal variability [18].

Index of concentration at the extremes

American Community Survey (ACS) 5-year (2015-2019) estimates for census-tracts were used to calculate the Index of Concentration at the Extremes (ICE), which quantifies the concentrations of top versus bottom distributions for racial segregation, income disparities, and combined racial segregation and income disparities [12,13]. ICE takes the total population from the most privileged and deprived extremes to calculate a value that ranges from -1 and 1, where -1 indicates 100% of the population was concentrated in the most deprived group, Quintile 1 [13]. Unlike other indices that quantify racial and income inequalities (e.g., the Gini Index, Index of Dissimilarity), ICE is praised for its effectiveness for analyzing societal distributions across both small and large spatial scales [13].

In addition to ICE, data on socioeconomic variables were compiled to estimate the present and future impacts of SLR on social determinants of health in coastal communities [19]. We pulled census variables that are known to influence vulnerability to exposure and adaptive responses to climate hazards, such as: poverty status, percent of Black and Hispanic populations, female-headed households, percentage of children and aging populations (over 65), percentage of populations with low English proficiency, percent without health insurance, educational attainment with high school or less, percentage of disabled population, and percentage of rented households [20]. These variables were imported into ArcGIS Pro and joined with SLR shapefiles for each increment of SLR (0-, 2-, and 4-ft). Files were clipped using the Clip tool to only display tracts that were impacted at each increment of SLR.

Risk mapping

Inundation and low-lying shapefiles were used to calculate the total area that is expected to be flooded at 0-feet, 2-feet, and 4-feet SLR scenarios. These increments were selected to represent 1) current SLR impacts at 0-feet, 2) impacts of SLR as it progresses throughout the century at 2-feet, and 3) maximum expected SLR impacts by 2100 at 4-feet. We used ACS 5-year estimates to calculate quintiles for the three ICE metrics in Microsoft Excel, displaying areas with the highest concentration of racial segregation, income disparities, and combined racial segregation/income disparities (e.g., Quintile 1 = most deprived and Quintile 5 = least deprived). Using the Clip tool in ArcGIS [21], we calculated the total extent of inundation within each ICE quintile. Area calculations of tidal inundation and low-lying areas were performed separately to determine which plays a larger role within vulnerable communities. This was an iterative process that required high processing power due to the large size of each SLR shapefile. We also calculated the number of residents anticipated to be affected by inundation and low-lying flooding, highlighting locations where SLR will be most impactful for vulnerable populations.

Results

Present level of SLR

Calculations at 0-feet represent the present level of SLR and the NC and SC populations that are currently being impacted (Supplemental Fig. 1). For the entire study area, nearly 2040 square miles (mi^2) ($5283.576 km^2$) are already feeling the effects of SLR, with $1922 mi^2$ ($4978 km^2$) resulting from tidal inundation and $117.5 mi^2$ ($304.3 km^2$) due to flooding of low-lying areas (Table 1). This translates to over 2 million Carolina residents currently being impacted by SLR, with at least 326,000 individuals in the most vulnerable quintile. Vulnerability based on racial segregation shows that roughly the same amount of area is affected for both the lowest and highest quintiles (approximately $500 mi^2/1295 km^2$), while the two metrics for income disparities and combined racial segregation/income disparities revealed Quintile 5 (Q5) (i.e., most privileged) exceeding Quintile 1 (Q1) (i.e., least privileged) by at least $100 mi^2/259 km^2$. Flooding of low-lying areas alone affected the most vulnerable population (Q1) by at least twice the rate of the most privileged group (Q5).

2-feet of SLR throughout 21st century

Inundation at 2-feet illustrates the projected impacts of SLR as it progresses throughout the century (Supplemental Fig. 2). Area calculations demonstrated a total of $3880 mi^2$ ($10049 km^2$) affected by SLR, with $3385 mi^2$ ($8767 km^2$) as a result of tidal inundation and nearly $500 mi^2$ ($1294 km^2$) due to flooding of low-lying areas. We estimated that over 2.1 million Carolina residents will be affected, with at least 340,000 individuals in the most vulnerable quintile (Q1) for all three ICE metrics (Tables 2.1–2.3). Vulnerability based on racial segregation revealed that more area will be covered in least vulnerable census-tracts (Q5) ($924 mi^2/2393 km^2$) compared to the most vulnerable (Q1) ($809 mi^2/2095 km^2$). However, the combined racial segregation/income disparities metric showed Q1 exceeding Q5 by $200 mi^2/518 km^2$, and Q1 surpassed Q5 by nearly two-fold when examining income disparities alone ($1097 mi^2/2841 km^2$ and $556 mi^2/1440 km^2$, respectively). For all three ICE metrics, lowland flooding impacted vulnerable populations at a much higher rate than tidal inundation, where Q1 exceeded Q5 by as much as seven times.

4-feet of SLR by 2100

Inundation at 4-feet displays the potential extent of SLR for the study area by 2100 (Supplemental Fig. 3). Our calculations revealed that SLR could impact a total of $5147 mi^2/13330 km^2$, with approximately $4464 mi^2/11562 km^2$ as a result of tidal inundation and $683 mi^2$ $/1769 km^2$ due to flooding of low-lying areas. By 2100, we can expect to see over 2.2 million Carolina residents affected by SLR, and at least 370,000 individuals affected in the least privileged quintile (Q1) (Tables 2.1–2.3). Vulnerability based on racial segregation estimates that more area will be covered in least vulnerable census-tracts ($1264 mi^2/3273 km^2$) compared to the most vulnerable ($985 mi^2/2551 km^2$). However, both metrics for income disparities and combined racial segregation/income disparities revealed Q1 to be most affected, with over $1500 mi^2/3885 km^2$ for income disparities alone, and over $1000 mi^2/2590 km^2$ for combined racial segregation/income disparities. Flooding of low-lying areas across all three metrics will most severely impact less privileged tracts by as much as $300 mi^2/777 km^2$.

Table 1
Total Sea Level Rise, Inundation, and Flooding of Low-lying Areas for each of the Index of Concentration of Extreme Metrics: Racial Segregation, Income Disparities, and Racial Segregation & Income Disparities for North and South Carolina (Square Miles). Final column represents the level of disproportionate impacts between Q1 (least privileged) and Q5 (most privileged) by subtracting Q1 from Q5.

Sea Level Rise: Total Inundation and Flooding of Low-lying Areas (Sq Mile)							
	Total	Quintile 1 (least privileged)	Quintile 2	Quintile 3 (moderate)	Quintile 4	Quintile 5 (most privileged)	Disproportionate Impacts: Q1-Q5
RACE							
0ft	2,039.9	521.0	501.4	172.2	220.7	546.0	-25.0
2ft	3,879.5	809.1	1352.9	285.2	409.3	923.8	-114.8
4ft	5,147.1	986.0	1898.0	365.5	523.0	1264.3	-278.3
INCOME							
0ft	2,039.9	336.2	359.8	520.5	296.5	439.5	-103.3
2ft	3,879.5	1096.6	628.1	985.4	482.2	555.6	541.0
4ft	5,147.1	1559.4	821.8	1336.7	653.1	660.5	898.9
RACE + INCOME							
0ft	2,039.9	336.2	534.4	276.8	328.1	481.4	-145.1
2ft	3,879.5	808.0	1164.8	531.0	706.9	604.9	203.1
4ft	5147.1	1094.7	1516.0	692.7	1017.2	707.6	387.1
Inundation (Sq Mile)							
	Total	**Quintile 1 (least privileged)**	**Quintile 2**	**Quintile 3 (moderate)**	**Quintile 4**	**Quintile 5 (most privileged)**	**Disproportionate Impacts: Q1-Q5**
RACE							
0ft	1922.4	492.1	438.5	166.8	216.4	530.6	-38.5
2ft	3384.7	734.0	1076.9	262.7	383.8	834.7	-100.6
4ft	4464.4	871.5	1556.7	323.1	478.6	1134.9	-263.3
INCOME							
0ft	1922.4	294.5	336.3	491.6	290.6	431.5	-137.0
2ft	3384.7	853.4	555.7	883.7	446.3	522.6	330.7
4ft	4464.4	1259.0	712.9	1199.0	595.2	598.6	660.4
RACE + INCOME							
0ft	1922.4	310.6	482.1	260.3	314.9	474.1	-163.5
2ft	3384.7	696.0	950.6	480.2	626.6	576.0	120.1
4ft	4464.4	931.0	1257.7	618.0	902.1	653.0	278.0
Flooding of Low-Lying areas (Sq Mile)							
	Total	**Quintile 1 (least privileged)**	**Quintile 2**	**Quintile 3 (moderate)**	**Quintile 4**	**Quintile 5 (most privileged)**	**Disproportionate Impacts: Q1-Q5**
RACE							
0ft	117.5	28.9	62.9	5.4	4.3	15.4	13.5
2ft	494.9	75.1	276.0	22.5	25.5	89.2	-14.1
4ft	682.6	114.4	341.3	42.4	44.5	129.4	-15.0
INCOME							
0ft	117.5	48.4	23.5	28.9	5.9	8.0	40.4
2ft	494.9	243.2	72.4	101.7	35.9	33.0	210.2
4ft	682.6	300.3	108.9	137.7	58.0	61.8	238.5
RACE + INCOME							
0ft	117.5	25.6	52.3	16.5	13.2	7.3	18.4
2ft	494.9	111.9	214.2	50.8	80.3	28.9	83.0
4ft	682.6	163.7	258.3	74.7	115.1	54.7	109.1

Table 2.1
Total population and least and most privileged populations (Q1, Q5) affected by 0-, 2- and 4-feet of Sea Level Rise for the Index of Concentration of Extreme Metrics: Racial Segregation. *Q1= most privileged; Q5=least privileged

Total Populations Affected by 0-ft SLR				Total Populations Affected by 2-ft SLR			Total Populations Affected by 4-ft SLR		
	Total Impact	Q1 (least privileged)	Q5 (most privileged)	Total Impact	Q1 (least privileged)	Q5 (most privileged)	Total Impact	Q1 (least privileged)	Q5 (most privileged)
Total Census-tracts	**477**	102	116	**502**	106	121	**524**	113	122
Total Population:	**2,049,906**	343,591	403,663	**2,164,117**	357,555	416,777	**2,277,089**	398,772	428,972
Total Population: Under 5 Years	**114,527**	20,466	17,496	**121,562**	21,525	17,832	**127,624**	24,412	17,832
Total Population: Under 18	**414,909**	74,747	71,533	**438,355**	78,854	72,637	**461,559**	89,504	72,929
Total Population: Over 65	**389,758**	59,398	110,908	**413,090**	60,808	115,863	**435,730**	65,445	125,482
Total Population: Black or African American Alone	**443,021**	191,002	8,692	**463,193**	198,508	8,920	**493,973**	216,793	9,259
Total Population: Hispanic or Latino	**130,909**	23,817	11,418	**139,376**	25,411	11,877	**150,955**	32,130	12,010
Low English Proficiency	**89,619**	18,672	8,044	**96,979**	20,122	8,529	**110,495**	27,658	8,925
Total Rented Population	**617,159**	137,615	76,243	**658,783**	145,541	79,974	**705,033**	169,772	80,517
Total Population: Poverty Status	**280,999**	80,698	29,081	**299,270**	84,557	29,977	**319,082**	95,137	30,429
No Health Insurance Coverage	**211,692**	48,553	28,876	**227,248**	51,800	30,159	**242,703**	60,208	30,597
Female-Headed Household	**94,153**	27,112	11,226	**99,532**	28,272	11,618	**106,302**	31,751	11,834
Education: High School or Less	**480,664**	116,625	66,704	**509,514**	121,138	69,958	**536,424**	133,251	72,163
Total Population: With Disability	**290,781**	57,653	51,640	**309,054**	59,423	54,162	**325,124**	64,324	57,481

Table 2.2
Total population and least and most privileged populations (Q1, Q5) affected by 0-, 2- and 4-feet of Sea Level Rise for the Index of Concentration of Extreme Metrics: Income Disparities. *Q1= most privileged; Q5=least privileged

Total Populations Affected by 0-ft SLR				Total Populations Affected by 2-ft SLR			Total Populations Affected by 4-ft SLR		
	Total Impact	Q1 (least privileged)	Q5 (most privileged)	Total Impact	Q1 (least privileged)	Q5 (most privileged)	Total Impact	Q1 (least privileged)	Q5 (most privileged)
Total Census-tracts	**477**	84	104	**502**	89	110	**524**	97	113
Total Population:	**2,049,906**	326,055	492,783	**2,164,117**	344,130	524,179	**2,277,089**	379,958	535,382
Total Population: Under 5 Years	**114,527**	17,281	25,140	**121,562**	18,299	27,341	**127,624**	20,911	27,859
Total Population: Under 18	**414,909**	65,149	96,909	**438,355**	68,922	103,744	**461,559**	77,503	106,213
Total Population: Over 65	**389,758**	54,415	109,195	**413,090**	58,761	113,626	**435,730**	63,039	115,353
Total Population: Black or African American Alone	**443,021**	145,161	35,772	**463,193**	151,460	41,733	**493,973**	165,659	43,242
Total Population: Hispanic or Latino	**130,909**	25,702	19,416	**139,376**	27,435	21,385	**150,955**	32,350	22,157
Low English Proficiency	**89,619**	18,027	12,025	**96,979**	19,441	14,027	**110,495**	24,843	15,410
Total Rented Population	**617,159**	144,470	92,427	**658,783**	153,763	99,081	**705,033**	176,178	101,441
Total Population: Poverty Status	**280,999**	86,683	26,236	**299,270**	91,770	28,133	**319,082**	102,572	28,848
No Health Insurance Coverage	**211,692**	44,121	29,404	**227,248**	48,015	32,176	**242,703**	54,285	32,915
Female-Headed Household	**94,153**	23,543	12,911	**99,532**	24,852	13,724	**106,302**	27,629	14,003
Education: High School or Less	**480,664**	100,560	66,681	**509,514**	106,411	71,473	**536,424**	115,680	73,343
Total Population: With Disability	**290,781**	53,180	48,585	**309,054**	56,196	51,825	**325,124**	60,766	53,202

Table 2.3
Total population and least and most privileged populations (Q1, Q5) affected by 0-, 2- and 4-feet of Sea Level Rise for the Index of Concentration of Extreme Metrics: Combined Racial Segregation & Income Disparities. *Q1= most privileged; Q5=least privileged

Total Populations Affected by 0-ft SLR				Total Populations Affected by 2-ft SLR			Total Populations Affected by 4-ft SLR		
	Total Impact	Q1 (least privileged)	Q5 (most privileged)	Total Impact	Q1 (least privileged)	Q5 (most privileged)	Total Impact	Q1 (least privileged)	Q5 (most privileged)
Total Census-tracts	**477**	82	110	**502**	85	114	**524**	91	117
Total Population:	**2,049,906**	333,964	473,953	**2,164,117**	343,721	483,364	**2,277,089**	373,867	502,008
Total Population: Under 5 Years	**114,527**	19,562	22,589	**121,562**	20,231	22,925	**127,624**	22,731	23,119
Total Population: Under 18	**414,909**	72,533	89,503	**438,355**	75,337	90,492	**461,559**	83,708	92,271
Total Population: Over 65	**389,758**	56,436	115,745	**413,090**	57,471	118,625	**435,730**	61,141	129,285
Total Population: Black or African American Alone	**443,021**	175,833	25,894	**463,193**	181,901	26,065	**493,973**	195,081	27,282
Total Population: Hispanic or Latino	**130,909**	22,616	17,081	**139,376**	23,661	17,426	**150,955**	28,424	17,799
Low English Proficiency	**89,619**	16,883	11,538	**96,979**	17,997	12,003	**110,495**	23,357	12,524
Total Rented Population	**617,159**	146,538	89,328	**658,783**	152,892	92,151	**705,033**	172,685	93,181
Total Population: Poverty Status	**280,999**	88,224	27,930	**299,270**	91,402	28,405	**319,082**	100,539	29,178
No Health Insurance Coverage	**211,692**	47,533	27,763	**227,248**	50,189	28,680	**242,703**	56,229	29,410
Female-Headed Household	**94,153**	27,093	12,264	**99,532**	27,996	12,500	**106,302**	30,684	12,828
Education: High School or Less	**480,664**	110,738	63,746	**509,514**	114,192	65,693	**536,424**	123,104	68,944
Total Population: With Disability	**290,781**	56,734	48,888	**309,054**	57,928	50,303	**325,124**	61,949	54,511

Social determinants of health

In general, when looking across the three separate SLR scenarios, results showed that a higher proportion of vulnerable residents (e.g., Black, Hispanic, limited English proficiency, financially poor, uninsured, in rental housing, high school or less education, female-headed households) were in the most vulnerable quintiles. Not surprisingly, results revealed communities in the least privileged quintile (Q1) exceeded the most privileged (Q5) by as much as nearly four times for Black and Hispanic/Latino populations, low English proficiency, individuals living in poverty, and female-headed households (Tables 2.1-2.3).

Discussion

In this study, we identified low-income and communities of color along the Carolina coastline that are expected to experience the most severe effects of SLR-related tidal inundation and inland flooding. Health impacts of sea level rise include increased risk for flood-related drowning, injury, indoor mold outbreak and respiratory illnesses, relocation and housing instability, disruptions to critical infrastructure and adverse pregnancy (e.g., low birth weight) and mental health impacts, and post-event disease transmission (e.g., waterborne, vectorborne) [22]. Low-income communities with a greater proportion of residents who are Black or Hispanice, un(der)insured, unemployed, and reside in flood prone and substandard housing developments will continue to experience greater vulnerability to SLR. While present tidal inundation (0-ft) affects high-income, white communities and low-income, Black communities roughly equally, as SLR progresses throughout the century, impacts grow increasingly disproportionate by as much as two-fold for low-income alone and low-income Black coastal communities at 2- and 4-ft of SLR (Fig. 2). The disparate impact of SLR on economically disadvantaged and racially segregated Black communities becomes even more dramatic when examining flooding of low-lying areas. In the near term, by around mid-century, results showed that 2-ft of SLR is expected to increase 700% for low-lying flooding in the most economically disadvantaged, Black communities compared to economically advantaged, white communities. While there are some risk-mapping tools currently available, none to date allow for the examination of community-level SLR impacts at the intersection of extreme racialized and economic segregation. To our knowledge, this is the first geospatial analysis to examine the impacts of SLR through an equity lens that sheds light on how the low-income and racially segregated, Black communities along the Carolina coast are particularly vulnerable to SLR in the form of tidal inundation and inland flooding. The most vulnerable subgroups included Black, Hispanic, or limited English proficiency residents,

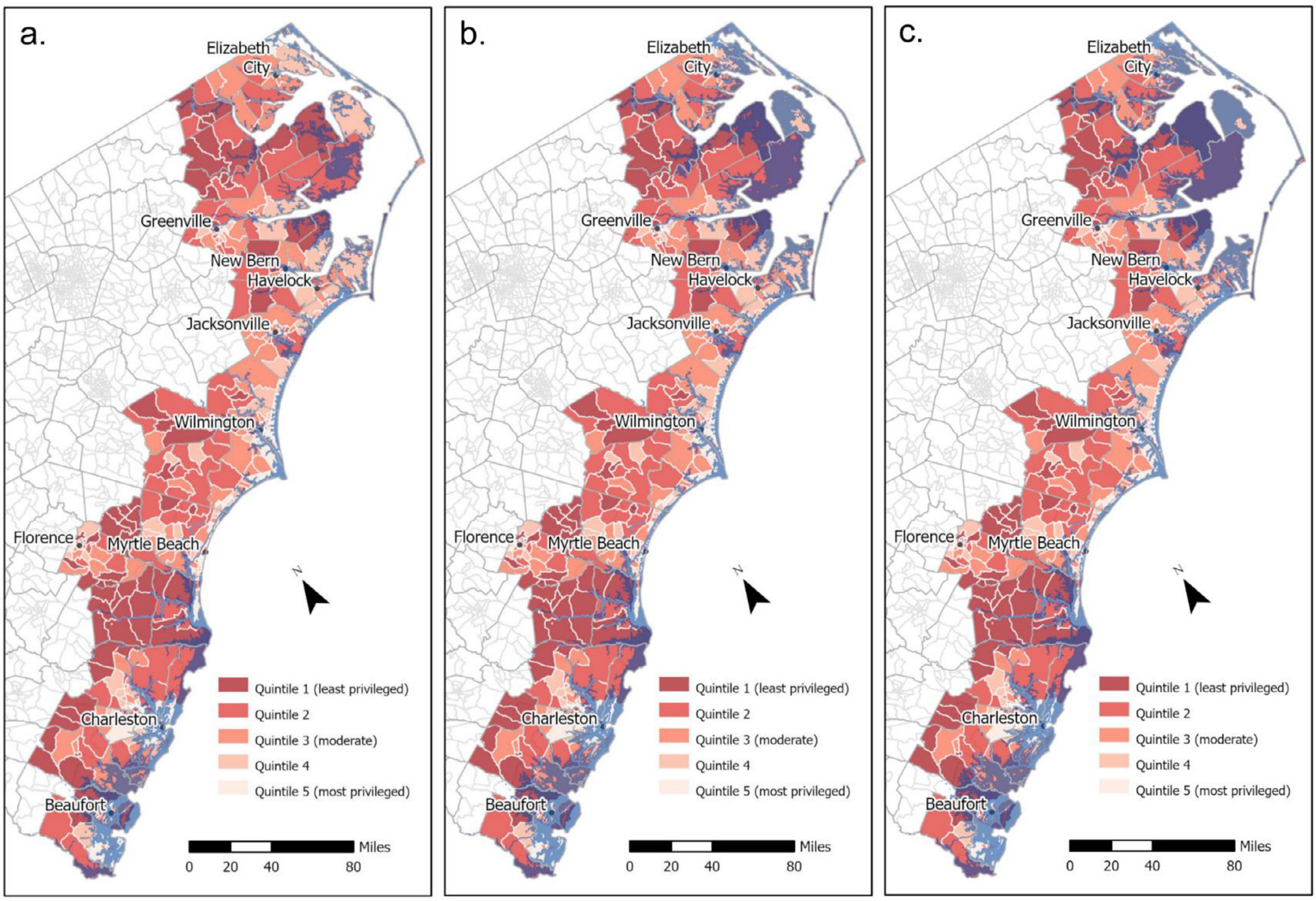


Fig. 2. Spatial vulnerability for least privileged (Q1) verses most privileged (Q5) for the Index of Concentration at the Extremes of Racial Segregation and Income Disparities at the census tract for a.) 0-feet b.) 2-feet and c.) 4-feet of Sea Level Rise.

as well as the financially poor, uninsured, those in need of affordable housing, and female-headed households.

Confirming our hypothesis, inland flooding impacts the most racially segregated and economically disadvantaged communities. Prior research has shown that more disadvantaged groups are typically located further inland, outside of cities and tourist destinations [e.g., 7]. A few studies have examined the compounding social and physical stressors behind increased vulnerability to SLR [4,23], but too few have narrowed in on the structural causes, like residential segregation (a proxy for structural racism [24]) behind the inequitable impacts of SLR. Local adaptive responses to rising sea levels can no longer remain colorblind and must acknowledge the racialized history behind coastal formation and the historical and present systemic causes of differential vulnerability and structuring of racial inequality [25]. Racial and economic segregation are two important drivers that independently and jointly contributed to the disproportionate impact of SLR in coastal Carolina communities.

We identified the northernmost counties in NC and southern half of SC as the most at-risk communities (Supplemental Figs. 4 and 5). These areas exhibited high potential for the most extensive impacts of SLR, as well as high rates of both racial segregation and income inequalities. It is likely many communities in these locations will suffer mitigation challenges as a result of geographic isolation and political marginalization. Conversely, the heavily developed coastline contains high population density with stark socioeconomic contrasts across the metropolitan area. These contrasts highlight how the cost of SLR will not be evenly distributed across coastal communities. Total expenses in SC could exceed $22 billion by 2100 for building over 3,000 miles of seawalls, and NC has estimated $34 billion for 5,320 miles of seawalls along the coastline [26]. Dare County, NC, which contains the Outer Banks tourist destination and consistently ranked in high privilege quintiles for all three ICE metrics, estimates a needed $5.4 billion for coastal protection [26]. Meanwhile, Tyrrell County, NC, which consistently ranked in the most deprived quintiles for all three ICE metrics will also be severely impacted by SLR with the estimated cost of SLR mitigation projected to be approximately $1 billion. The stark contrast in costs between the most and least privileged coastal communities highlights how SLR protection will not be equally distributed in low-income communities and communities of color. It is important to note that these estimates only consider coastline protection and do not fully account for all anticipated expenses in protecting communities from SLR such as elevating buildings, insurance, utilities, healthcare and community preparedness, telecommunications, transportation, environmental protection and remediation, and water and wastewater [26]. These additional expenses will likely further exacerbate the inequalities in exposure to SLR among affluent and disadvantaged communities in the Carolinas [27].

Strengths and Limitations

There were some limitations with this study. SLR shapefiles were extremely large and required high processing power which may have resulted in a small margin of error in area calculations. ACS census data also contains margins of error, and therefore, our population totals were estimates and should not be interpreted as a precise level of impact. Moreover, population estimates were pulled from current ACS data, and do not account for anticipated population changes that will occur throughout the century. It is likely that there will be substantial changes to our estimations of the populations affected by SLR at 2- and 4-ft. Additionally, shapefiles did not show depth of inundation, so we were unable to determine the severity of inundation. Future studies should consider examining inundation depth in order to more accurately assess how inhabitable some of these coastal areas may become. Nevertheless, our results highlight the disproportionate impact of SLR on historically underserved communities, and addresses the need to target mitigation plans towards the most vulnerable and economically-disadvantaged communities.

Conclusion

SLR will inevitably continue to impact the Carolina coastline. Our analysis showed that many low-income and primarily Black communities are already being affected by SLR and will continue to experience more severe effects in the future. Poverty and residential segregation were two important drivers that independently and jointly contributed to the disproportionate impact of current and future SLR on vulnerable populations in coastal Carolina communities. In order to effectively address climate injustice, more work is needed to ensure that all communities' voices are being represented and elevated in the decision-making and planning process to achieve equitable and holistic climate change resilience in coastal communities. Results demonstrated the disproportionate exposure to SLR in some economically-disadvantaged and Black communities, and identified high-risk areas along the coast of North and South Carolina in need of more targeted mitigation plans. Findings highlight the urgent need for additional resources and adaptive measures that target low-income, black communities who already are and will continue to be disproportionately impacted by SLR in coastal Carolina.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.joclim.2021.100028.

References

[1] Nichols RJ, Cazenave A. Sea level rise and its impact on coastal zones. Science 2010;328(5985):1517–20. doi: 10.1126/science.1185782.

[2] Kunkel KE, Easterling DR, Ballinger A, Bililign S, Champion SM, Corbett DR, Dello KD, Dissen J, Lackmann GM, Luettich Jr. RA, Perry LB, Robinson WA, Stevens LE, Stewart BC, Terando AJ. North Carolina climate science report 2020:233 https://ncics.org/nccsr.

[3] IPCC. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press; 2019.

[4] Dolan AH, Walker IJ. Understanding vulnerability of coastal communities to climate change related risks. J Coastal Res 2006;39:1316–23 www.jstor.org/stable/25742967.

[5] State Climate Summaries (SCS). NOAA National Centers for Environmental Information. https://statesummaries.ncics.org/chapter/nc/ [accessed 13 May 2021].

[6] Martinich J, Neumann J, Ludwig L, Jantarasami L. Risks of sea level rise to disadvantaged communities in the United States. Mitig Adapt Strateg Glob Change, 18; 2013. p. 2013169–85. doi: 10.1007/s11027-011-9356-0.

[7] Bhattachan A, Jurjonasb MD, Moody AC, Morris PR, Sanchez GM, Smart LS, Taillie PJ, Emanuel RE, Seekamp EL. Sea level rise impacts on rural coastal social-ecological systems and the implications for decision making. Environ Sci Policy 2018;90:122–34. doi: 10.1016/j.envsci.2018.10.006.

[8] Parker CL. Health impacts of sea-level rise. Plann Environ Law 2014;66(5):8–12.

[9] Dvorak AC, Solo-Gabriele HM, Galletti A, Benzecry B, Malone H, Boguszewski V, Bird J. Possible impacts of sea level rise on disease transmission and potential adaptation strategies, a review. J Environ Manag 2018;217:951–68.

[10] Palinkas LA, Wong M. Global climate change and mental health. Curr. Opin. Psychol. 2020;32:12–6.

[11] Rudolph L, Harrison C, Buckley L, North S. Climate change, health, and equity: a guide for local health departments. Oakland, CA and Washington D.C.: Public Health Institute and American Public Health Association; 2018.

[12] Massey DS. The age of extremes: Concentrated affluence and poverty in the twenty-first century. Demography, 33; 1996. p. 1996395–412. doi: 10.2307/2061773.

[13] Krieger N, Kim R, Feldman J, Waterman PD. Using the Index of Concentration at the Extremes at multiple geographical levels to monitor health inequities in an era of growing spatial social polarization: Massachusetts, USA (2010−14). Int. J. Epidemiol. 2018;47(3):788–819.

[14] Gornitz V. Vulnerability of the east coast USA to future SLR. J. Coast. Res. 1990;9:201–37 http://www.jstor.org/stable/44868636.

[15] Sea Level Rise: South Carolina (SLRSC). https://sealevelrise.org/states/south-carolina/, [accessed 13 May 2021].

[16] Wright LD, Resio DT, Nichols CR. Causes and impacts of coastal inundation. Wright L, Nichols C, editors. Causes and impacts of coastal inundation. Tomorrow's coasts: complex and impermanent. coastal research library 2018:27. doi: 10.1007/978-3-319-75453-6_7.

[17] CCSP. Coastal sensitivity to sea-level rise: a focus on the mid-atlantic region. A report by the U.S. climate change science program and the subcommittee on global change research. [James G. Titus (Coordinating Lead Author), K. Eric Anderson, Donald R. Cahoon, Dean B. Gesch, Stephen K. Gill, Benjamin T. Gutierrez, E. Robert Thieler, and S. Jeffress Williams (Lead Authors)]. Washington D.C., USA: U.S. Environmental Protection Agency; 2009.

[18] Office for Coastal Management (OCM). Sea level rise data: sea level rise, NOAA office for coastal management. 2021 https://coast.noaa.gov/slrdata/.

[19] Oppenheimer M, Glavovic BC, Hinkel J, van de Wal R, Magnan AK, Abd-Elgawad A, Cai R, Cifuentes-Jara M, DeConto RM, Ghosh T, Hay J, Isla F, Marzeion B, Meyssignac B, Sebesvari Z. Sea level rise and implications for low-lying islands, coasts and communities. IPCC special report on the ocean and cryosphere in a changing climate; [Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B, Weyer NM (eds.)]. In press.

[20] U.S. Census Bureau. American community survey 5-year estimates. 2019 https://www.socialexplorer.com/explore-tables.

[21] ESRI 2011. ArcGIS desktop: release 10. Redlands, CA: Environmental Systems Research Institute.

[22] Bell JE, Herring SC, Jantarasami L, Adrianopoli C, Benedict K, Conlon K, Escobar V, Hess J, Luvall J, Garcia-Pando CP, Quattrochi D, Runkle J, and Schreck CJ III. Ch. 4: Impacts of Extreme Events on Human Health. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program; 2016:99−128. http://dx.doi.org/10.7930/J0BZ63ZV.

[23] Clark GE, Moser SC, Ratick SJ, Dow K, Meyer WB, Emani S, Schwarz HE. Assessing the vulnerability of coastal communities to extreme storms: the case of Revere, MA., USA. Mitigation Adaptat. Strat. Global Change 1998;3(1):59–82.

[24] Gee GC, Ford CL. Structural racism and health inequities: old issues, new directions1. Du Bois Rev. 2011;8(1):115.

[25] Hardy RD, Milligan RA, Heynen N. Racial coastal formation: the environmental injustice of colorblind adaptation planning for sea-level rise. Geoforum 2017;87:62–72.

[26] LeRoy S, Wiles R, Chinowsky P, Helman J. High Tide Tax: The price to protect coastal communities from rising seas. Center for Climate Integrity; 2019 https://climatecosts2040.org/files/ClimateCosts2040_Report-v4.pdf [accessed May 13, 2021].

[27] Neumann J, Hudgens D, Herter J, Martinich J. The economics of adaptation along developed coastlines. Wiley Interdis Rev Cli Chg 2010;2:89–98. doi: 10.1007/s11027-011-9356-0.