CLIMATE CENTRAL

GEORGIA AND THE SURGING SEA

A vulnerability assessment with projections for sea level rise and coastal flood risk

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GEORGIA AND THE SURGING SEA

A VULNERABILITY ASSESSMENT WITH PROJECTIONS FOR SEA LEVEL RISE AND COASTAL FLOOD RISK

ABOUT CLIMATE CENTRAL

Climate Central surveys and conducts scientific research on climate change and informs the public of key findings. Our scientists publish and our journalists report on climate science, energy, sea level rise, wildfires, drought, and related topics. Climate Central is not an advocacy organization. We do not lobby, and we do not support any specific legislation, policy or bill. Climate Central is a qualified 501(c)3 tax-exempt organization.

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CONTENTS

CONTENTS

EXECUTIVE SUMMARY

Floods exceeding today's historic records in the Savannah area, about 3.5 feet above the local high tide line, are likely to take place by 2040 under a mid-range sea level rise scenario. Low-range projections lead to a better than even chance of floods exceeding 3 feet over the same period – levels not seen in the last half-century. Under high-range projections, there is a near-certain chance of floods above 8 feet by end of century. The southern Georgia coast faces a very similar risk of 3- and 8-foot floods.

More than 178,000 acres of land lie less than 3 feet above the high tide line in Georgia, after accounting for potential protection from levees and other features. Some $2.5 billion in property value, and 12,500 homes sit on this land – with over 80% in Chatham and Glynn Counties. More than one quarter of the property at risk in the state is located in Savannah, and more than 1 in 6 of the state's homes at risk are in St. Simons. Totals jump to some $9.2 billion in property and 57,000 homes on 465,000 acres of exposed land under 8 feet.

The state has more than 350 miles of road on land below 3 feet, plus 8 houses of worship; 2 schools; and 46 EPA-listed sites such as hazardous waste dumps and sewage plants. At 8 feet, these numbers grow to nearly 2,000 miles of road, plus 29 schools, 116 houses of worship, and more than 183 EPA-listed sites.

Sea levels are rising at an accelerating rate, and the scientific community is confident that global warming is the most important cause. Higher sea levels translate to more and higher coastal floods. To forecast future risk, this analysis integrates historic local sea level trends and flood statistics with global sea level rise scenarios, developed by a multi-agency federal task force led by NOAA in support of the recent U.S. National Climate Assessment.

This report is being released as a high-level summary of findings and methods, coincident with the online launch of a Surging Seas Risk Finder tool for the state, providing much more detailed and localized findings, and accessible via http://sealevel.climatecentral.org/ssrf/georgia.

The tool includes:

- Interactive local projections of sea level rise and increasing coastal flood risk from 1-10 feet by decade;
- A zooming, zip-searchable map of low-lying areas threatened, plus layers showing social vulnerability, population density and property value;
- Detailed assessments of populations, property, infrastructure and contamination sources exposed, for each implicated county, city, town, zip code, planning district, legislative district and more;
- State- and county-wide heat maps facilitating high-level vulnerability comparisons; and
- Brief customized "fast look" reports that integrate key findings from across all analyses for each locality, and provide interpretation and context.

Detailed knowledge of vulnerability is a critical tool for communities seeking to build resiliency to the climate challenges of today and the future.

01. INTRODUCTION

IN BRIEF

In March 2012, Climate Central released its first analysis of sea level rise and coastal flood threats in the United States. We published two scientific papers in a peer-reviewed journal; a national report; fact sheets for each coastal state; and an interactive online map called *Surging Seas*. About 800 stories in local to national media covered our findings, and a U.S. Senate committee invited Climate Central to testify about the research in April 2012 – six months before Hurricane Sandy.

This report represents a major extension to our analysis for Georgia, using the same essential methods as our original work, but incorporating greatly improved and expanded data. The report summarizes major themes and findings taken from a much larger body of results accessible via a new interactive online tool, the Surging Seas Risk Finder, available for a growing set of coastal states throughout the U.S.

RESEARCH IMPROVEMENTS

Our 2012 analysis used the best available national coverage elevation dataset at the time. This analysis uses far more accurate laser-based (lidar) elevation data. Our 2012 research assessed land, population and housing vulnerable to sea level rise and coastal flooding. This research assesses over 100 additional variables, including socially vulnerable populations, populations by racial and ethnic group, property value, roads, rail, airports, power plants, sewage plants, hazardous waste sites, schools, churches, and hospitals. Our 2012 analysis tabulated exposure at state, county, and city levels. This analysis adds zip codes, congressional districts, planning districts, state and local legislative districts, and more.

For sea level rise projections, this report relies primarily upon scenarios produced by a multiagency task force for the U.S. National Climate Assessment (Parris et al 2012), locally adapted to Georgia. However, the full analysis and Risk Finder also include many other global sea level rise models and projections -- also locally adapted – not included in our 2012 analysis. We localize by factoring in local effects, such as sinking land, employing the same methods as in our original peer-reviewed research.

We also carry forward the same methods we previously used to characterize storm surge risk, and integrate it with projected sea levels, to develop projections of overall local flood risk by decade. However, we have updated analysis inputs to include the full available record of hourly water levels at each water level station through the end of 2012. This means decades more data for most stations than the standard 30-year period used in the original analysis, increasing the robustness of our findings.

SURGING SEAS RISK FINDER: A NEW ONLINE TOOL

The Surging Seas Risk Finder is searchable by geography, and offers easy navigation and visualization of analysis results from hundreds of thousands of combinations of location, water level, and risk element. The Risk Finder is divided into five components:

- **Map:** Interactive zooming map of sea level and flood risk zones
- **Forecast:** Projections of sea level rise and flood risk
- **Analysis:** Detailed analysis of exposed population, assets and infrastructure by individual location, from zip to state level
- **Comparison:** Comparisons of exposure across the whole state or selected county
- **Fast Look:** Brief customized reports that integrate key findings from across all analyses for each locality, and provide interpretation and context

02. A TIMELINE OF GROWING RISKS

Long before sea level rise permanently submerges new land, it will make its presence felt through higher and more frequent coastal floods, because higher seas raise the launch pad for storm surge.

In fact, every coastal flood today is already wider, deeper and more damaging because of the roughly 8 inches (IPCC 2013) of warming-driven global sea level rise that has taken place since 1900. This analysis finds that an intermediate high sea level rise scenario leads to better than even chances of a record flood in the Savannah area by 2030 to 2040. Along the southern coast, low-range projections lead to nearly a 1 in 2 chance of a flood exceeding 3 feet by 2030 – levels not seen in the last half-century. Under high-range projections, floods exceeding 4 feet – a level not seen in the past 100 years – become every-year events by 2060 from the south to the north alike.

This section explores projected sea level rise and how it aggravates coastal flooding.

SEA LEVEL RISE PROJECTIONS

Using scenarios from a NOAA-led technical report to the National Climate Assessment (Parris et al 2012), this analysis makes mid-range or "intermediate high" local sea level rise projections for Georgia of roughly 1-1.2 feet by mid-century, and 3.7-4 feet by 2100, depending on location. These figures all use sea level in 2012 as the baseline.

Global Sea Level Rise Projections

The Earth's average temperature has warmed by more than one degree Fahrenheit over the last century, and scientists overwhelmingly agree that most or all of this warming comes from human influence (IPCC 2013). This influence comes mainly through the burning of fossil fuels and resulting accumulation of carbon dioxide in the atmosphere.

Global sea level rise is one of the scientifically best-established consequences of this warming. Warming shrinks glaciers and ice sheets, adding water to the ocean; and also heats up the ocean, expanding it. Over the past two decades, global sea level has risen roughly twice as fast as it did during the 20th century.

Projecting future sea level is a difficult scientific challenge, not least because it will depend upon how much more carbon humans put into the atmosphere. For global sea level rise projections, this analysis relies on scenarios developed by the National Oceanic and Atmospheric Administration (NOAA) and collaborating agencies for the U.S. National Climate Assessment (Parris et al 2012). We focus on the intermediate low, intermediate high, and highest sea level rise scenarios, which point to 1.6 ft, 3.9 ft, or 6.6 ft of sea level rise globally by 2100, from a 1992 starting point. For simplicity, we call these scenarios "slow", "medium" and "fast."

We omit the NOAA lowest scenario in this report. This scenario projects this century's average rate of sea level rise as the same as last century's, lower than the average rate from the last two decades. Such an outcome seems very unlikely given projections for warming this century, and the strong observed relationship between global temperature and sea level change over the last century (Vermeer and Rahmstorf 2009).

The Intergovernmental Panel on Climate Change recently released its Fifth Assessment Report on climate science (IPCC 2013). IPCC's sea level projections range from 0.9-3.2 feet by 2100, but explicitly do not include a potential rapid ice sheet breakdown scenario. NOAA's highest projection is intended to capture such a possibility, and thus the highest plausible sea level rise for the century, as an indicator of maximum risk for planning purposes.

Research published since these projections were made indicates that the West Antarctic Ice Sheet has begun an unstoppable collapse that will likely lead to 10-plus feet of rise over centuries (Joughin et al 2014, Rignot et al 2014). Further research indicates that Antarctic ice loss rate has recently doubled, albeit over a short measurement period (McMillan et al 2014), and that Antarctica contributed more than 6 feet of sea level rise per century during a geologically recent warming episode (Weber et al 2014).

Surging Seas Risk Finder, the interactive web tool accompanying this report, includes projections based on scenarios developed by NOAA for the National Climate Assessment; IPCC projections; U.S. Army Corps of Engineers guidelines, semi-empirical projections developed by Vermeer and Rahmstorf (2009); and a no-global-warming scenario for comparison. We will add additional global sea level rise projections over time.

Local Sea Level Rise Projections

Local sea level rise can differ from global sea level rise for many reasons. The ocean is not flat, and shifting currents and sea surface temperatures can alter local sea level trends over years or decades. In addition, the land itself is slowly sinking or (more rarely) rising in many coastal areas, augmenting or diminishing local sea level rise. Later in the century, gravity effects will also play a role: as ice sheets diminish, so will the gravitational force they exert on the oceans, and ocean surface water will make subtle adjustments accordingly.

For its main projections, this analysis uses locally adapted scenarios from NOAA's report to the National Climate Assessment (Parris et al 2012). For estimates based on global projections from other studies, this analysis employs the same method as Tebaldi et al (2012) to develop projections for each location studied. In essence, we compare global sea level rise to local sea level rise measured at a water level station over a 50-year period. We use the difference to define a local component of sea level rise, and assume that the local component rate will continue unchanged into the future. This is a reasonable assumption at least for the effects of sinking or rising land, effects important enough to account for most or all of the long-term local component in most places (Tebaldi et al 2012). (See Appendix A or Tebaldi et al (2012) for more detail.)

For this report and as presented by the Surging Seas Risk Finder, we developed projections at long-term NOAA water level stations at Fort Pulaski, Georgia, to the south (near Savannah); and Fernandina Beach, FL, to the south, near the Georgia-Florida state line, 9 miles from the city of St. Marys. Our "medium" projections averaged 1.1 feet by 2050 and 3.8 feet by 2100, with each site varying from these averages by not more than two inches. The full range of projections, slow to fast, was 0.5-1.8 ft by midcentury, and 1.6-6.4 ft by 2100.

The projections given in this analysis should be taken as indicative of long-term trends, and not as precise projections for specific years. Global and local sea level experience natural ups and downs over years and decades that may temporarily obscure the underlying trend, but which will balance out over time.

COASTAL FLOODING: HISTORY AND PROJECTIONS

Rising seas raise the launch pad for storm surge, driving coastal floods higher. This study projects future flood risk by superimposing sea level rise projections onto historical patterns of flooding. In other words, we assume that coastal storm statistics remain constant – the same frequency and intensity of coastal storms – while sea levels rise. If storms instead worsen, then this analysis would underestimate flood risk.

Historical Analysis to Define Extreme Floods

The first step in this approach is to characterize historical coastal flood risk at each study site – in this case, each water level station assessed in and near Georgia. We apply standard methods to estimate the precise relationship between a flood's height and its annual likelihood (the higher the rarer), based on a long historical record of hourly water levels. For example, based on sea level in 2012, we estimate that a flood with a 1% annual chance – what we call an "extreme" flood in this study, and commonly referred to as a "100-year" flood – reaches 3.2 feet above the high tide line at Fort Pulaski, near Savannah; and 3.1 feet at Fernandina Beach, FL, near the southern edge of Georgia's coast. In more than a half-century of records at each location, no flood has exceeded 3 feet – nor has a flood has exceeded 4 feet this century or last.

We apply the same methods as Tebaldi et al (2012) for this analysis (see Appendix A for a briefer summary). However, we update our previous findings by now including water level records through the end of 2012, and back to the earliest year with reliable records at each water level station. This allows us to project future risks of "unprecedented" floods as well as statistically "extreme" ones.

In this report, we give all flood heights and water levels in elevations relative to Mean Higher High Water (MHHW), or what we more simply call today's "high tide line," defined based on tide levels during NOAA's standard 1983-2001 tidal "epoch."

Our purpose is to give a good sense of how high floods might reach above normal local high water lines. Note that different sources use different reference frames; tidesandcurrents.noaa.gov (more specifically here) provides data for inter-conversions at most stations, for example to and from Mean Lower Low Water (MLLW) and standard modern map elevation (North American Vertical Datum 1988, or NAVD88).

Coastal Flood Projections

As sea levels rise, they increase the chances of extreme floods by today's standards. For example, an extreme flood reaching 3.2 feet above the present high tide line at Fort Pulaski, near Savannah, would today require a 1%-annual-chance combination of storm surge and tide. But after 0.7 ft of sea level rise, a flood reaching the same absolute elevation would only require a 0.7-foot lesser combination of storm and tide, coming with a roughly 10% annual chance. This transition from rarity to fairly common event would take place in under 30 years in a "medium" sea level rise scenario.

We assessed when floods would exceed the highest-ever observed flood at each of the study stations (see http://tidesandcurrents.noaa.gov/est/Top10_form_ft.pdf for historic flood listings), and found greater than 50 percent chances within the next 20-30 years, based on NOAA's intermediate high scenario ("medium" rise, here), at Fort Pulaski, where the record flood came in 1947 at 3.4 feet. At Fernandina Beach, FL, the likelihood of a flood exceeding its record of 6.9 feet during the 1898 Georgia hurricane is about 5% by the end of the century. However, under a "fast" rise scenario, floods topping Fernandina Beach's record would become every-year events in the last decade of the century.

We conducted the same essential analysis for standard water levels from 1-10 ft above the high tide line, computing probabilities for each level by decade, for all of the stations analyzed.

For example, there is a 2 in 3 chance of floods exceeding 3 feet MHHW within 20-30 years, depending on the site, under NOAA's intermediate low ("slow") sea level rise scenario. The high (or "fast") scenario increases these chances to a near-certainty within the same date range.

Floods reaching more than 8 feet MHHW become a near-certainty by end-of-century at both sites under NOAA's high ("fast") sea level rise projections, and floods exceeding 9 feet have better than even chances at Fort Pulaski, but floods exceeding 10 feet have low chances.

Therefore, 3-to-8 feet can be viewed as a reasonable range where extreme floods are *likely* this century along the whole Georgian coast, depending upon sea level rise scenario. Much higher floods are also possible but with lower probability.

Floods have not topped 4 feet this or last century at Fort Pulaski or Fernandina Beach, but under a mid-range SLR scenario, the chances are better than even that this level will be topped by 2060. Under high-range projections, by this same decade, floods exceeding 4 feet become every-year events.

The Surging Seas Risk Finder presents complete results for all levels and locations.

It is important to note that while sea level rise projections are fairly similar for most neighboring water level stations, local flood risk profiles tend to vary more substantially (as illustrated here by the differences in projected flood risks according to location). In general, flood risk by elevation can vary significantly across short distances, depending upon local geography. Thus the escalating flood risks computed for each station may be taken as *indicative* of increasing risk in its wider area, but should not be interpreted as providing *predictions* for nearby areas.

Global warming multiplies extreme flood risk

Since sea level rise multiplies extreme coastal flood risk, and global warming contributes to sea level rise, global warming multiplies flood risk. This effect is independent of any potential warming influence on storm frequency or intensity. We assessed the sea level driven global warming multiplier by comparing flood probabilities with and without the global component of sea level rise (leaving out local components that might come from sinking or rising land).

We found that global warming has already doubled the likelihood of extreme floods at both Fort Pulaski and Ferdandina Beach, FL.

Multipliers for cumulative flood probabilities behave more complexly, because the cumulative risk for an extreme flood becomes substantial when accumulated across many decades, even in the absence of global sea level rise. This puts a cap on multiplier values: for example, a background 50% cumulative risk cannot have a multiplier any greater than 2X.

03. PEOPLE, PROPERTY AND INFRASTRUCTURE IN HARM'S WAY

More than 178,000 acres of land lie less than 3 feet above the high tide line in Georgia, after accounting for potential protection from levees and other features. Some $2.5 billion in property value, and 12,500 homes sit on this land – with over 80% in Chatham and Glynn Counties. More than one quarter of the property at risk in the state is located in Savannah, and more than 1 in 6 of the state's homes at risk are in St. Simons.. Roughly 22,000 people are residents in the homes below 3 feet. Totals jump to some $3.4 billion in property and 33,000 residents in 18,000 homes on 220,000 acres of exposed land under 4 feet. At 8 feet, the totals jump further: $9.2 billion in property and 112,000 residents in 57,000 homes on 465,000 acres of exposed land.

The state has more than 350 miles of road on land below 3 feet, plus 8 houses of worship; 2 schools; and 46 EPA-listed sites such as hazardous waste dumps and sewage plants. At 8 feet, these numbers grow to nearly 2,000 miles of road, plus 29 schools, 116 houses of worship, and more than 183 EPA-listed sites.

LAND

Georgia has more than 178,000 acres of land at less than 3 feet MHHW, increasing to 220,000 at 4 feet, and increasing to more than 465,000 acres less than 8 ft above the tide line, after taking potential protections into account. Camden, Chatham, and Glynn Counties combine to make over half of the 3-foot exposure.

These values are based on analysis of high-resolution land and tidal elevation data from NOAA, after screening out areas classified as saltwater wetlands by the U.S. Fish and Wildlife Service (see Appendix A for more detailed methodology).

As part of our research, we analyzed how much low-lying land might be protected by levees or other flood control structures (as represented in FEMA's Midterm Levee Inventory), or natural features such as ridges (as represented in the elevation data): just 8 percent of the total exposed area at 3 feet, and 4 percent at 8 feet. Protection, or isolation, currently appears to be a relatively unimportant factor in the state, but we do take it into account when providing exposure estimates here.

Our approach does not take into account, and also avoids complications from, future erosion or the migration of marshes as sea levels rise. It also does not address the uneven surfaces of floodwaters driven by individual storms, and influenced by details of local geography.

Overall, the maps and analyses here should not be taken as precise predictions or flood emergency guides. Rather, we present them as risk indicators in a world of rising sea levels and increasing floods.

CLIMATE CENTRAL

PEOPLE, PROPERTY AND INFRASTRUCTURE

Once maps of vulnerable land are established, it is relatively straightforward to account for the populations, property and infrastructure exposed within these zones. The Surging Seas Risk Finder presents hundreds of thousands of combinations of analysis results by geography, water level, and variable. Here we present some of the major categories and highlights, with a focus on exposure below 3, 4 and 8 feet.

We find that in Georgia, some $2.5 billion in property value sits on land less than 3 feet above the local high tide line. Seventy-five percent of this property is in Chatham County, and more than half of the total exposed property in the state is concentrated in just 4 Savannah zip codes: 31411, 31405, 31404, and 31406. Over 12,500 homes sit on land below the same level, over 80% of which sit in Chatham and Glynn Counties, with about 40% concentrated in just three zip codes: 31522 (St. Simons Island, nearly 20%), 31419 (Savannah) and 31328 (Tybee Island). Roughly 22,000 people are residents in the homes below 3 feet. Totals jump to some $3.4 billion in property and 18,000 homes with 33,000 residents on 220,000 acres of exposed land under 4 feet.

Exposure increases further on land below 8 feet, with $9.2 billion in property and 57,000 homes with 113,000 residents.

Nonresidential buildings and infrastructure are widely at risk as well. All told, over 350 miles of road lie on land below 3 feet in the state; 2 schools; 8 houses of worship; and 46 EPA-listed sites, screened to include mostly hazardous waste sites, facilities with significant hazardous materials, and wastewater generators. At 4 feet, these numbers grow to 546 miles of road, 5 schools, 11 houses of worship, and 56 EPA-listed sites. At 8 feet, these numbers grow to nearly 2,000 miles of road, 29 schools, 116 houses of worship, and 183 EPA-listed sites.

This analysis simplifies most facilities as points with a single latitude and longitude. It also evaluates exposure by evaluating the height of the land that structures sit upon. It takes into account neither the full footprint of a facility; nor the potential elevation of structures or equipment above ground; nor the possibility of unsealed basement areas. We regard such analysis as useful for assessing the general exposure of different facility types across different geographies, and as useful for screening the possible exposure of individual facilities. However, authoritative assessments for individual facilities are best served by on-the-ground measurement. .

THE MOST VULNERABLE

Social vulnerability is a broad term that describes the sensitivity of populations to the impacts of environmental risks and hazards, including coastal flooding. Social vulnerability helps explain why some places can experience hazards differently even without differences in exposure. The Social Vulnerability Index is a tool that synthesizes socioeconomic characteristics of populations – characteristics known to influence a community's ability to prepare for, respond to, and recover from hazard events like floods (see e.g. Emrich and Cutter 2011; Finch et al 2010; Cutter et al. 2013).

Our analysis found nearly 5,000 people in the high Social Vulnerability Index class below 3 feet across Georgia. The total jumps to more than 25,000 below 8 feet.

The Social Vulnerability Index compares places based on their relative levels of social vulnerability. For this analysis, vulnerability was assessed at the Census tract level, using 27 variables from the 2010 Census and the 2006-10 American Community Surveys (see Appendix A for further methodological details). The online Submergence Risk Map that accompanies this report includes a feature visualizing social vulnerability levels in areas that are physically vulnerable to coastal flooding and sea level rise.

The Social Vulnerability Index shows where there is uneven capacity for preparedness and response and where pre and post-event resources might be most effectively used to reduce pre-existing vulnerability and increase resilience post-disaster. The index is also a useful indicator in understanding spatial differences in disaster recovery. It has been used in combination with other disaster data to provide emergency responders with a much clearer understanding of disaster impacts, thus providing decision makers with an objective comparison of damages sustained across the full spectrum of affected communities (see http://webra.cas.sc.edu/hvri/products/SoVIapplications.aspx).

04. CONCLUSION

Long before rising seas redraw local maps, they will result in more coastal floods reaching higher. They are already having this effect.

The research in this report underscores the high concentration and wide range of populations, property, infrastructure, buildings, and potential contamination sources in low-lying coastal areas. In the densest areas, the most socially vulnerable populations are exposed the most. Patterns vary from place to place.

It will not require major storms to cause extensive economic damage and suffering in the future. Knowledge of vulnerabilities can lead to better preparation for the next inevitable flood, and the ones after. Higher floods in the future are certain, but how much damage they inflict is not – and will depend on the measures coastal communities take.

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PROJECTING LOCAL SEA LEVEL RISE

To localize the various global sea level rise projections used, including the scenarios prepared for the National Climate Assessment (Parris et al 2012), we followed the same essential methods as Tebaldi et al (2012). In that study, we added "semi-empirical" projections of global sea level rise to separate local sea level change components developed for 55 water level stations around the contiguous U.S. Here we use the example of projections built on top of a semi-empirical model, as in Tebaldi et al., to explain the methodology.

For the global component in our semi-empirical approach, we used projections from Vermeer and Rahmstorf (2009). Their approach, based on the recent historic relationship between global sea level and global average temperature, has successfully hind-casted sea level rise over the last century and millennium with great fidelity. The relation estimated over the past observed records of sea level rise and global warming can be applied to projections of future temperature change produced by climate models. By this approach, therefore, future global sea level rise is not directly derived from the output of climate models, but is projected on the basis of the future temperature projections of these models. As projections based on historical observed relationships generally do, this approach assumes that the dynamics captured by the past relation will remain the same for the projected future period. If the ongoing increase in global temperatures leads ice sheets to unravel in ways not experienced during the model's twentieth century calibration period, then this approach may understate the problem.

Use of Vermeer and Rahmstorf's approach allowed this analysis to take into account a wide range of possible futures, from ones where humanity continues to send great amounts of heat-trapping gasses into the atmosphere, to ones where we sharply reduce these emissions. Through Vermeer and Rahmstorf's method we were also able to incorporate a range of possible relationships between emissions and global temperature increases (by using a range of climate model parameters and thus exploring the dimension of model uncertainty), and a range of possible relationships between temperature and sea level (by considering the uncertainty in the parameters of the empirical model). Our analysis rolled all of these factors together to produce one set of best estimates, and a range of potential outcomes around them.

For the current Surging Seas Risk Finder, we updated our semi-empirical projections to employ the most recent carbon emissions scenarios ("Representative Concentration Pathways") and warming models being used by the global scientific community (Moss et al 2010).

In addition to future SLR estimates based on the empirical relation fitted between global temperature projections and SLR, we used global SLR models and scenarios that NOAA prepared for the National Climate Assessment (Parris 2012), and from the IPCC (2013) and from the U.S. Army Corps of Engineers (2011).

Changes in local sea level come not only from changes in global sea level, but also from local effects such as the slow rising or sinking of coastal land, driven largely by the ancient retreat of massive ice sheets across North America. To determine local effects, we removed global rise from the total observed local sea level increase over a 50-year period (1959-2008) at each of the 55 nationwide stations we analyzed in our original study. The difference between the total observed local component and global rise during the same period (both of them expressed as linear trends of sea level change per year) is what we call the local component, and, in our projections, we assumed that each local component will continue as a constant rate into the future that offsets or adds on to the global component as an additive term. A detailed analysis using multiyear data from high-precision continuous GPS stations showed that vertical land motion can explain most or all of these local components. The forces behind such motion generally stay constant for thousands of years.

Our projections should not be interpreted as precise predictions for specific years, but rather best estimates that indicate overall trends, because of all of the factors that could lead to a range of outcomes (for example, different emissions futures) and because of natural year-to-year and decade-to-decade variability. For this reason, we present projections at the decade scale only.

PROJECTING COASTAL FLOOD RISK

In Tebaldi et al (2012) and here, to project the probabilities of reaching different high water levels in the future, through combinations of storms, tides and sea level rise, we developed statistics based on patterns of historical extreme water levels, and then superimposed projected sea level rise onto these. For this report, we used local statistics and local sea level projections for each of the Georgia area water level stations analyzed.

We used statistical methods specialized for handling extreme values to analyze records of hourly data. We expanded our analysis from the fixed standard 30-year period (1979-2008) used in Tebaldi et al, to use the maximum available high quality data for each water level station through the end of 2012 – starting as early as 1897 (Fernandina Beach, FL) or as recently as 1935 (Fort Pulaski).

We estimate the parameters of a Generalized Pareto Distribution at each station, characterizing the probability density of extreme water levels at that location, and on the basis of those parameters we derive what is called a "return level curve" for each water level station. Our return level curves relate water heights (in MHHW) to their annual probability (given sea level in 2012): for example, heights with a 1% chance of being reached in any given year ("100-year" or "century" or "extreme" floods) are higher than heights with a 10% chance ("decade floods"), and so forth. We filtered out the effects of ongoing historic sea level rise at each station by estimating a linear trend over the length of the record and subtracting it out, in order to calculate baseline return level curves influenced only by tides, storms, and seasonal shifts in water level.

Once we establish a curve for the baseline period (that we can think of as today in most cases), it is easy to modify it for a given time in the future, on the basis of the effects of sea level rise alone. For example, if at that future time sea level has risen by one foot, an event reaching 5 feet of elevation will have at that future time the same probability of occurring as a minor event reaching 4 feet has today. Thus, sea level rise will make rare high water events of today more likely in the future.

These considerations allow us to compute the chance that a particular height H will be reached in some future year (say, for example the chance that an event reaching 5 feet will happen in 2030). All that is needed is the amount of sea level rise, say L, between today (the baseline) and that target year, and the return level curve for the baseline: we then take H, subtract L and find, on the curve, the probability associated to the event of size H-L.

Slightly more complex is the computation of the cumulative risk of at least one such event by some future year, i.e., the estimate of the chance that a particular height H will be reached or exceeded by some future year. The way to think of this is as the complement of (i.e., one minus) the probability that such event will never be reached by that year. As an example, let's say the event H is currently a "100-year" event. That means that this year it has 0.01 chances of occurring, and therefore 0.99 chances of not occurring. Next year, if nothing changed, the chance of it not occurring would be the same, therefore the probability of H not occurring this year or next year would be 0.99*0.99=0.98; its complement, that is the chance of H occurring by next year, would be 1-0.98=0.02.

The same calculation applies for any number of years until the target year. We simply multiply the chances of the event H not occurring every year for the entire period, and then take its complement.

Critically, however, sea level rise makes the chance of any event higher –at least on average decade after decade. Therefore we compute changing probabilities over the years, taking into account the effect of sea level rise. To do so, we incorporate local projections of sea level rise decade by decade, not just the total rise projected by the target year.

More specifically, we used the return level curve for each decadal year, e.g. 2040, incorporating sea level rise projected through that year, and applied the same curve for the five preceding and four succeeding years as well. We then used the probability of exceeding H each year between 2011 and the target year to compute the overall odds of exceeding H at least once during the period.

To continue with the example of H as the 100-year event of today one can imagine that for a target year far enough in the future the multiplication will involve values sooner or later (depending on the pace of sea level rise at this station and on the shape of its return level curve) significantly smaller than 0.99, therefore producing a significantly larger value of the complement, by the target year, compared to that computed under the assumption of no sea level rise.

As with our projections of sea level rise, and for similar reasons, we limit our presentation to odds of reaching different flood levels at decade resolution. Any given year, even within a steady long-term trend of sea level rise, may see dips and jumps in the actual value of sea level rise at a given location. Our estimates of sea level rise are appropriate only as long-term average trends, decade after decade.

Note that the same type of calculation performed for a detailed range of values and years in the future allow us to answer a question mirroring the one above. We can search among our results for which size event will become, say, at least Q% likely by the next 20 years, rather than starting with a given size event and ask what its likelihood of occurring at least once in the next 20 year will be. Similarly we can ask questions about waiting times, looking for the number of years it will take for a given size event to occur with at least an Q% chance.

APPENDIX A: METHODS

Our calculations all concern flood levels reaching elevations relative to a stable baseline, the average high tide level during a fixed historic reference period at each station, the so called tidal datum epoch (the current standard epoch is 1983-2001). This way of measuring flood levels is different than pure storm surge, which is calculated as the extra water height above the predicted tidal water level for the very same moment in time. Our focus was not storm surge, but rather how high water actually gets, due to storm surge, plus tide, plus sea level rise.

This analysis assumed that historic storm patterns will not change; in other words, it did not address the possibility that storms might become more or less frequent or severe due to climate change.

This analysis was based on data taken at water level stations. Tides, storm surge, and the resulting statistics vary from place to place, sometimes over short distances, due to factors including land and ocean geometry and storm directions. On the other hand, in our national analysis (Tebaldi et al 2012), results for distantly spaced water level stations within the same region were often similar. Therefore, results from stations may be taken as rough indicators but not precise estimates for their neighborhoods and regions, and the quality and coverage of indication will vary.

ESTIMATING GLOBAL WARMING FLOOD RISK MULTIPLIERS

To estimate how global warming is shifting the odds of high storm surges, through sea level rise, we calculated the odds of extreme events in a hypothetical world with no past or future global sea level rise due to warming, to compare against our original calculations, which included warming. We did this comparison at each water level station in the study. The approach basically translated to subtracting out the roughly 8 inches of historical global sea level rise measured from 1880-2009, and then also assuming no future global sea level rise, for the no-warming scenario at each station (a scenario viewable in the Surging Seas Risk Finder). The no-warming scenarios still included local sea level rise from factors other than warming, such as sinking or lifting land — the full local component of sea level rise.

We made one further adjustment, which was to add back 10% of the historic global sea level rise (10% of 8 inches), in the event that some of the observed historic rise has come from factors other than warming. Research on the sea level budget assigns the great majority of the 8 inches to warming-caused effects: expansion of the ocean as it has warmed, and the melting and calving of glaciers and ice sheets. Small fractions of global sea rise unaccounted for are widely viewed to come at least in part from additional ice loss. We assume 90% of the 8 inches are due to global warming, and thus deduct this amount for our comparison.

For comparison of odds with and without warming, we used standard "100-year" or "century" floods as our reference, meaning water station water levels high enough that they have just a 1% chance of occurring in any given year. We calculated the elevations 100-year floods reach when starting on top of baseline 2012 sea level at each station, using the same data and methods as for our overall water level probability projections. Elevations were relative to average local high tide (MHHW) during a fixed past reference period (the 1983-2001 tidal epoch), as with all elevations in related studies.

In comparing the probabilities of flood levels with and without global warming, we cut ratios off at ten, because higher ratios start to lose a sense of meaning. We also do not compute ratios at all when the chance of flooding is very close to zero without global warming. These situations create very large ratios whose exact values are meaningless: tiny changes in near-zero odds (odds without global warming) would lead to enormous changes in the ratio value.

This analysis did not address the possibility that storms might become more or less frequent or severe due to climate change. We also limited ourselves to looking at the total effects of global warming, and did not aim to separate fractions caused by humans versus natural variations. The strong scientific consensus points to people as causing most, if not all, of the average warming observed over the last century, and to being the dominant cause of future warming.

MAPPING LOW COASTAL AREAS

To develop our maps of at-risk areas, we used high-resolution, high-accuracy laser-based (lidar) elevation data provided by NOAA. These data have a roughly 5 m (16.5 ft) horizontal resolution. In any small fraction of low-lying areas not covered, we used the highest resolution data available from the National Elevation Dataset (NED), a product of the U.S. Geological Survey.

For general discussion of the accuracy of elevation data and what it means for our maps and statistics, see Strauss et al (2012), which used 1/3 arc-second NED data exclusively, as lidar data were not sufficiently available. This discussion concluded that NED quality data are sufficient for the types of analysis conducted here. Nonetheless, the reported vertical accuracy (root mean square error) of lidar data, as used in this analysis, is roughly ten times more accurate than NED.

We began our process by classifying all cells as ocean (ocean, bay, estuary or saltwater wetland) or land (land or freshwater wetland), because ocean or saltwater marsh misclassified as land would lead to overestimates of susceptible total land area. We admitted cells as land according to a conservative consensus of three independent data sets. First, the cells had to be designated as land within the elevation data itself. Second, we included only cells with centers landward of NOAA's Medium Resolution Digital Vector Shoreline. Finally, we eliminated cells with centers inside areas classified in the National Wetlands Inventory (NWI) as estuarine or marine wetland or deepwater. In computing total land area susceptible, we included NWI freshwater wetlands.

Next, we adjusted the elevation of each cell to be in reference to the nearest average high tide line, instead of a standard zero. For example, if a cell's elevation were five feet, but the local high tide reached three feet, then we would compute an elevation of two feet relative to the tide line. Clearly, sea level rise or a storm surge would need to reach only two feet above high tide to threaten this cell with inundation. Sea level and tidal amplitude vary sometimes widely from place to place, and therefore also the average height of high tide. For local high tide elevations, we used values of Mean Higher High Water from VDatum, a NOAA data product and tidal model.

Based on these elevations adjusted relative to MHHW, we identified the set of cells beneath each water level threshold from one to ten feet above local high tide, and drew maps of each area.

Finally, we distinguished areas connected to ocean at a given water level, versus isolated areas, to use in different exposure analyses, and for differential display in our online mapping application. We included levees from the Midterm Levee Inventory in this analysis of connectivity, assuming each levee to be of sufficient height and condition to offer protection at every water level. Additional discussion can be found in the main body of this report (see "Land" in Table of Contents).

ASSESSING SOCIAL VULNERABILITY

The Social Vulnerability Index for 2006-10 marks a change in the formulation of the SoVI® metric from earlier versions (see e.g. Emrich and Cutter 2011). New directions in the theory and practice of vulnerability science emphasize the constraints of family structure, language barriers, vehicle availability, medical disabilities, and healthcare access in the preparation for and response to disasters, thus necessitating the inclusion of such factors in SoVI®. Extensive testing of earlier conceptualizations of SoVI®, in addition to the introduction of the U.S. Census Bureau's five-year American Community Survey (ACS) estimates, warrants changes to the SoVI® recipe, resulting in a more robust metric. These changes, pioneered with the ACS-based SoVI® 2005-09, carry over to SoVI® 2006-10, which combines the best data available from both the 2010 U.S. Decennial Census and five-year estimates from the 2006-2010 ACS.

The table below gives a complete list of the 27 variables used in SOVI® 2006-10 for Census tract level analysis.

APPENDIX A: METHODS

Table A1. Variables Used in Social Vulnerability Analysis

VARIABLE	DESCRIPTION
QASIAN	Percent Asian
QBLACK	Percent Black
QHISP	Percent Hispanic
QNATAM	Percent Native American
QAGEDEP†	Percent of Population Under 5 Years or 65 and Over
QFAM†	Percent of Children Living in Married Couple Families
MEDAGE	Median Age
QSSBEN	Percent of Households Receiving Social Security
QPOVTY	Percent Poverty
QRICH200K	Percent of Households Earning Greater Than $200,000 Annually
PERCAP	Per Capita Income
QESL†	Percent Speaking English as a Second Language with Limited English Proficiency
QFEMALE	Percent Female
QFHH	Percent Female Headed Households
QNRRES	Percent of Population Living in Nursing and Skilled-Nursing Facilities
QED12LES	Percent with Less Than 12th Grade Education
QCVLUN	Percent Civilian Unemployment
PPUNIT	Per Unit
QRENTER	Percent Renters
MDHSEVAL†	Median House Value
MDGRENT†	Median Gross Rent
QMOHO	Percent Mobile Homes
QEXTRCT	Percent Employment in Extractive Industries
QSERV	Percent Employment in Service Industry
QFEMLBR	Percent Female Participation in Labor Force
QNOAUTO†	Percent of Housing Units with No Car
QUNOCCHU	Percent Unoccupied Housing Units

For this analysis, we assessed Social Vulnerability Index scores by Census tract across the entire state. We then assigned tracts high, medium, or low social vulnerability scores, based on whether they fell within the top 20%, middle 60%, or bottom 20%, respectively, of vulnerability for the whole set within each state.

More information on the Social Vulnerability Index is available at http://webra.cas.sc.edu/hvri/products/sovi.aspx

APPENDIX A: METHODS

ESTIMATING EXPOSURE OF PEOPLE, PROPERTY, AND INFRASTRUCTURE

To calculate potential risks at each water level within areas such as zip codes, cities or counties, we used boundaries provided by the 2010 U.S. Census to overlay against our maps of land beneath different water level thresholds. We then computed the amount of land below each threshold in each place. For denominators in percentage calculations, we used our own computations of land area for each place, because our definitions of coastline differed slightly in places from that of the Census.

To tabulate population and housing potentially affected, we used block-level data from the 2010 U.S. Census, and assumed development on dry land only (neither freshwater nor saltwater wetland). For each Census block, we divided the population and number of housing units by the number of dry land cells with centers inside the block. We assigned the resulting per-cell density values back to each cell, creating new datasets for population and housing unit density. To estimate the population or housing at risk for a particular water level, we simply added up population and housing densities of land cells affected under the specification. Our analysis considered the elevation of land upon which housing stands, and made no special provision for elevated or multi-story buildings.

We followed the same approach for property value, computing value density based on Census block group resolution data from Neumann et al (2010). The property value is derived almost exclusively from individual parcel assessed just values, evaluated in 2008, which we adjusted using the Consumer Price Index to 2012 dollars. The data include residential, commercial, industrial, institutional and government property, both taxable and tax-exempt.

For analysis of linear features such as roads and rail, we computed the length of each feature on land below the water level in question, and made totals by feature type (e.g. total roads, federally-owned roads, or mainline rail).

For airports, we used linear runway data, and determined the percentage of runway length on land below each water level. We counted an airport as vulnerable at a given level when this percentage exceeded a threshold of 25%.

For point features, we simply use latitude/longitude coordinates overlaid onto our MHHW elevation map to evaluate whether a building, site or facility falls below a given water level. This approach does not take into account the actual footprint of a structure, nor the possibility that critical features may be elevated above the ground (or stored in an unsealed basement).

The first step in each analysis is to properly filter and de-duplicate records for the feature class or subclass of interest from a source dataset – for example, state-owned roads, commuter rail stations, nuclear power plants, or major hazardous waste sites. We primarily used federal datasets. References for each are accessible via the Surging Seas Risk Finder (within the “Analysis” section, click on a tile to see a details panel with sources listed, linked, and described (via tool tips on a mouse hover)).

APPENDIX B: GLOSSARY AND ABBREVIATIONS

EPA – U.S. Environmental Protection Agency

Extreme flood – As used in this report, a coastal flood height with a 1% or lower annual chance, assuming the sea level for 2012.

High tide line – see MHHW

IPCC – Intergovernmental Panel on Climate Change

Lidar – Light detection and ranging technology. A method of measuring distance that relies on firing laser beams and analyzing their returned, reflected light.

MHHW – Mean Higher High Water: a local frame of reference for elevation based on the elevation of the higher of the two high tides each day averaged across a reference period. The reference period used is the current tidal epoch, 1983-2001. This report uses "high tide line" as the equivalent of the height of MHHW.

MLLW – Mean Lower Low Water. See MHHW; MLLW is instead a frame of reference based on the elevation of the lower of the two low tides each day.

NCA – National Climate Assessment

NOAA – National Oceanic and Atmospheric Administration

NRC – National Research Council

Sea level rise, slow – In this report, the NRC lower-range sea level rise projection

Sea level rise, medium – In this report, the NRC main sea level rise projection

Sea level rise, fast – In this report, the NRC upper-range sea level rise projection

SLR – Sea level rise

Social vulnerability - A broad term that describes the sensitivity of populations to the impacts of environmental risks and hazards, including coastal flooding; related to a community's ability to prepare for, respond to, and recover from hazard events.

Storm tide – The height of tidal stage plus storm surge

Tidal epoch – Period over which tidal levels are defined. See definition for MHHW.

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