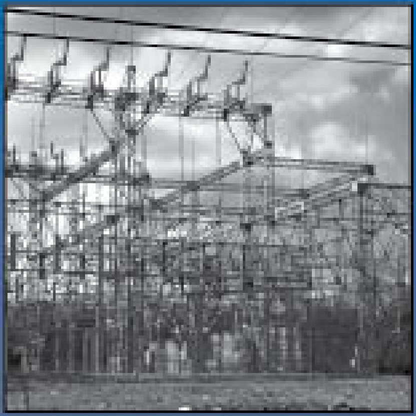

Effect of Sea Level Rise on Energy Infrastructure in Four Major Metropolitan Areas

September 2014

U.S. Department of Energy
Office of Electricity Delivery and Energy Reliability

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For Further Information

This report was prepared under the auspices of the Energy Infrastructure Modeling and Analysis (EIMA) division of the Office of Electricity Delivery and Energy Reliability (OE). OE's vision is a U.S. energy delivery system that is reliable in the face of all hazards and resilient to disruptions, supports U.S. economic competitiveness, and minimizes impacts on the environment. EIMA's mission is to ensure the reliability and resiliency of U.S. energy infrastructure and systems through robust analytical, modeling, and assessment capabilities to address energy issues of national importance. The Division is focused on conducting risk analyses and predictive modeling, and providing analytical products intended to inform decision makers at the public and private levels.

Leonard Crook, Kevin Chamberlain, and Peter Schultz of ICF International provided analytical support in conducting the study under the direction of David Ortiz, Deputy Assistant Secretary for EIMA and Alice Lippert, Senior Technical Advisor to EIMA.

Specific questions about this report may be directed to Alice Lippert, Senior Technical Advisor, EIMA Division (alice.lippert@hq.doe.gov). For more information regarding the EIMA division, please contact oe-eima@hq.doe.gov.

1. Introduction

Changes in the Earth's climate are under way, including increasing temperatures, changes in precipitation, rising sea levels, and increases in the severity and frequency of severe weather events.[1] Sea level rise (SLR) has the potential to directly impact coastal infrastructure and exacerbate other coastal hazards, including storm surge, coastal erosion, and degradation of natural protective sea barriers.

The President's Executive Order on Climate Preparedness (2013) directs federal agencies to support the development of climate resilient infrastructure and provide information, data, and tools to increase climate change preparation and resilience.[2] The Administration's Quadrennial Energy Review (QER), due in January 2015, will address energy infrastructure interdependencies and vulnerabilities to climate change.[3]

The Office of Electricity Delivery and Energy Reliability (OE) undertook this pilot study for the four metropolitan areas of New York City, Houston, Miami, and Los Angeles—as defined by each city's Census Bureau Metropolitan Statistical Area (MSA) boundary—to help establish a baseline understanding of the specific threat SLR poses to coastal energy infrastructure. A primary goal of this study has been to develop and test a proof-of-concept approach for identifying energy infrastructure at risk to SLR. These cities were selected given their proximity to the coast, past exposure to significant storm events, and their geographic dispersion along the coastlines likely to be affected by SLR: the northern mid-Atlantic coast, south-Atlantic coast, Gulf Coast, and the Pacific coast. The approach used in this study can be applied to any coastal region or coastal MSA.

The study overlays information about potential SLR exposure to energy infrastructure locations, using Geographic Information Systems (GIS) tools. To assess possible exposure to SLR, the study uses recent government data and modeling results, including:

- Global SLR scenarios that are based on alternative assumptions about the effects of climate change on sea levels, from the Third National Climate Assessment (NCA).
- Analyses of the geographic extent of inundation from higher sea levels, from the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (CSC).
- Locations of energy assets identified by the OE as part of ongoing studies of energy infrastructure.

This report is divided into five main sections. Following this introduction, Section 2 reviews the recent trends in SLR and explains how NCA projections were used in this study. Section 3 offers

[1] See GAO (2014) and Walsh et al. (2014)

[2] The White House (2013)

[3] The White House (2014)

an overview of the technical approach used to develop the information in this study and the limitations of that information. Section 4 provides summary results for each of the MSAs included in the pilot study: New York City (Section 4.1); Miami (Section 4.2); Houston (Section 4.3); and Los Angeles (Section 4.4). The final section of the report includes initial observations and implications for the analysis. The report also includes two appendices: a bibliography and an overview of selected recent SLR studies.

2. Sea Level Rise Trends

Rising sea levels threaten coastal communities and vital local infrastructure along the U.S. coast. The Department of Energy is particularly concerned about the threat SLR poses to energy assets. One of the lessons emerging from Hurricane Sandy's impact on the New York City region is the vulnerability of energy facilities to storm surges, which SLR is likely to exacerbate. Establishing sea level trends is critical for understanding the risk SLR poses to coastal communities and infrastructure over time.

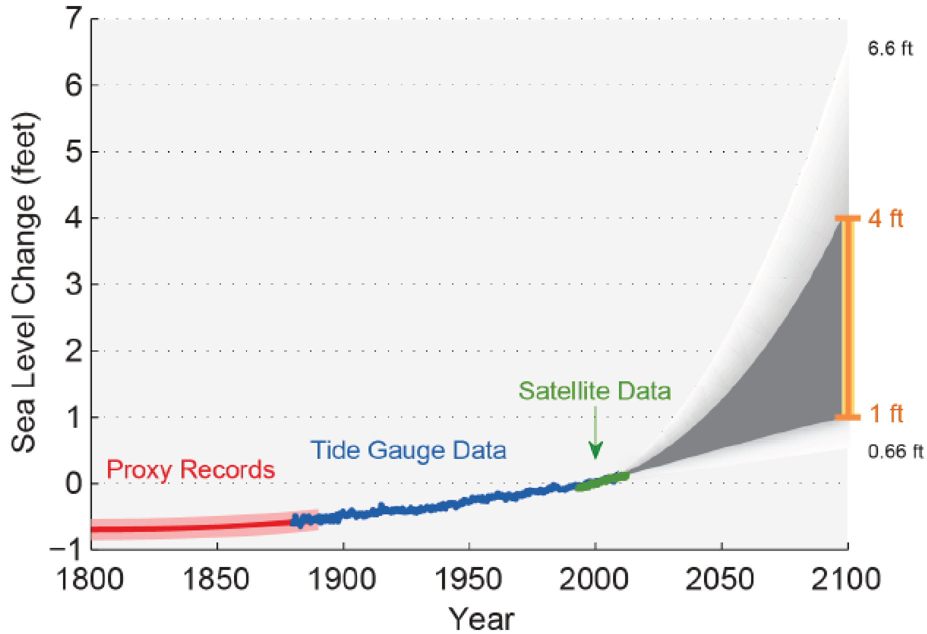
Sea level is measured both by tidal gauges and satellites and can be reported as a global average or as local rates. Changes in mean *global sea level*—resulting from the transfer of fresh water from land to oceans (from land-based ice sheets and mountain glaciers) and from the thermal expansion of ocean water due to higher global temperatures—contribute to the sea level change experienced at a particular coastal location.

During the 20th century, global sea level rose at a rate of approximately 6.8 inches per century; but over the last 20 years the rate has accelerated to approximately 11.8 inches per century.[4] The U.S. National Climate Assessment (NCA) provides a range of plausible global SLR scenarios, ranging from 8 inches to 6.6 feet by 2100.[5] The NCA focuses on the 1 to 4 foot range (see orange line highlighting the 1 to 4 foot range in Exhibit 2-1 below), noting that global SLR of 6.6 feet should be considered in situations where there is little tolerance for risk (e.g. for new infrastructure with a long anticipated life cycle such as a power plant). In contrast, global SLR of 8 inches (0.66 foot) should be considered where there is a great tolerance for risk.

[4] NOAA, Science on a Sphere, http://sos.noaa.gov/Datasets/dataset.php?id=184. Accessed 9-15-2014, converted to inches.

[5] Parris et al. (2014)

Exhibit 2-1. Historical and Projected Global Sea Level Rise[6]



In contrast to global sea level, *relative sea level* refers to the height of the sea surface relative to a specific point on land. Relative sea level measurements account for both changes in global sea level, as well as the effect of local factors, including vertical land motion[7], ocean circulation patterns, salinity, sedimentation, and erosion.[8] High rates of subsidence in coastal regions can significantly accelerate the effects of global SLR, while high rates of uplift can reduce the impacts of global SLR. Generally, relative SLR will have the greatest and most immediate impact in low-relief, low-elevation parts of the United States and on coasts containing deltas, coastal plains, tidal wetlands, bays, estuaries, and coral reefs.

As a guide to assess future exposure to SLR, this study applies the four global SLR scenarios developed for the NCA, after adjusting for local factors based on historical trends.[9] For example, Exhibit 2-2 below shows the adjusted relative sea level rise projected in Miami by 2100, along with each of the NCA's four baseline global SLR scenarios. Because of the relatively low historical trend in relative SLR for Miami (averaging approximately 0.09 inches per year) the

[6] The source of the figure is Melillo et al. (2014). It shows estimated, observed, and possible future amounts of global sea level rise from 1800 to 2100, relative to the year 2000. The future scenarios range from 0.66 feet to 6.6 feet by 2100. These scenarios are not based on climate model simulations, but rather reflect the range of possible scenarios based on other scientific studies. The orange line at right shows the currently projected range of sea level rise of 1 to 4 feet by 2100, which falls within the larger range that encompasses the high and low extremes.

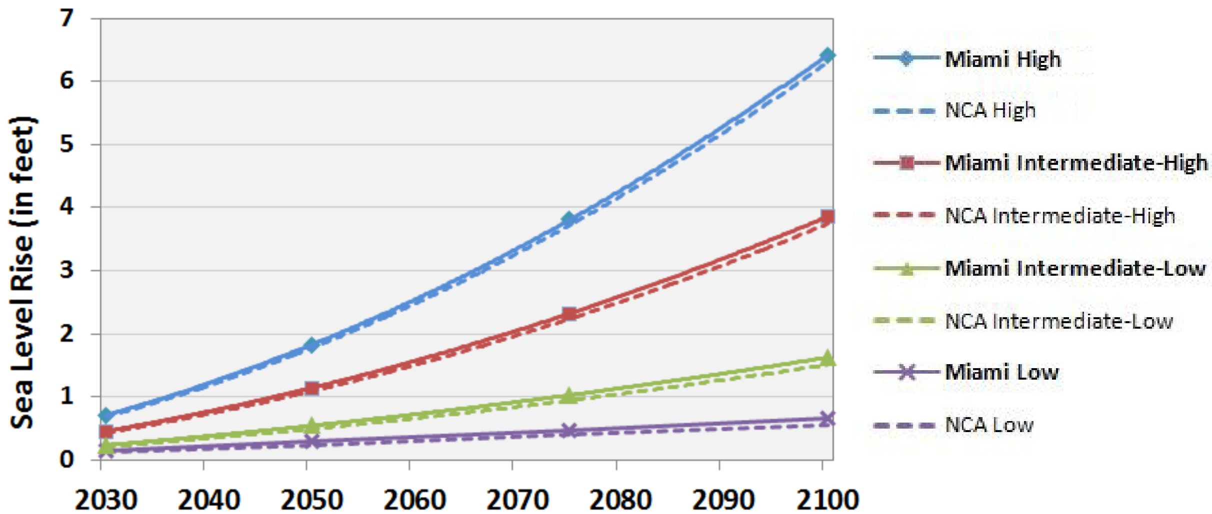
[7] Vertical land motion includes subsidence, or the sinking of land; and uplift, or the increase of land elevation. Vertical land motion can occur as a result of subsurface fluid withdrawal (fossil fuels or water), isostatic rebound from the retreat of glaciers, ground faulting (i.e., earthquake response), and other factors.

[8] NOAA, National Ocean Service (2010)

[9] The scenarios are explained in Parris et al. (2012).

adjustments from the baseline NCA global scenarios are minimal. (In the example graph below, the dotted lines are the projected NCA global scenarios of SLR and the solid lines are the adjusted relative SLR for Miami for each NCA scenario.) Especially relevant to this study are the years in which specific increments of sea level rise (e.g., 1 foot, 2 feet) occur, since that information is necessary for informing SLR risk relative to infrastructure planning timeframes.

Exhibit 2-2. Miami SLR Projections, based on NCA Global SLR Scenarios



As can be seen from the exhibit above, there is considerable uncertainty in the NCA about the rate of global sea level rise through the end of the current century. The greatest source of uncertainty is attributable to a lack of scientific understanding of how large ice sheets (primarily in Greenland and West Antarctica) will respond as warming proceeds. The broad range of the NCA's projections encompass a wide array of recent estimates of potential global SLR through 2100, and have therefore been selected for this study to help bound the extent of anticipated risk from SLR due to changes in global sea level.[10]

Historical change in relative sea level varies along U.S. coasts. However, most regions in the lower 48 states are experiencing change in relative sea level equal to or greater than the global average, meaning that relative sea levels are increasing in those places. Specifically, rates that are higher than the global average are seen on the mid-Atlantic and Gulf coasts primarily due to subsidence. Portions of Texas, Louisiana, and the mid-Atlantic, for example, have seen relative sea level increases in excess of 8 inches since 1960.[11] Rates lower than the global average are seen in some parts of the Pacific Northwest and most of Alaska. Relative SLR is anticipated to increase in coastal states after 2050, driven by predicted increases in the rate of global SLR.

[10] For example, a study by the National Resource Council (NRC) includes global SLR scenarios of 40, 48, and 56 inches by 2100 under three different GHG emissions scenarios (see NRC (2010)).

[11] NOAA, National Ocean Service. 2013 update to data originally published in: NOAA. 2001. Sea level variations of the United States 1854–1999.

Increases in relative sea levels threaten the nation's coastal energy infrastructure, both through direct inundation and in combination with storm surge. First, higher sea levels may inundate some energy assets wholly or partially, or may envelop the surrounding areas rendering some assets inaccessible. Second, higher sea levels will make assets more susceptible to inland surge during tropical and extra-tropical storms.

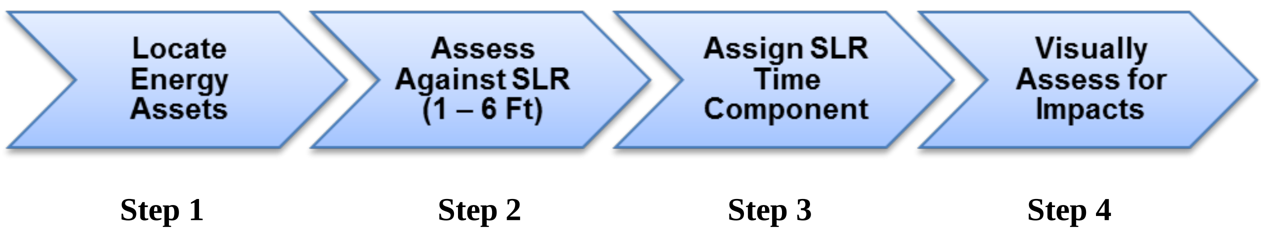
The approach used in this study to estimate the potential effects of SLR on energy assets is described in the next section. The focus of this study is on SLR; and although a baseline assessment of storm surge risk was conducted for each MSA, the study does not attempt to quantify the compound effect of storm surge and higher sea levels for the MSAs assessed.[12]

[12] Appendix B summarizes several other illustrative studies of SLR. Some of these, including the Mobile, Alabama and North Carolina studies, include the effects of storm surge at specific coastal locations.

3. Approach Overview and Data

The approach used for this study included four steps, illustrated in Exhibit 3-1 below. The study aimed to use information and data from authoritative federal government sources. The use of publically available data provides a higher level of transparency in the results and helps ensure that the assessments can be scaled to all of the United States, as well as repeated over time as the underlying climate science evolves. The results of the study can also be replicated by local and state organizations using data accessible to them.

Exhibit 3-1. Study Approach in Four Steps



3.1. Step 1: Locate Energy Assets

The study used various public and subscription sources to provide location data for energy assets within each of the pilot MSAs. In some cases, GIS data and maps had been previously developed for OE. Exhibit 3-2 below lists the types of energy assets that were included in the analysis, as well as asset types that were excluded. For many energy assets, there is no comprehensive public source for information.

For each MSA, a list of all relevant energy assets was compiled, along with coordinate location information and descriptive attributes (e.g. capacity, ownership).

Exhibit 3-2. Energy Assets Included in the Study

Sector	Assessed	Not Assessed
Electricity	• Power Plants • Substations	• Transmission and Distribution Lines • Control Systems
Natural Gas	• Processing Plants • LNG Facilities • Storage • Pipelines	• Wells & Associated Equipment and Infrastructure • Control Systems • Distribution Systems
Petroleum	• Refineries • Terminals • Strategic Reserves • Pipelines	• Wells & Associated Equipment and Infrastructure • Ethanol and Biofuel Refineries • Rail Lines, Cars, and Facilities • Control Systems

3.2. Step 2: Assess Against SLR Increments

Next, the study incorporated SLR estimates from the NOAA CSC to assess how different increments of SLR are projected to affect each MSA's coastal areas, such as how far inland the coastline may extend and what depth of inundation may be experienced at each location. NOAA's SLR data set was critical to this analysis because it enabled identification of the energy assets that may be inundated at different increments of local SLR. NOAA's method is briefly summarized below.

- NOAA models the present-day tidal surface at each point along the U.S. coast. This is done using the higher of high tides (referred to as Mean Higher High Water or MHHW[13]), with interpolated data from individual tide gauges.
- Using GIS tools, NOAA increases the present-day MHHW tidal surface with SLR. The increases are shown from 1 to 6 feet, in one foot increments.
- NOAA extends the increased tidal surface inland over a detailed topography model, until it is constrained by land. Elevation data for inland regions is obtained from the U.S. Geological Survey (USGS).

NOAA's analysis takes hydrologic connectivity into account, that is, connectivity between the tidal surface and inland regions that are at or below the elevation of the modeled tidal surface. As a result, the model allows for an elevated tidal surface to flow inland to areas of lower elevation, but prevents disconnected areas of lower elevation to fill with water unless there is a suitable flow path.[14]

The processed data sets are released publically by NOAA, and were obtained in GIS data format for use in this study. An example of how the data were used is shown in Exhibit 3-3 below. The figure on the left shows the location of the Arch Street substation in Miami, which was mapped in step one. NOAA's SLR data enables the present-day highest high tide, or MHHW, to be mapped (shown in blue) in relation to the substation. In the figure on the right, a 5 foot SLR increase above present-day MHHW is shown in purple (areas of deeper inundation symbolized in darker purple). In this example, the substation is not inundated by 5 feet of SLR, but is located within several blocks of the new coastline that would result from 5 feet of SLR.

For each MSA, all assets were analyzed at each one foot increment of SLR, between 1 foot and 6 feet, to determine whether they would be inundated. Note that this approach does not account for the erosion that may occur as sea level rises or the prevention of inundation through construction of sea walls and other means.

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13 MHHW is "the average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch," according to the NOAA Tidal Datums website (http://tidesandcurrents.noaa.gov/datum_options.html).

14 Issues modeling hydrologic connectivity (such as the inability for a topography model to accurately reflect sub-surface drainage, small levees or dams, etc.) will reduce accuracy, which can vary based on the original method of data collection for building the topography model as well as the subsequent processing steps.

Exhibit 3-3. Mapping SLR in Miami using NOAA Data

Miami – 0 Feet of SLR (current state) | Miami – 5 Feet of SLR

3.3. Step 3: Assign SLR Time Component

The next step involved projecting the year in which the increments of SLR would occur by relating each one foot increment to a specific time period based on the NCA's global SLR scenarios, adjusted for local factors based on historical trends (as depicted for the Miami MSA in Exhibit 2-2).

This step involved two activities. First, the NCA's global SLR scenarios were refined to account for relative sea level effects for the individual MSAs in the study. Second, the relative SLR rates for the MSAs were related to specific timeframes, to identify risks as they pertain to infrastructure planning.

Under the first activity, historical tidal data from NOAA's tide gauge network were used to establish a regional trend that reflects localized factors such as subsidence, ocean currents, salinity, and temperatures. Historical trends were assessed for each of the relevant coastal counties in the pilot MSAs, using data from the nearest tide gauge. These trends were then incorporated into the NCA's four scenarios for future global SLR, to generate the required relative SLR rates for each county in each MSA.[15]

Under the second activity, NOAA's GIS data of SLR (depicting SLR of 1 foot to 6 feet in one foot increments) were associated with the timeframes of the locally adjusted NCA scenarios. This exercise provided a projected year for each one foot increment of SLR under each scenario for each location.

[15] In some cases, there are multiple tide gauges across an MSA that have recorded different rates of SLR, depending on their location. These different rates of historical SLR are reflected in the projections. For example, in Harris County, Houston, 1 foot of SLR is projected by approximately 2036 under the NCA Intermediate-High Scenario, while for Brazoria County, 1 foot of SLR is projected by approximately 2040. The timeframe established in the study for 1 foot of SLR for Houston under the Intermediate-High Scenario is approximately 2036 to 2040.

An example is shown for Miami in Exhibit 3-4 below. It depicts projected SLR through 2100 under each of the four NCA scenarios: High (blue), Intermediate-High (red), Intermediate-Low (green), and Low (purple). The arrows indicate when 3 feet of SLR is projected to occur under the two higher NCA scenarios. Under the High Scenario (after accounting for local trends in relative SLR), Miami would experience SLR of 3 feet in approximately 2066; under the Intermediate-High Scenario it would experience SLR of 3 feet in approximately 2087, 21 years later. The approach outlined in this report can be repeated as the climate change science evolves and the global SLR scenarios are updated.

Exhibit 3-4. SLR Projections Over Time for Miami by NCA Scenario, with Projected Dates for 3 feet of SLR Highlighted

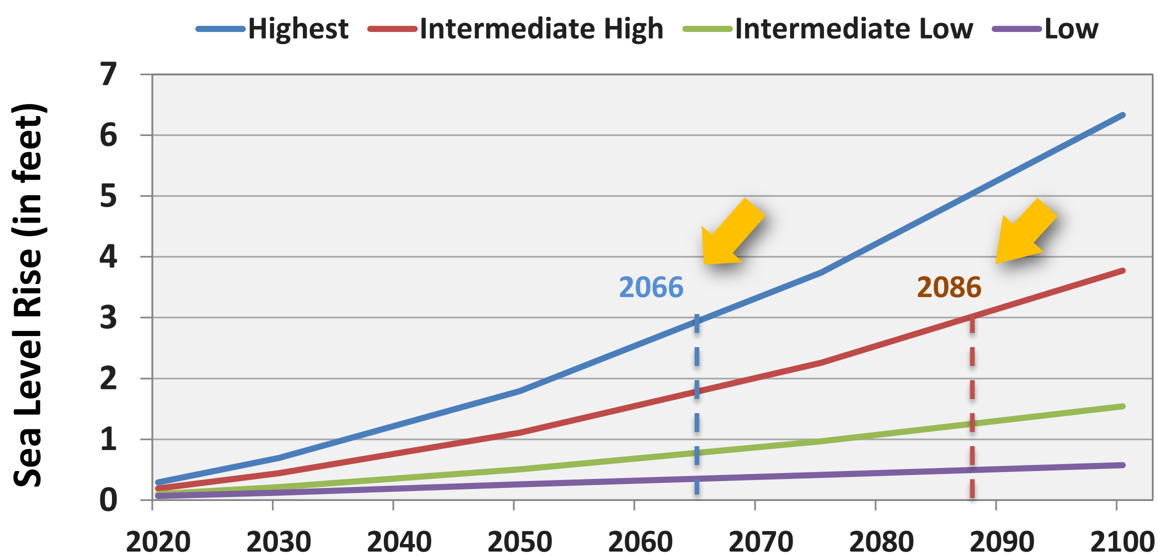


Exhibit 3-5 below shows a table of years corresponding to each 1 foot SLR increment, for each NCA scenario, for the counties in the Miami MSA. A comparable table was generated for each MSA and is presented in Section 4. The tables have been color-coded to draw attention to the important time frames: red cells highlight SLR increments (at least 1 foot) reached before or around 2050; yellow cells highlight measurable SLR increments (at least 1 foot) reached between 2050 and 2100.

Exhibit 3-5. Years Corresponding to SLR Increments in Miami MSA under Four NCA Scenarios

	NCA Low Scenario						NCA Intermediate-Low Scenario					
County	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
Broward	2146	2282	2418	2554	2690	2826	2073	2113	2145	2172	2197	2219
Miami-Dade	2146	2282	2418	2554	2690	2826	2073	2113	2145	2172	2197	2219
Palm Beach	2146	2282	2418	2554	2690	2826	2073	2113	2145	2172	2197	2219
	NCA Intermediate-High Scenario						NCA High Scenario					
	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
Broward	2046	2068	2086	2102	2115	2127	2035	2052	2065	2077	2087	2096
Miami-Dade	2046	2068	2086	2102	2115	2127	2035	2052	2065	2077	2087	2096
Palm Beach	2046	2068	2086	2102	2115	2127	2035	2052	2065	2077	2087	2096

3.4. Step 4: Visually Assess for Impacts

The analysis described above uses data sets, GIS, and modeled outputs. By combining these large quantities of data, the analysis can evaluate the effects of SLR over time for large areas, relative to energy assets. The final step was to perform a visual assessment of the assets to ensure that the results make sense and to identify other factors that warrant consideration. The visual assessment did identify a result that the "automated" approach did not capture; some assets were identified as being not inundated, but surrounded by water under some SLR increments. The analysis of facilities therefore makes a distinction between inundated facilities (some portion under water) and operationally affected facilities (not under water but surrounded by water).

3.5. Caveats

While this study has several technical limitations that affect its usefulness for measuring asset-specific risk from SLR, the approach used provides a comparative assessment of high-level infrastructure risk in different U.S. coastal regions and metropolitan areas, based on the best currently available data. Its value lies in helping to focus subsequent, more-detailed assessments on particular geographic areas and on particular types of highly-vulnerable energy sub-sectors or asset-types.

An overview of some technical limitations is provided below.

Useful Life of Energy Assets – The SLR study extends beyond the economic life of most of the energy assets shown to be affected. Many of these assets could be retired within the next 25 to 30 years. The analysis does identify, however, the potential risk areas for the location of replacement assets.

Asset Hardening – The data do not indicate whether utility or facility operators have undertaken projects to reduce exposure to higher sea levels. In some areas, asset owners have been making efforts to minimize exposure to high water—by the construction of berms, for example. However, information on the types of hardening or resilience measures taken by asset owners and operators is not accounted for in the study.

Asset Interdependencies – The study does not identify interdependencies among energy assets, such as for example, the effect of a substation outage on another energy asset.

Data Limitations – The study relies on data regarding energy assets drawn from numerous sources.[16] The scope of this study included thousands of assets, including many small assets. Sometimes these data are incomplete or assets are not accurately located.

Modeling Limitations – Modeling limitations can be divided into two groups. First, as mentioned above, modeling future changes to global sea levels and the interactive effects with relative sea levels are highly uncertain. Second, the ability to model sea level rise in a GIS setting has inherent challenges, and is limited by the accuracy of interpolation of intermediate data, for example, high-resolution elevation and present-day tidal surfaces.

Future Policy – The results, as presented, assess exposure of present-day energy infrastructure over the next 85 years to SLR. Future changes to energy infrastructure—through modifications such as asset hardening and new construction, among others—are not accounted for in this study.

[16] Asset data used was identical to those used in OE Criticality Studies. Data sources included the following: For electric assets: Homeland Security Infrastructure Protection (HSIP) 2011, FERC 2011 Commission Form 715, and Ventyx. For natural gas assets: EIA-176 data through 2010, HSIP 2011, company websites and communications. For petroleum assets: EIA Prime Supplier Sales Volumes, DOI Bureau of Safety and Environmental Enforcement, Louisiana DNR, 2012 OPIS/Stelsby Petroleum Terminal Encyclopedia, Louisiana Department of Environmental Quality, HSIP 2012, and company websites and communications.

4. Results for the Four Pilot MSAs

This section provides an overview of the pilot study findings for the four MSAs. The presentation of MSA-specific results focuses on large[17] energy assets inundated by the years 2050 and 2100, under the NCA **Intermediate-High Scenario**, though all energy assets in each MSA were assessed under the 1-foot SLR increments. The Intermediate-High Scenario (corresponding to 4 feet of global SLR by approximately 2100) was selected because it has been highlighted in the NCA, and because it corresponds to the upper global SLR scenario from the most recent Intergovernmental Panel on Climate Change (IPCC) report.[18] This study's full analysis allows for an assessment of inundation under all four NCA scenarios, but the Intermediate-High Scenario was chosen for presentation as a reasonable outlook for risk-averse planning.

Exhibit 4-1 below shows the count of energy assets projected to be inundated in each MSA, under the four NCA scenarios, by approximately 2050 and approximately 2100.[19] The table includes counts for **all assets** that are inundated, whereas the presentation of individual MSA results shown in the maps below focuses only on large capacity assets. The MSA with the most assets inundated under the NCA Intermediate-High Scenario is New York City, with 72 out of 1,447 assets inundated by 2100. Of these 72 assets, 19 are large capacity assets, as shown in Exhibit 4-5.

Exhibit 4-1. Count of Inundated Assets under Four NCA Scenarios

		NCA Low Scenario		NCA Intermediate-Low Scenario		NCA Intermediate-High Scenario		NCA High Scenario	
MSA	**Total Assets**	**Year 2050**	**Year 2100**	**Year 2050**	**Year 2100**	**Year 2050**	**Year 2100**	**Year 2050**	**Year 2100**
New York City	1,447	0	11	11	17	11	72	17	170
Houston	1,363	0	16	0	23	16	54	16	67
Miami	217	0	0	0	1	0	9	1	49
Los Angeles	1,099	0	0	0	10	10	19	11	29

Exhibit 4-2 below shows the percentage of energy assets projected to be inundated in each MSA, under the four NCA scenarios, by approximately 2050 and approximately 2100. For each

17 Large energy assets are defined as follows: Power plants with generation capacity of 100 MW or greater; substations of 230 kV or greater; petroleum terminals with total product storage of 100,000 bbl or greater. Other asset types, such as LNG terminals and refineries, did not have a capacity threshold and are presented in the results regardless of size.

18 IPCC (2013)

19 Count of inundated assets are tied to 1 foot SLR increments, and so are not based on exact SLR projections for 2050 and 2100. For a listing of the exact years used to approximate 2050 and 2100 impacts, see the individual tables in the MSA subsections below.

MSA, percentage calculations are based on the number of inundated assets in that MSA divided by the total number of assets in that MSA which were included in the study.

Exhibit 4-2. Percent of Inundated Assets under Four NCA Scenarios

		NCA Low Scenario		NCA Intermediate-Low Scenario		NCA Intermediate-High Scenario		NCA High Scenario	
MSA	Total Assets	Year 2050	Year 2100	Year 2050	Year 2100	Year 2050	Year 2100	Year 2050	Year 2100
New York City	1,447	0%	1%	1%	1%	1%	5%	1%	12%
Houston	1,363	0%	1%	0%	2%	1%	4%	1%	5%
Miami	217	0%	0%	0%	0%	0%	4%	0%	23%
Los Angeles	1,099	0%	0%	0%	1%	1%	2%	1%	3%

In addition, the Gulf and southern Atlantic coasts are prone to experiencing hurricanes, while the mid- and northern Atlantic coasts are subject to nor'easters. Storm surge from hurricanes and nor'easters will be exacerbated by SLR.

4.1. New York City MSA

The New York City MSA is large, covering 20 relevant coastal counties in New York and New Jersey. The relevant coastal counties in the MSA are listed in Exhibit 4-3 below (inland counties not affected by SLR are excluded from the table). This exhibit shows the year that each level of SLR would occur in each county in the MSA under each of the NCA scenarios.

Exhibit 4-3. Years Corresponding to SLR Increments in New York MSA under Four NCA Scenarios

	NCA Low Scenario						NCA Intermediate-Low Scenario					
County	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
New York												
Bronx	2148	2287	2425	2563	2702	2841	2074	2114	2146	2173	2197	2219
Dutchess	2136	2263	2389	2515	2642	2768	2072	2111	2143	2170	2194	2216
Kings	2126	2243	2358	2475	2591	2707	2070	2109	2140	2167	2191	2213
Nassau	2148	2287	2425	2563	2702	2841	2074	2114	2146	2173	2197	2219
New York	2126	2243	2358	2475	2591	2707	2070	2109	2140	2167	2191	2213
Orange	2126	2243	2358	2475	2591	2707	2070	2109	2140	2167	2191	2213
Putnam	2136	2263	2389	2515	2642	2768	2072	2111	2143	2170	2194	2216
Queens	2148	2287	2425	2563	2702	2841	2074	2114	2146	2173	2197	2219
Richmond	2126	2243	2358	2475	2591	2707	2070	2109	2140	2167	2191	2213
Rockland	2148	2287	2425	2563	2702	2841	2074	2114	2146	2173	2197	2219
Suffolk	2143	2276	2409	2542	2675	2808	2073	2113	2144	2172	2196	2218
Westchester	2148	2287	2425	2563	2702	2841	2074	2114	2146	2173	2197	2219
New Jersey												
Bergen	2126	2243	2358	2475	2591	2707	2070	2109	2140	2167	2191	2213
Essex	2126	2243	2358	2475	2591	2707	2070	2109	2140	2167	2191	2213
Hudson	2126	2243	2358	2475	2591	2707	2070	2109	2140	2167	2191	2213
Middlesex	2091.2	2172	2254	2335	2416	2497	2061	2097	2127	2153	2177	2198
Monmouth	2091.2	2172	2254	2335	2416	2497	2061	2097	2127	2153	2177	2198
Somerset	2126	2243	2358	2475	2591	2707	2070	2109	2140	2167	2191	2213
Ocean	2089.3	2169	2248	2327	2407	2486	2060	2096	2126	2152	2176	2197
Union	2126	2243	2358	2475	2591	2707	2070	2109	2140	2167	2191	2213

	NCA Intermediate-High Scenario						NCA High Scenario					
	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
New York												
Bronx	2046	2069	2086	2102	2115	2128	2036	2052	2065	2077	2087	2096
Dutchess	2045	2068	2086	2101	2114	2127	2035	2052	2065	2076	2086	2095
Kings	2045	2067	2085	2100	2113	2126	2035	2051	2064	2076	2086	2095
Nassau	2046	2069	2086	2102	2115	2128	2036	2052	2065	2077	2087	2096
New York	2045	2067	2085	2100	2113	2126	2035	2051	2064	2076	2086	2095
Orange	2045	2067	2085	2100	2113	2126	2035	2051	2064	2076	2086	2095
Putnam	2045	2068	2086	2101	2114	2127	2035	2052	2065	2076	2086	2095
Queens	2046	2069	2086	2102	2115	2128	2036	2052	2065	2077	2087	2096
Richmond	2045	2067	2085	2100	2113	2126	2035	2051	2064	2076	2086	2095
Rockland	2046	2069	2086	2102	2115	2128	2036	2052	2065	2077	2087	2096
Suffolk	2046	2068	2086	2101	2115	2127	2035	2052	2065	2076	2087	2096
Westchester	2046	2069	2086	2102	2115	2128	2036	2052	2065	2077	2087	2096
New Jersey												
Bergen	2045	2067	2085	2100	2113	2126	2035	2051	2064	2076	2086	2095
Essex	2045	2067	2085	2100	2113	2126	2035	2051	2064	2076	2086	2095
Hudson	2045	2067	2085	2100	2113	2126	2035	2051	2064	2076	2086	2095
Middlesex	2042	2063	2080	2095	2109	2121	2033	2049	2062	2073	2083	2092
Monmouth	2042	2063	2080	2095	2109	2121	2033	2049	2062	2073	2083	2092
Somerset	2045	2067	2085	2100	2113	2126	2035	2051	2064	2076	2086	2095
Ocean	2041	2063	2080	2095	2108	2120	2033	2049	2062	2073	2083	2092
Union	2045	2067	2085	2100	2113	2126	2035	2051	2064	2076	2086	2095

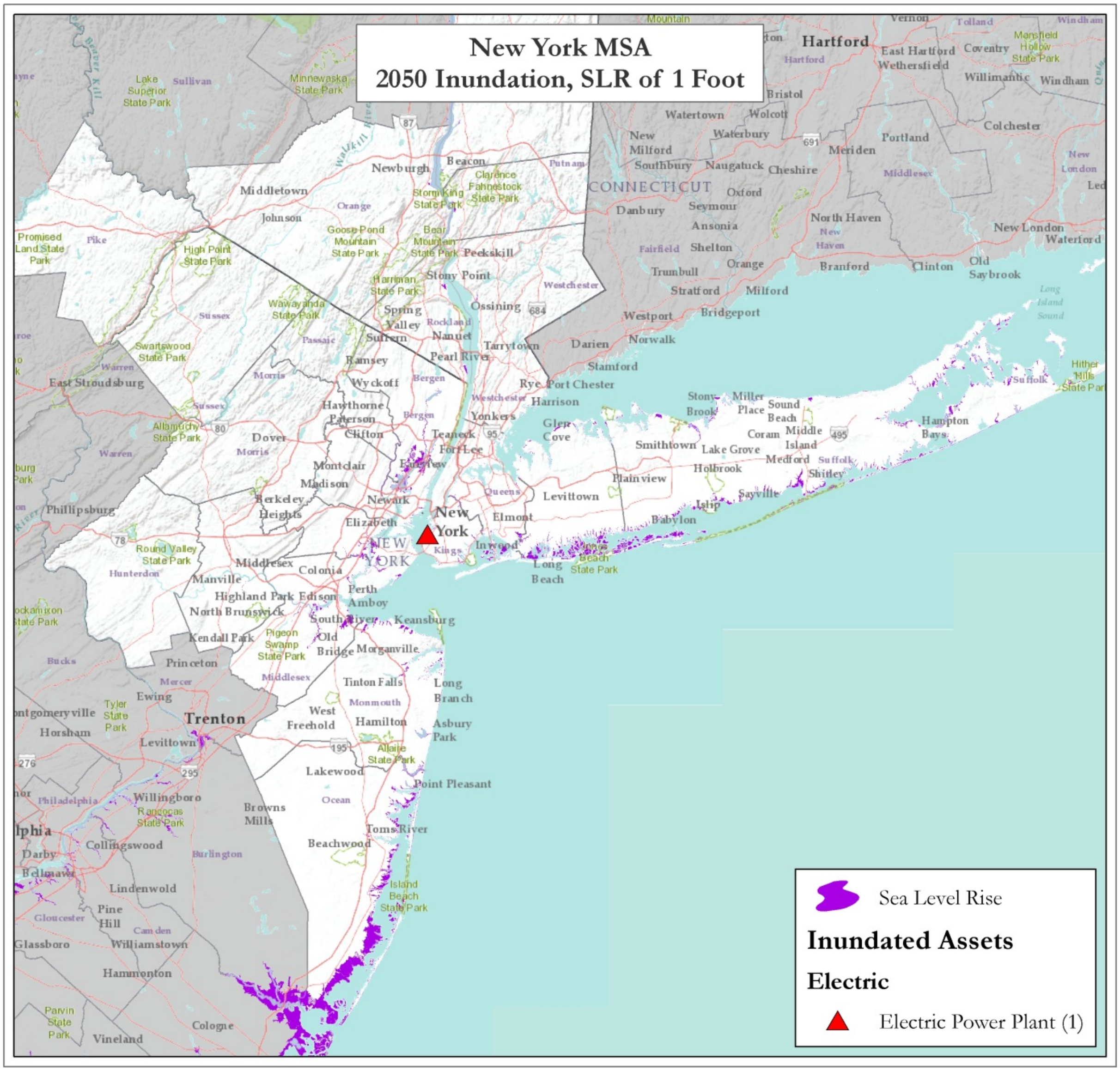
The New York City region has experienced SLR of approximately 8 inches from 1960 to 2012.[20]

Under the two lower NCA scenarios, SLR of 1 foot would not occur until after 2050. In three New Jersey counties, SLR of 2 feet would occur by approximately 2100 under the Intermediate-Low Scenario. Under the Intermediate-High Scenario, there would be at least 1 foot of SLR in all of the MSA counties by 2050, as highlighted in the column colored red. After 2050 and by approximately 2100, up to 4 feet of SLR would occur in all of the counties of the MSA. Only under the NCA High Scenario does 2 feet of SLR occur by approximately 2050. Under the NCA High Scenario, 6 feet of SLR is projected to occur for all counties by 2100.

Exhibit 4-4 below shows the extent of inundation under the NCA Intermediate-High Scenario of 1 foot SLR (by approximately 2050). **This and all subsequent maps show the large assets projected to be inundated. Large assets include power plants of 100 MW capacity or greater, substations of 230kV or greater, and terminals with 100,000 barrels capacity or greater, refineries of any size and LNG terminals.**

[20] NOAA (2009)

Exhibit 4-4. Areas and Large Energy Assets in New York MSA Inundated by SLR by Approximately 2050 under the NCA Intermediate-High Scenario (1 foot SLR)



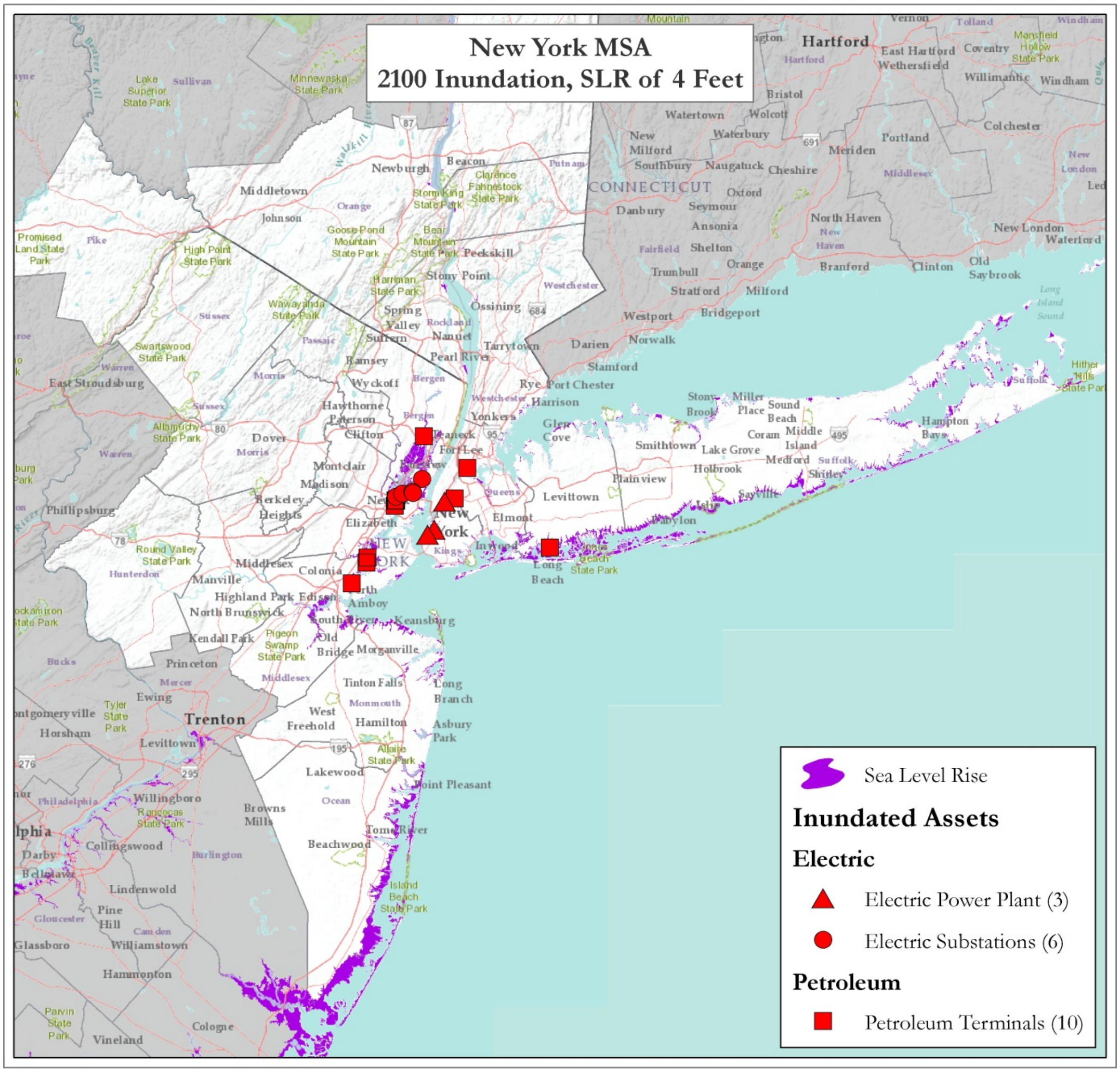
Under the NCA's Intermediate-High Scenario, one of the MSA's large electric generation assets is projected to be inundated by approximately 2050. Based on a visual assessment, a number of other electric and petroleum assets may be operationally affected by SLR[21] by approximately 2050.

Exhibit 4-5 below shows the areas and large assets that would be inundated by approximately 2100. In the NCA's Intermediate-High Scenario, a number of the region's electric generation and substation assets, including three power plants and six electric substations, are projected

[21] Surrounded by water and isolated, but not inundated.

to be inundated by approximately 2100. In addition, this analysis indicates that 10 petroleum terminals are projected to be inundated by approximately 2100. Minimal impacts to natural gas facilities and pipelines are expected, with some inundation of major interstate pipeline rights-of-way in northern New Jersey.

Exhibit 4-5. Areas and Large Energy Assets in New York MSA Inundated by SLR by Approximately 2100 under the NCA Intermediate-High Scenario (4 feet SLR)



The New York MSA is an asset-rich environment vulnerable to SLR because of its topography, location, and concentration of power generation facilities, substations, and petroleum terminals. The MSA, particularly New York City, has a number of assets in low lying areas that are susceptible to inundation from SLR.

4.2. Miami MSA

The Miami MSA consists of three counties, Broward, Miami-Dade, and Palm Beach. Between 1960 and 2012, Miami has experienced SLR of approximately 4 to 6 inches.[22] The projections for future SLR based on the NCA's scenarios are shown in Exhibit 4-6 below.

Exhibit 4-6. Years Corresponding to SLR Increments in Miami MSA under Four NCA Scenarios

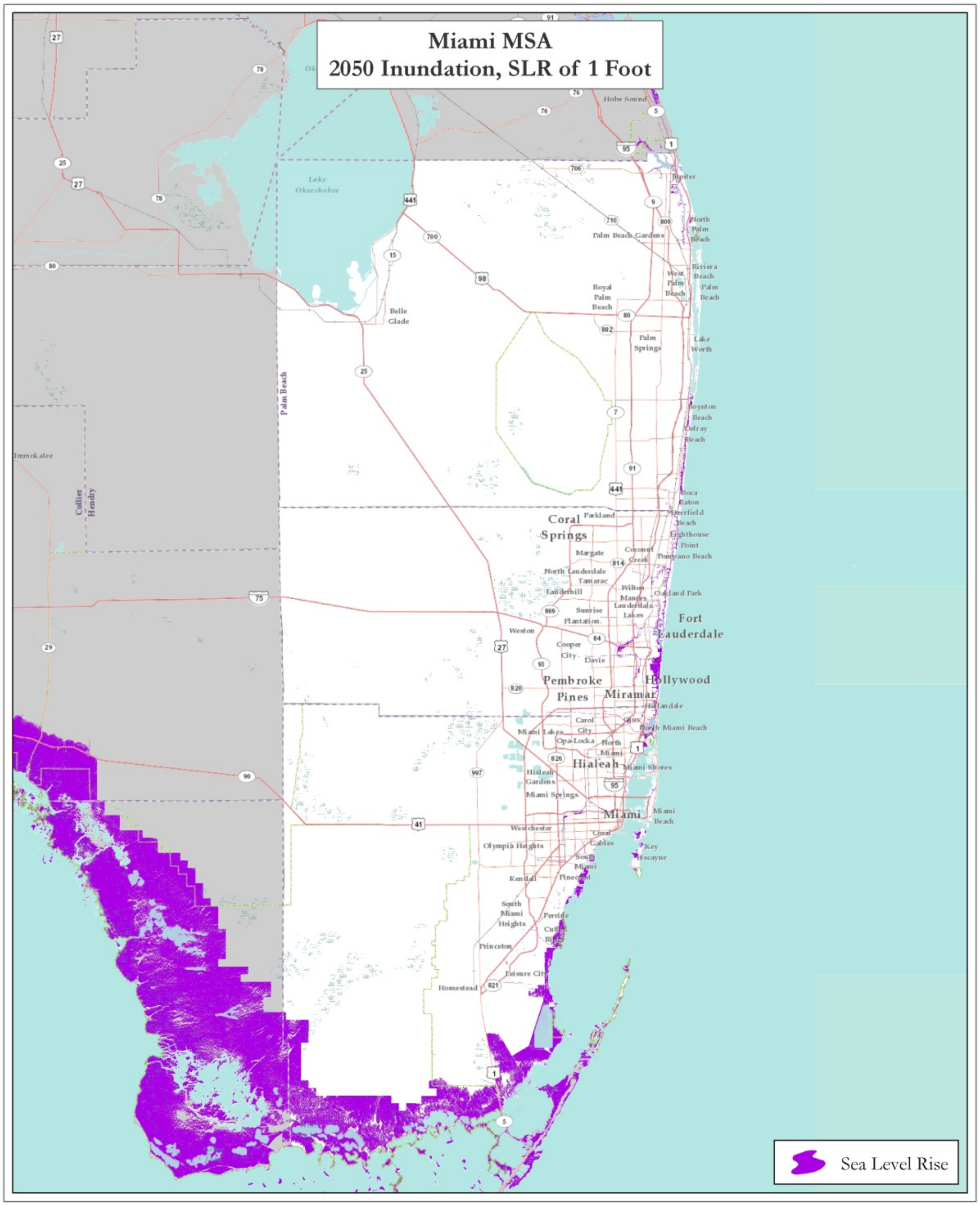
	NCA Low Scenario						NCA Intermediate-Low Scenario					
County	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
Broward	2146	2282	2418	2554	2690	2826	2073	2113	2145	2172	2197	2219
Miami-Dade	2146	2282	2418	2554	2690	2826	2073	2113	2145	2172	2197	2219
Palm Beach	2146	2282	2418	2554	2690	2826	2073	2113	2145	2172	2197	2219
	NCA Intermediate-High Scenario						NCA High Scenario					
	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
Broward	2046	2068	2086	2102	2115	2127	2035	2052	2065	2077	2087	2096
Miami-Dade	2046	2068	2086	2102	2115	2127	2035	2052	2065	2077	2087	2096
Palm Beach	2046	2068	2086	2102	2115	2127	2035	2052	2065	2077	2087	2096

Under the two lower NCA scenarios, there would be no or very little SLR before approximately 2073. Under the Intermediate-Low Scenario, 1 foot of SLR would occur in approximately 2073. Under the NCA Intermediate-High Scenario, 1 foot of SLR is projected by approximately 2050 and 4 feet of SLR is projected by approximately 2100. Under the NCA High Scenario, 2 feet of SLR is projected by approximately 2050, with up to 6 feet by approximately 2100. The NCA High Scenario is the only scenario that projects greater than 4 feet of SLR by 2100 in the Miami MSA.

[22] NOAA (2009)

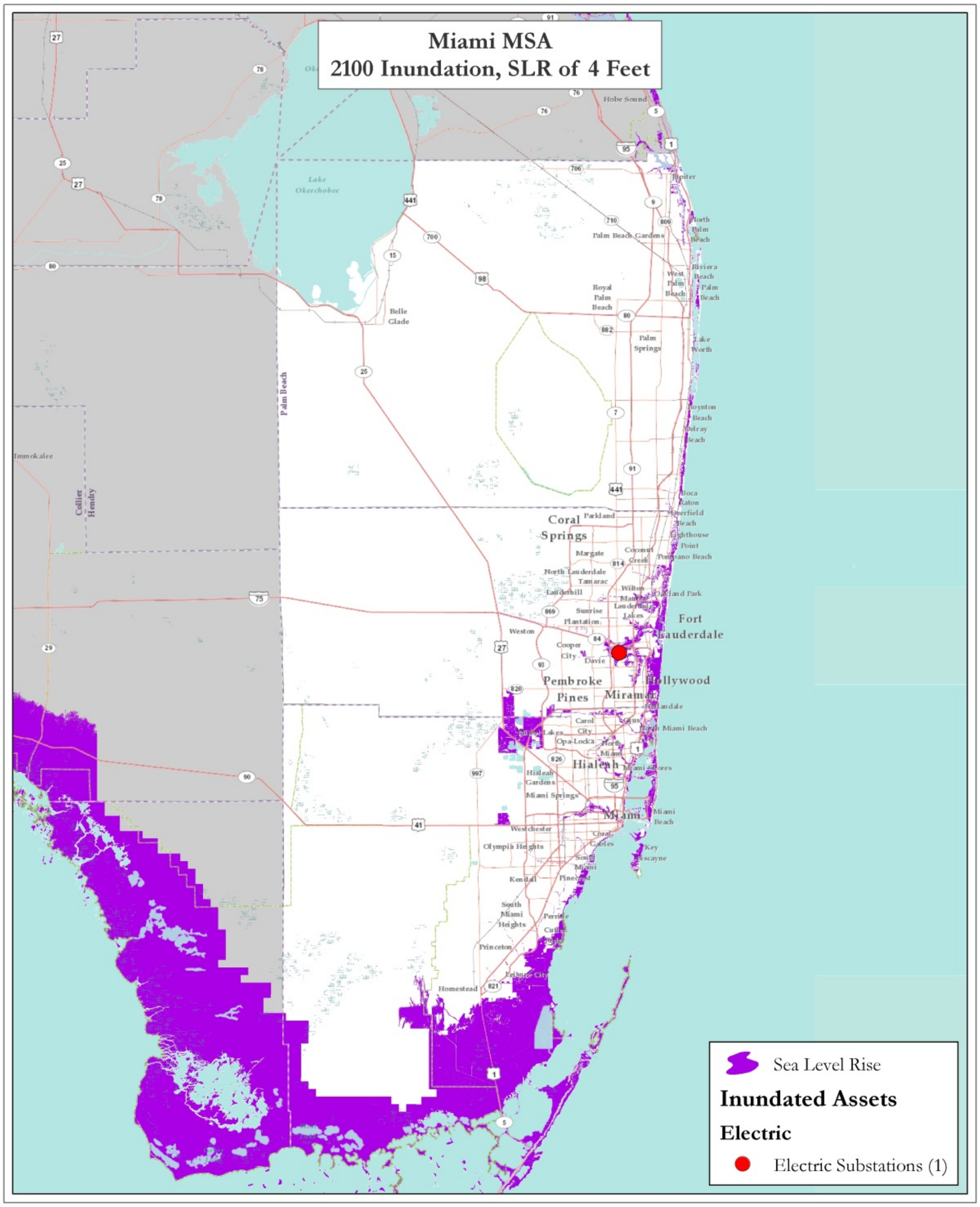
Exhibit 4-7 below shows the extent of inundation under the NCA Intermediate-High Scenario of 1 foot of SLR (expected to occur by approximately 2050). No large capacity assets are projected to be inundated by this level of SLR in Miami.

Exhibit 4-7. Areas and Large Energy Assets in Miami MSA Inundated by SLR by Approximately 2050 under the NCA Intermediate-High Scenario (1 foot SLR)



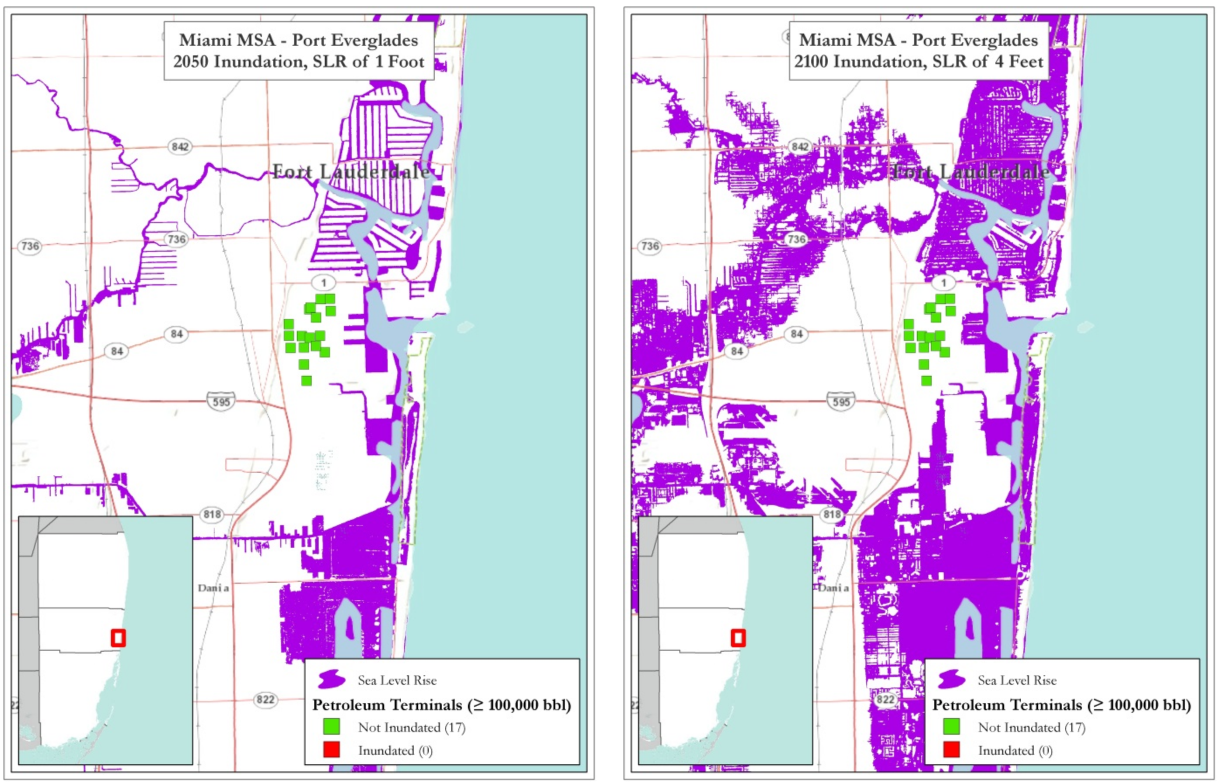
The number of inundated Miami assets is low under the Intermediate-High Scenario. By approximately 2050, no large capacity assets would be inundated and by 2100—when SLR would reach 4 feet under this scenario—only one large (230 kV) substation would be inundated. It appears that many coastal assets are already elevated to protect against hurricane-related storm surge. Exhibit 4-8 below shows the inundated areas and inundated assets in approximately 2100.

Exhibit 4-8. Areas in Miami MSA Inundated by SLR by Approximately 2100 under the NCA Intermediate-High Scenario (4 feet SLR)



A visual assessment of the inundated areas identified some assets that would be likely affected by SLR, even though many of them would not be inundated. One example is a large power plant in southern Miami-Dade County where the facility would be closely surrounded by water, but the facility itself would remain above water. A second area of interest is the Port Everglades marine petroleum terminals. The potential impact of SLR on these terminals is shown in Exhibit 4-9 below. By approximately 2050, the docking areas supporting the terminals would be inundated. By approximately 2100, while the terminal tankage would not be inundated, the surrounding inundation would effectively isolate the terminal complex and inundate the receiving docks.

Exhibit 4-9. Port Everglades Petroleum Terminals Inundated by SLR by Approximately 2050 (1 foot SLR, left) and Approximately 2100 (4 feet SLR, right) under the NCA Intermediate-High Scenario



In summary, the Miami MSA is not projected to experience the same inundation of assets as the other pilot MSAs under the NCA Intermediate-High Scenario, despite the fact that a substantial amount of the MSA is projected to be inundated by 2100. The fact that so few assets are located in low-lying areas seems to indicate a degree of asset protection in the face of periodic tropical storms in the region. Miami assets would become more vulnerable to storm surge in the future with higher sea levels.

4.3. Houston MSA

The Houston MSA consists of the counties of Brazoria, Galveston, Chambers, and Harris, and is a major center for the U.S. oil and gas industry. The counties in the MSA surround a major body of water, Galveston Bay and the Houston Ship Channel, where a major petrochemical industrial complex is located. The Houston region has experienced SLR greater than 8 inches from 1960 to 2012.[23] SLR projections for the Houston area are shown in Exhibit 4-10 below.

Exhibit 4-10. Years Corresponding to SLR Increments in Houston MSA under Four NCA Scenarios

	NCA Low Scenario						NCA Intermediate-Low Scenario					
County	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
Brazoria	2083	2155	2227	2300	2373	2445	2058	2093	2123	2148	2171	2193
Chambers	2059	2108	2156	2205	2254	2303	2047	2078	2104	2128	2150	2170
Galveston	2059	2108	2156	2205	2254	2303	2047	2078	2104	2128	2150	2170
Harris	2059	2108	2156	2205	2254	2303	2047	2078	2104	2128	2150	2170
	NCA Intermediate-High Scenario						NCA High Scenario					
	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
Brazoria	2040	2062	2079	2094	2107	2119	2033	2048	2061	2072	2082	2091
Chambers	2036	2056	2072	2086	2099	2111	2030	2045	2057	2068	2078	2087
Galveston	2036	2056	2072	2086	2099	2111	2030	2045	2057	2068	2078	2087
Harris	2036	2056	2072	2086	2099	2111	2030	2045	2057	2068	2078	2087

In addition to having higher rates of relative SLR in comparison to the other pilot study MSAs, the Houston MSA's low-relief and low elevation coastline may result in substantial encroachment of water by approximately 2050. Under the NCA Low Scenario, all of the MSA's coastal counties are projected to experience 1 foot of SLR prior to 2100. Under the Intermediate-Low Scenario, 1 foot of SLR is projected to occur prior to 2050. Under the Intermediate-High and High Scenarios, over 2 feet of SLR could affect all coastal counties in the MSA by approximately 2050.

SLR impacts in the Houston region primarily affect the natural gas and petroleum sectors, and are concentrated in two areas: Texas City and Freeport. Under the NCA Intermediate-High Scenario, inundation of assets due to SLR by approximately 2050 would be limited to an LNG terminal in Freeport (See Exhibit 4-11). A number of storage and processing facilities for natural gas and petroleum are projected to be inundated by SLR by approximately 2100 under this scenario. (See Exhibit 4-12). Inundated assets include two oil refineries, six petroleum terminals, two natural gas storage facilities, and one LNG terminal. A number of additional natural gas and petroleum assets and supporting facilities are projected to be operationally affected by approximately 2100 under the NCA Intermediate-High Scenario. Visual

[23] NOAA (2009)

assessments of the area indicated that there are many natural gas and petroleum assets that could be operationally affected by SLR.

Exhibit 4-11 below shows the areas and assets projected to be inundated by approximately 2050.

Exhibit 4-11. Areas and Large Energy Assets in Houston MSA Inundated by SLR by Approximately 2050 under the NCA Intermediate-High Scenario (2 feet SLR)

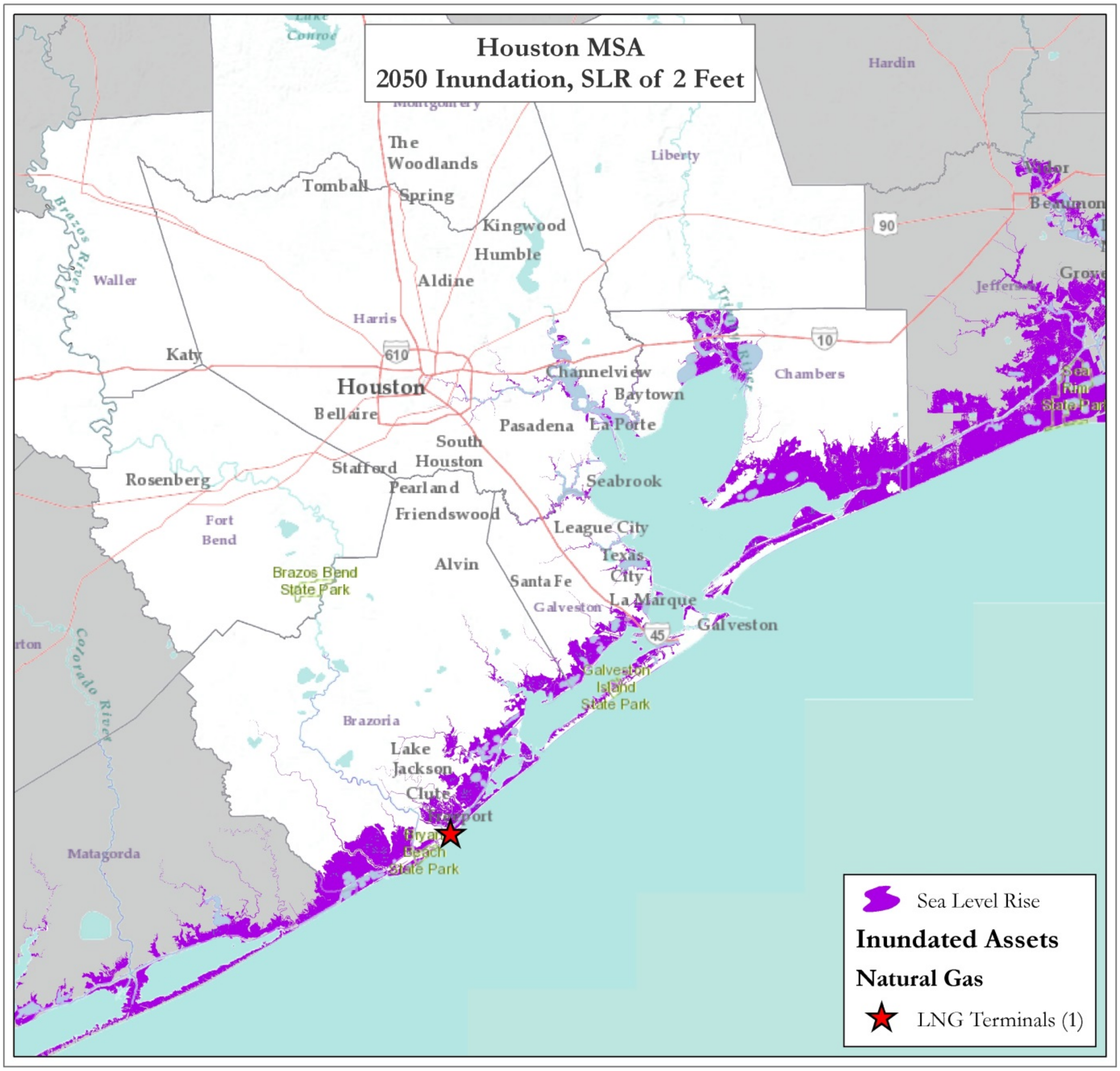
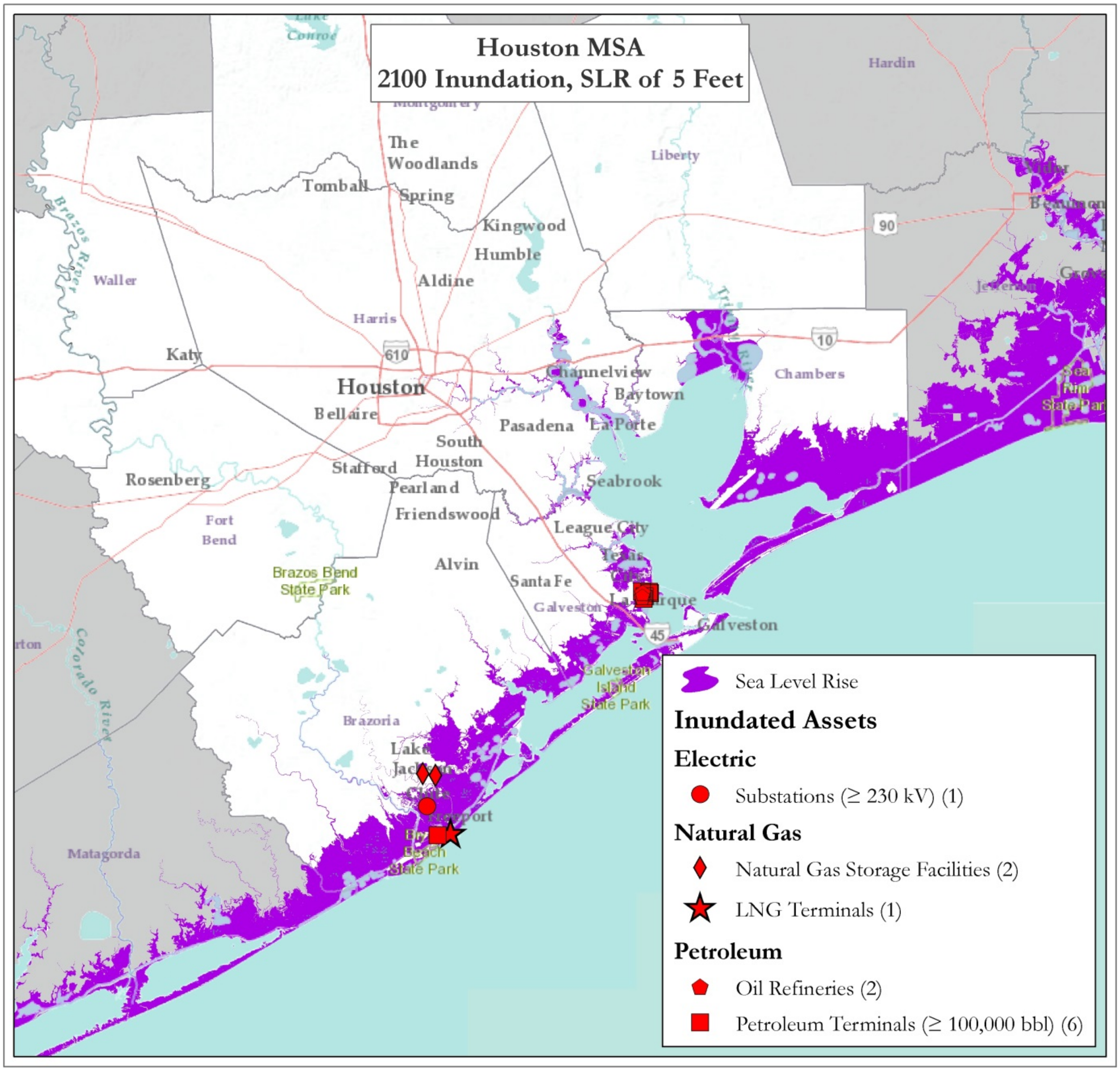


Exhibit 4-12 below shows the areas and assets projected to be inundated by approximately 2100.

Exhibit 4-12. Areas and Large Energy Assets in Houston MSA Inundated by SLR by Approximately 2100 under the Intermediate-High Scenario (5 feet SLR)



In summary, Houston has an abundance of energy assets that could be affected by SLR. It is part of a larger Gulf Coast energy complex where oil and gas, as well as major petrochemical industrial facilities, are located near the coast. In addition to SLR, storm surges exacerbated by SLR may have a significant impact on these facilities.

4.4. Los Angeles MSA

The Los Angeles MSA includes Los Angeles and Orange Counties. The Los Angeles region has experienced SLR of between 2 and 4 inches from 1960 to 2012.[24] Projected SLR in the Los Angeles MSA is shown in Exhibit 4-13 below.

Exhibit 4-13. Years Corresponding to SLR Increments in Los Angeles MSA under Four NCA Scenarios

	NCA Low Scenario						NCA Intermediate-Low Scenario					
County	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
Los Angeles	2457	2904	3350	3797	4245	4692	2091	2134	2167	2196	2220	2243
Orange	2157	2304	2451	2598	2745	2893	2075	2115	2147	2175	2199	2221
	NCA Intermediate-High Scenario						NCA High Scenario					
	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
Los Angeles	2051	2075	2093	2109	2122	2135	2038	2055	2069	2080	2091	2100
Orange	2046	2069	2087	2102	2116	2128	2036	2052	2066	2077	2087	2096

Under the two lower NCA scenarios, SLR is minimal and is projected to occur well after 2050. Under the NCA Intermediate-High Scenario, 1 foot of SLR would occur by approximately 2050 but most SLR would occur in the post-2050 timeframe. The NCA High Scenario projects 2 feet of SLR by approximately 2050.

Los Angeles has a large number of energy assets, but projected inundation from SLR is relatively low and primarily concentrated in the Long Beach area. This is partly due to the region's higher elevations just inland from the coast, which limits the extent of SLR encroachment. Under the NCA Intermediate-High Scenario, four Long Beach assets are projected to be inundated by 2050, including a power plant, two electric substations, and one petroleum terminal (see Exhibit 4-14). Under the same scenario, 12 assets are projected to be inundated by approximately 2100, including a power plant, two electric substations, an oil refinery, and numerous petroleum terminals (see Exhibit 4-15). A natural gas storage facility farther north is also projected to be inundated.

While Los Angeles is generally not exposed to storm surge from land-falling tropical storms, it is susceptible to storm surge from offshore tropical cyclones and from remnants of tropical cyclones. Storm surge is likely to be exacerbated by SLR.

[24] NOAA (2009)

Exhibit 4-14 below shows the areas and assets projected to be inundated by approximately 2050.

Exhibit 4-14. Areas and Large Energy Assets in Los Angeles MSA Inundated by SLR by Approximately 2050 under the Intermediate-High Scenario (1 foot SLR)

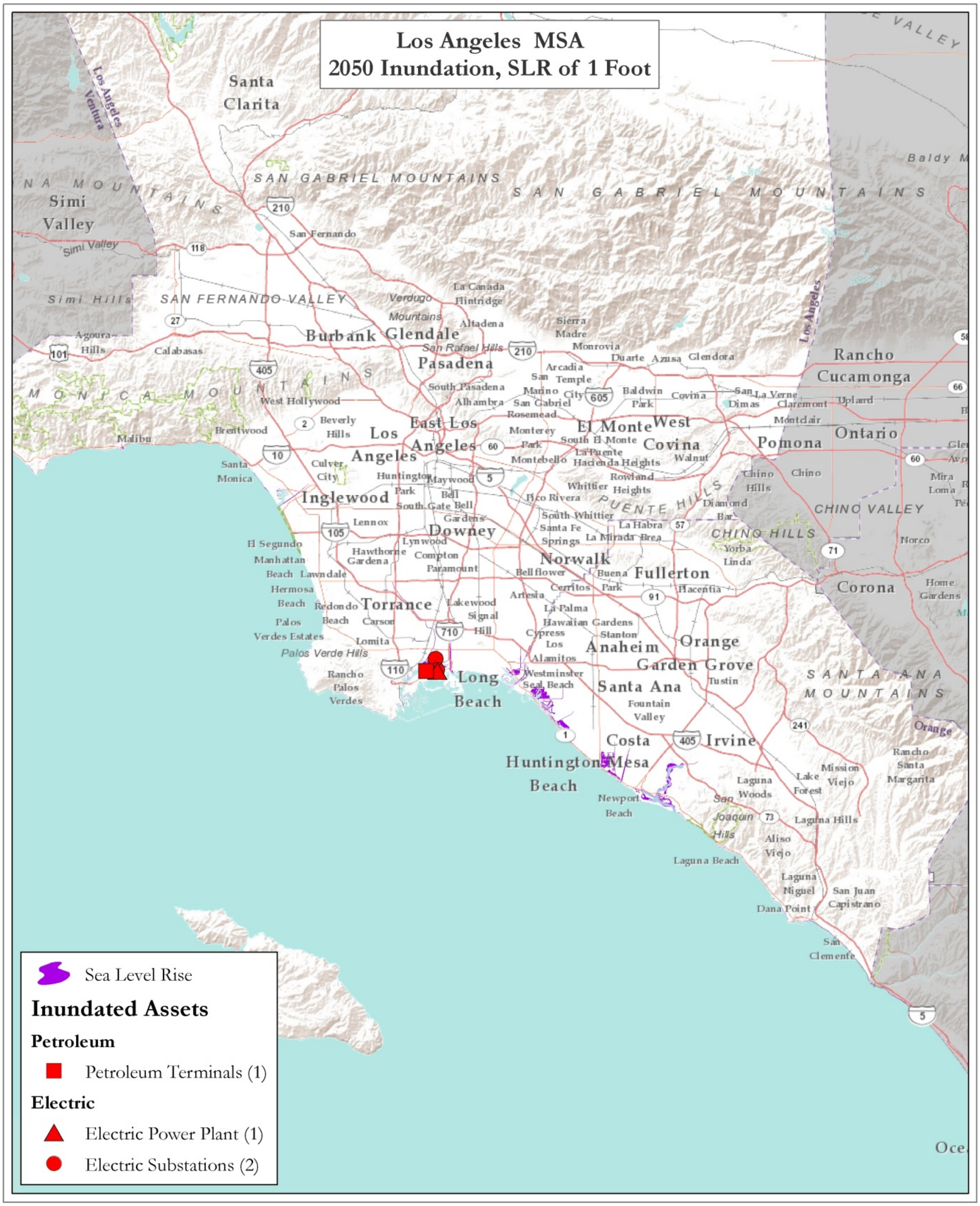


Exhibit 4-15 below shows the areas and assets projected to be inundated by approximately 2100.

Exhibit 4-15. Areas and Large Energy Assets in Los Angeles MSA Inundated by SLR by Approximately 2100 under the Intermediate-High Scenario (4 feet SLR)

5. Observations and Next Steps

As a pilot study, this exercise has demonstrated that by using SLR information from NOAA modeling and SLR projections from the NCA (adjusted for local conditions), analysts can generate credible projections of potential SLR impacts on energy system assets, thus supporting improved decision making related to asset protection and possible siting of new infrastructure.

This approach and information should be useful to planners for determining the potential impacts of SLR related to energy assets and, by extension, to other assets as well (e.g., water treatment, sewage, transportation), provided that GIS information for these assets exist. Such analysis can be accomplished at relatively low cost because of the work already done by NOAA and the organizations involved in developing the periodic NCAs.

Observations stemming from this analysis seem especially pertinent:

- Most of the energy assets projected to be affected by SLR will likely have become obsolete by the time SLR is projected to occur. Thus, by taking SLR into account during asset replacement or refurbishment in at-risk areas, planners can avoid SLR impacts.
- SLR may affect energy assets without inundating them. For example, SLR can isolate assets, impairing their functionality and increasing their exposure to storm surge threats.

While this study has developed and tested a proof-of-concept approach for identifying energy infrastructure at risk to SLR, there are a number of ways the approach can be expanded and improved. For example:

- This study did not directly address storm surge or model the behavior of storm surge on top of SLR and the combined effects on the shoreline. Nevertheless, storm surge effects will likely be the major near-term threat to energy infrastructure. Therefore, storm surge requires additional study as it will have a significant impact on coastal energy assets whether they are affected by SLR or not.
- This study has focused on energy assets where public data are available. As such, some important asset classes are not represented (e.g., natural gas distribution facilities and petroleum product retail facilities such as gasoline stations). Given appropriate data, the mapping of SLR can be used locally to incorporate this information in planning future energy infrastructure.
- As noted in the caveats section, this study did not take into account efforts by facility operators or owners to reduce an asset's exposure to higher sea levels. Future risk

analysis could incorporate planned or implemented mitigation efforts for individual assets.

- Finally, the study did not take into account the interdependency of energy assets and systems. OE will consider an approach for addressing energy interdependencies.

This pilot study has demonstrated the scalability of this approach and this analysis can be expanded to other cities and coastal regions. The Office of Electricity Delivery and Energy Reliability intends to share this pilot study with the areas studied and with others who have an interest in planning to adapt to potential SLR. The analysis can be corroborated and improved by incorporating other regional and local studies. Because many parts of the country have undertaken their own extensive studies, these can also be applied to improve the level of detail and applicability to local scenarios.

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Appendix B: Literature Review

Sea Level Rise Studies: An illustrative comparison of methodologies and analyses within the United States

This appendix presents at a high level some of the other studies on sea level rise (SLR), commenting on their analytical approaches and results. Following that section, a list of illustrative reports and articles are provided for each of the MSAs included in this study.

1. Evaluating Future Climate Change-Driven Risks to Coastal Systems: The North Carolina Sea Level Rise Risk Management Study

REFERENCE: North Carolina Division of Emergency Management, Office of Geospatial and Technology Management. 2011. "North Carolina Sea Level Rise Risk Management Study: Conceptual Model." Accessed April 2014. http://ericnatthomas.files.wordpress.com/2013/12/conceptual-model-report_ver2-2_20110502.pdf

DATE OF STUDY: 2010 – Present, final report to be released in 2014
LOCATION: North Carolina **TIME:** 2025, 2050, 2075, and 2100
ASSESSMENT: Six major groups of receptors including land, ecological systems, agriculture and aquaculture assets, buildings, critical infrastructure, and societal systems
SLR MODEL: Iterative geomorphological analysis and numerical 2D hydrodynamic modeling to project landscape response and simulate sea level rise, respectively
GLOBAL SLR SCENARIOS: Not disclosed in conceptual report
REGIONAL SLR SCENARIOS: Adjustments to the GSLR scenarios through consideration of uplift, subsidence, development, and exposure to the 100- and 500-year storms

SUMMARY:
The North Carolina Sea Level Rise Risk Management Study (NC SLRRMS) evaluates changes in risk using a source-pathway-receptor framework applied at distinct time periods between 2025 and 2100. Four emission scenarios representing a reasonable range of greenhouse gas emissions were used to initiate the model. Then, four plausible scenarios of sea level rise coupled with extreme storm events were applied to each emission scenario. The combined sea level and storm intensity and frequency models produced landform and hydrology responses, for which future erosion and flood risk were estimated. Wind, as a separate hazard, was not examined. After the authors determined the risks, development scenarios (based on historical growth) were overlaid in the study area to assess impacts on critical infrastructure, buildings, and structures, and ecology. The cumulative impacts of each receptor system were then translated to a societal impact that included effects on population displacement, health, recreation, economy, commerce, and other socioeconomic measures.

2. The Impact of Climate Change and Population Growth on the National Flood Insurance Program through 2100

REFERENCE: Federal Emergency Management Agency and AECOM. 2013. "The Impact of Climate Change and Population Growth on the National Flood Insurance Program through 2100." Accessed April 2014.
http://www.aecom.com/deployedfiles/Internet/News/Sustainability/FEMA%20Climate%20Change%20Report/Climate_Change_Report_AECOM_2013-06-11.pdf

DATE OF STUDY: 2013
LOCATION: National **TIME:** 2020, 2040, 2060, 2080, and 2100
ASSESSMENT: National Flood Insurance Program (NFIP) communities
SLR MODEL: Bathtub model[25] with 13 zones of local sea level rise in the United States (accounting for subsidence and tectonic effects).
GLOBAL SLR SCENARIOS: 1.2m by 2100, which is the average over the three scenarios used
REGIONAL SLR SCENARIOS: Adjustments to the GSLR scenarios through consideration of uplift and subsidence derived from tide gauges. The average relative rate of SLR was obtained for each zone.

SUMMARY:

The study provides an estimate of the likely financial impact on the NFIP resulting from climate change and population growth through the year 2100. Rather than attempt a detailed site-by-site evaluation of conditions throughout the United States, the study's results were based upon regional methods and engineering inference. No new climate modeling or projections were developed, and estimates were based on available material published through the United States Global Change Research Program.

All engineering analyses were based on equal consideration of three greenhouse gas emissions scenarios, A2, A1B, and B2, as well as changes in population and development. For this study, the U.S. coast was divided into 13 zones, so that the projected SLR within each zone was approximately uniform. The influence of changes in tropical storm and hurricane frequency was based on data taken from existing coastal flood insurance studies on a county basis. Flood stage-frequency curves were then taken from the existing FEMA flood studies and adjusted for both projected changes in storm frequency and storm intensity. For coastal regions, this was done in two ways. First, it was assumed that existing shorelines would be maintained through 2100, despite sea level rise and erosive forces tending to cause shoreline recession. Second, similar to the assumption made in FEMA's 1991 sea level rise study, it was assumed that shorelines would retreat so as to compensate for SLR. The study then concludes with economic findings (e.g., average loss cost per policy) for the year 2100.

[25] A bathtub model is a simple inundation model in which water is assumed to inundate the topography at a constant elevation or simply raise the water level.

3. Gulf Coast Study Phase 2, Task 2: Climate Variability and Change in Mobile, Alabama

REFERENCE: Federal Highway Administration and ICF International. 2012. "Gulf Coast Study Phase 2, Task 2 Final Report: Climate Variability and Change in Mobile, Alabama." Accessed April 2014.
http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/_gulf_coast_study/phase2_task2/

DATE OF STUDY: 2012
LOCATION: Gulf Coast outside of Mobile, AL **TIME:** 2020, 2040, 2060, 2080, and 2100
ASSESSMENT: Transportation assets (e.g. ports, highways, airports, railway, terminals, etc.)
SLR MODEL: High resolution bathtub model
GLOBAL SLR SCENARIOS: 0.3m, 0.75m, and 2.0m by 2100; interpolation to 2050
REGIONAL SLR SCENARIOS: Adjustments to the GSLR scenarios through consideration of uplift and subsidence derived from tide gauges and InSAR data. Also accounts for storm surge through consideration of representative storms, including the effects of climate change on storm intensity.

SUMMARY:
The study uses global sea level rise (GSLR) and changes in land uplift and subsidence to model sea level rise scenarios in Mobile Bay, Alabama. Local sea level rise (LSLR) was estimated by adding the current rates of subsidence or uplift to each global sea level rise scenario. Vertical change rates for the 75 benchmarks considered for the LSLR adjustment ranged from -0.08 to 0.02 inches per year (-1.9 to 0.5 millimeters per year) with a mean of -0.03 inches per year (-0.75 millimeters per year).

The data was then overlaid on a high resolution LiDAR-based Digital Elevation Model to estimate the vertical position of the land surface out to 2050 and 2100. Other factors (e.g. sedimentation, gravitational change, oceanic circulation patterns, and changes in ocean density) were not considered in this study because they were estimated to not significantly affect the results. In addition, vertical addition or subtraction of sediment through coastal engineering, changes in the vertical accretion rate of wetlands, and small-scale protective barriers were not taken into account.

4. The Economics of Adaptation Along Developed Coastlines

REFERENCE: Neumann, James, Daniel Hudgens, John Herter and Jeremy Martinich. 2010. "The Economics of Adaptation Along Developed Coastlines." 2010. Accessed April 2014. http://onlinelibrary.wiley.com/doi/10.1002 /wcc.90/abstract

DATE OF STUDY: 2010
LOCATION: National **TIME:** 1990-2100, using baseline, low, mid, high scenarios
ASSESSMENT: Coastal properties (based on U.S. Census)
SLR MODEL: Bathtub Model using 30m digital elevation models from the USGS
GLOBAL SLR SCENARIOS: 18.7cm, 28.5cm, 66.9cm, and 126.3cm by 2100 compared to 1990
REGIONAL SLR SCENARIOS: Adjustments to the GSLR scenarios through consideration of uplift and subsidence derived from tide gauges

SUMMARY:
The study presents a framework for developing sea level rise scenarios along the U.S. coastline. Four scenarios were considered, including a Baseline, Low (or IPCC B1), Mid (or IPCC A1b), and High (IPCC Maximum) Scenarios, implying SLR of 18.7cm, 28.5cm, 66.9cm, and 126.3cm by the year 2100 compared to 1990. For each scenario, the fixed annual rate of land subsidence was estimated, based on NOAA tide gauge data from 68 sites with at least 25 years of continuous measurements. In addition, an estimated 1.7mm/year was subtracted from each tide gauge annual average to account for the component of relative SLR. Using property values from residential, commercial, industrial, institutional, and government structures to assess coastal risk, the authors estimated that the Mid Scenario would result in total undiscounted costs of $230 billion.

5. Assessing Sea-Level Rise Impacts: A GIS-Based Framework and Application to Coastal New Jersey

REFERENCE: Neumann, James, Daniel Hudgens, John Herter and Jeremy Martinich. 2010. "Assessing Sea-Level Rise Impacts: A GIS-Based Framework and Application to Coastal New Jersey." Accessed April 2014. http://www.tandfonline.com/doi/abs/10.1080/08920753.2010.496105#.U2J9HYFdWSo

DATE OF STUDY: 2010
LOCATION: Multi-county section of New Jersey's Atlantic coast **TIME:** 2020, 2040, 2060, 2080, and 2100
ASSESSMENT: Coastal properties (based on county parcel data from Monmouth, Ocean, Atlantic, and Cape May)
SLR MODEL: Bathtub Model using 30m digital elevation models from the USGS
GLOBAL SLR SCENARIOS: 28cm, 67cm, and 126cm by 2100 compared to 1990
REGIONAL SLR SCENARIOS: Adjustments to the GSLR scenarios through consideration of 2.7mm/year land subsidence

SUMMARY:

The study is part of a larger approach to produce two types of results: national-level estimates of the benefits of reducing sea level rise through control of greenhouse gas emissions; and local-level results assessing management actions that could facilitate adaptation to sea level rise risks. To develop the SLR model, elevation data were based on 30m digital elevation modeling (DEM), calibrated to a zero elevation in the year 2000 as represented by the mean spring high water mark. Estimated tide ranges and sea level trends by the National Ocean Service (NOS) helped determine the location of spring high water.

The authors of the study then used information provided from the MAGICC[26] and Rahmstorf[27] SLR models to generate decadal estimates of sea levels in future years. Using these inputs, three SLR scenarios (plus a baseline) were developed: the low scenario is consistent with just over 28 cm SLR by 2100, the middle scenario is consistent with almost 67 cm by 2100, and the high scenario is consistent with more than 126cm by 2100. The model excludes land subsidence and uplift. The study concludes with a summary of recommended adaptation option types across counties, as well as a discussion of the potential evaluation of these risks for policy and planning audiences, with more comprehensive estimates of SLR and storm effects.

[26] MAGICC is the "Model for the Assessment of Greenhouse-gas Induced Climate Change" and is a coupled gas-cycle/climate model. The IPCC used MAGICC as a primary model to project future increases in global mean temperature and SLR for the Third Assessment Report.

[27] Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. Science 315:368–370.

6. Climate Central Surging Seas Report and Web Application

REFERENCE: Strauss, Benjamin H, Remik Ziemlinski, Jeremy L Weiss, and Jonathan T Overpeck. 2010. "Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States." Accessed April 2014. http://iopscience.iop.org/1748-9326/7/1/014033

DATE OF STUDY: 2012
LOCATION: U.S. Coast **TIME:** Not applicable
ASSESSMENT: Population, Homes, and Land Area based on overall exposure according to 2010 Census
MODEL: Bathtub Model using 30m digital elevation models from the USGS.
GLOBAL SLR SCENARIOS: SLR is presented between 1ft and 10ft
REGIONAL SLR SCENARIOS: Adjustments to the GSLR scenarios through consideration of uplift and subsidence derived from tide gauges

SUMMARY:

The Surging Seas report and its associated materials, based on two recently published peer-reviewed studies (including the reference by Strauss above), is the first major national analysis of sea level rise in 20 years, according to the organization. It was the first to include the following: estimates of land, population, and housing at risk; evaluations of every low-lying coastal town, city, county, and state in the contiguous United States.; localized timelines of storm surge threats integrating local sea level rise projections; and a freely available interactive map and data to download online (see SurgingSeas.org).

Since neither years nor scenarios are contextualized in the study, the National Elevation Dataset (NED) comprised the core data input for the analysis. Specifically, the study used the 1/3 arcsec dataset, the finest resolution data publicly available with full coastal coverage. To be considered 'above land', cells (each measuring 10m x 10m) had to have a non-zero elevation, had to not be included in the National Wetlands Inventory dataset, and had to be above the local tidally adjusted Mean High Water (MHW) elevation. The results from the study are best observed through their interactive map, which shows the population and assets exposed to SLR under the given sea level scenario.

7. Potential Inundation Due to Rising Sea Levels in the San Francisco Bay Area

REFERENCE: Knowles, N. 2010. Potential Inundation Due to Rising Sea Levels in the San Francisco Bay Area. *San Francisco Estuary and Watershed Science.* Volume 8, Issue 1. Accessed April 2014. http://escholarship.org/uc/item/8ck5h3qn#page-1

DATE OF STUDY: 2010
LOCATION: San Francisco Bay **TIME:** Not applicable
ASSESSMENT: Population, Homes, and Acres based on overall exposure according to 2010 Census
SLR MODEL: TRIM-2D, a 2-dimensional hydrodynamic model, was used to simulate SLR using a 200m horizontal grid
GLOBAL SLR SCENARIOS: GSLR is presented in half-meter increments: 0, 50, 100, and 150 cm
REGIONAL SLR SCENARIOS: Adjustments to the GSLR scenarios through consideration of uplift and subsidence derived from tide gauges. The RSL was then coupled with the 1-, 10-, 50-, 100-, and 500-year storm return periods.

SUMMARY:
For this study, sea level rise was evaluated in half-meter increments—0, 50, 100, and 150 cm—which would respectively occur as follows: present-day, 2050–2100, 2080–, and 2105– (based on the widely circulated analysis by Rahmstorf,[28] the projections do not extend far enough into the future to provide end dates for the highest two values). Each water-height field was compared at all points along the bay's shoreline to the adjacent LiDAR-based land surface elevation to assess what areas would be inundated (at least as often as the specified return interval, on average).

The effect of present or future levees, potential accumulation of sediment and organic matter, and shoreline erosion were not included in the study. Further, attenuation of short-term variability over inundated areas was not accounted for; as a result, vulnerability to inundation may be over-estimated for areas removed from the bay's present day shoreline. The estimates presented in this study did not take into account the effect of wind waves on water levels. The effect of freshwater inflows on water heights were accounted for, but only corresponding to historical climate; increased winter flood peaks associated with climate warming could produce greater inundation vulnerabilities than shown.

[28] Rahmstorf S. 2007. A semi-empirical approach to projecting future sea-level rise. Science 315:368–370.

8. Retrospective and Prospective Model Simulations of Sea Level Rise Impacts on Gulf of Mexico Coastal Marshes and Forests in Waccasassa Bay, Florida

REFERENCE: Geselbracht, Laura, Kathleen Freeman, Eugene Kelly, Doria R. Gordon, and Francis E. Pultz. 2011. Retrospective and Prospective Model Simulations of Sea Level Rise Impacts on Gulf of Mexico Coastal Marshes and Forests in Waccasassa Bay, Florida. *Climatic Change*, Volume 107.

DATE OF STUDY: 2011
LOCATION: Waccasassa Bay, Florida **TIME:** Not applicable
ASSESSMENT: Coastal wetlands and vulnerable species
SLR MODEL: Sea Level Affecting Marshes Model (SLAMM), which was then compared and calibrated to 30 years of field plot data
GLOBAL SLR SCENARIOS: GSLR is presented using 0.64 m, 1 m and 2 m scenarios by 2100
REGIONAL SLR SCENARIOS: Adjustments to the GSLR scenarios through consideration of land subsidence derived from tide gauges, as well as local rates of erosion, sedimentation, and accretion (required for SLAMM Modeling)

SUMMARY:
The study assesses the effect of sea level rise on coastal wetlands in southern Florida by determining inundation levels at 0.64m, 1m, and 2m SLR. The 0.64m scenario was chosen to allow comparison with the results of a previous study; the other two SLR scenarios were based on recent projections of the magnitude of SLR by 2100. In all the model runs, LiDAR-derived elevation data (with +/- 0.3m vertical accuracy at the 95th percentile) were used. SLAMM provided the tool necessary to model such changes in wetlands as result of SLR. Following a calibration effort in which hindcast models were validated with 30-years of field data, the results for the future scenarios predicted substantial changes in the 100-year period. The study does not document the SLAMM model, but does include a discussion of additional factors of interest including erosion, overwash, saturation, and accretion.[29] It is not clear if the study considers land subsidence or uplift.

[29] Warren Pinnacle SLAMM Model Overview.
http://www.warrenpinnacle.com/prof/SLAMM/SLAMM_Model_Overview.html

Listed below are other reports and activities that the reader may wish to consult for a deeper understanding of sea level rise risk in the four metropolitan regions included in this pilot study.

New York City, NY

- New York City Office of Emergency Management. 2014. 2014 Natural Hazard Mitigation Plan. http://www.nyc.gov/html/oem/html/planning_response/planning_hazard_mitigation_2014.shtml
- PlaNYC. 2013. A Stronger, More Resilient New York. http://www.nyc.gov/html/sirr/html/report/report.shtml
- New York City Office of City Planning. 2013. Coastal Climate Resilience: Designing for Flood Risk. http://www.nyc.gov/html/dcp/html/sustainable_communities/sustain_com6.shtml
- New York City Office of City Planning. 2013. Urban Waterfront Adaptive Strategies. http://www.nyc.gov/html/dcp/html/sustainable_communities/sustain_com7.shtml
- New York City Panel on Climate Change. 2013. Climate Risk Information 2013: Observations, Climate Change Projections, and Maps. C. Rosenzweig and W. Solecki (Eds.), NPCC2. Prepared for use by the City of New York Special Initiative on Rebuilding and Resiliency, New York, New York. http://www.nyc.gov/html/planyc2030/downloads/pdf/npcc_climate_risk_information_2013_report.pdf
- New York City Office of City Planning. 2011. Increase Climate Resilience. In Vision 2020: The NYC Comprehensive Waterfront Plan. http://www.nyc.gov/html/dcp/pdf/cwp/vision2020/chapter3_goal8.pdf
- New York State Sea Level Rise Task Force. 2010. Report to the Legislature. http://www.dec.ny.gov/docs/administration_pdf/slrtffinalrep.pdf
- Strange, E.M. 2008. New York City, the Lower Hudson, and Jamaica Bay. Section 3.4 in: Background Documents Supporting Climate Change Science program Synthesis and Assessment Product 4.1: Coastal Elevations and Sensitivity to Sea Level Rise [Titus, J.G. and E.M. Strange (eds.)]. EPA 430R07004. U.S. Environmental Protectio Agency, Washington, DC, pp. 222-229. http://papers.risingsea.net/federal_reports/Titus_and_Strange_EPA_may2008.pdf
- Jacob, K., V. Gornitz, and C. Rosenzweig. 2007. Vulnerability of the New York City metropolitan area to coastal hazards, including sea-level rise: Inferences for urban coastal risk management and adaptation policies. In Managing Coastal Vulnerability. L. McFadden, R. Nicholls, and E. Penning-Rowsell (Eds.). Elsevier, 139-156. http://pubs.giss.nasa.gov/docs/2007/2007_Jacob_etal_1.pdf

Miami, FL

- Miami-Dade Sea Level Rise Task Force. 2014. Miami-Dade Sea Level Rise Task Force Report and Recommendations. http://www.miamidade.gov/planning/library/reports/sea-level-rise-final-report.pdf
- Southeast Florida Regional Climate Change Compact. 2014. Integrating Climate Change & Water Supply Planning In Southeast Florida. https://southeastfloridaclimatecompact.files.wordpress.com/2014/06/rcap-igd-water-supply-final-v-3.pdf
- Tompkins, Forbes and Christina DeConcini. 2014. Sea-Level Rise and Its Impact on Miami-Dade County. World Resources Institute. http://www.wri.org/publication/sea-level-rise-and-its-impact-miami-dade-county
- DeConcini, Christina and Forbes Tompkins. 2012. Sea-Level Rise and Its Impact on Florida. World Resources Institute. http://www.wri.org/publication/sea-level-rise-and-its-impact-florida
- Southeast Florida Regional Climate Change Compact Inundation Mapping and Vulnerability Assessment Work Group. 2012. Analysis of the Vulnerability of Southeast Florida to Sea Level Rise. http://southeastfloridaclimatecompact.files.wordpress.com/2014/05/vulnerability-assessment.pdf
- Southeast Florida Regional Climate Change Compact Technical Ad hoc Work Group. 2011. A Unified Sea Level Rise Projection for Southeast Florida. A document prepared for the Southeast Florida Regional Climate Change Compact Steering Committee. http://southeastfloridaclimatecompact.files.wordpress.com/2014/05/sea-level-rise.pdf

Houston, TX

- Port of Houston Authority. 2013. *Bayport Terminal Climate Change Study.* Presentation. https://www.h-gac.com/taq/airquality/raqpac/documents/2013/September%2026%202013%20Meeting/Bayport%20Terminal%2004%2004%2013.pdf
- Texas Sea Grant. 2013. *The Risk of Rising Sea: Texas Universities Ready and Able to Help Coastal Communities Adapt.* http://texas-sea-grant.tamu.edu/includes/TheRiskofRisingSeaFinal.pdf
- Gilmer, B., J. Brenner, and J. Sheets. 2012. *Informing Conservation Planning Using Sea-level Rise and Storm Surge Vulnerability Assessments: Galveston Bay and Jefferson County, Texas.* The Nature Conservancy. http://stormsmart.org/goma/slr/interface/reports/Texas_Conservation_Analysis_Report.pdf

- Texas Sea Grant. 2009. *Governments Plan for Development of Land Vulnerable to Rising Sea Level: Greater Houston, Texas.* Excerpts from report *State and Local Governments Plan for Development of Most Land Vulnerable to Rising Sea Level along the U.S. Atlantic Coast.* http://risingsea.net/ERL/TX-Galveston-Bay.html
- Yoskowitz, D., J. Gibeaut, and A. McKenzie. 2009. *The Socio-Economic Impact of Sea Level Rise in the Galveston Bay Region.* A report for Environmental Defense Fund. http://www.edf.org/sites/default/files/9901_EDF_Sea_Level_Rise_Report.pdf

Los Angeles, CA

- California Coastal Commission. 2013. *Draft Sea-Level Rise Policy Guidance.* http://www.coastal.ca.gov/climate/slr/guidance/CCC_Draft_SLR_Guidance_PR_10142013.pdf
- Grifman, P., J. Hart, J. Ladwig, A. Newton Mann, and M. Schulhof. 2013. *Sea Level Rise Vulnerability Study for the City of Los Angeles.* University of Southern California Sea Grant Program. http://www.usc.edu/org/seagrant/research/sea_level_rise_vulnerability.html
- Adapting to Rising Tides. 2012. *Vulnerability and Risk Assessment Report.* http://www.adaptingtorisingtides.org/vulnerability-and-risk-assessment-report/
- Heberger, M., H. Cooley, E. Moore, and P. Herrera. 2012. *The Impacts of Sea Level Rise on the San Francisco Bay.* California Climate Change Center. http://www.energy.ca.gov/2012publications/CEC-500-2012-014/CEC-500-2012-014.pdf
- Russell, N. and G. Griggs. 2012. *Adapting to Sea Level Rise: A Guide for California's Coastal Communities.* California Energy Commission. http://calost.org/pdf/announcements/Adapting%20to%20Sea%20Level%20Rise_N%20Russell_G%20Griggs_2012.pdf
- Knowles, N. 2010. Potential Inundation Due to Rising Sea Levels in the San Francisco Bay Region. *San Francisco Estuary and Watershed Science, 8(1).* http://escholarship.org/uc/item/8ck5h3qn
- Heberger, M., H. Cooley, P. Herrera, P. Gleick, and E. Moore. 2009. *The Impacts of Sea-Level Rise on the California Coast.* California Climate Change Center. http://www.energy.ca.gov/2009publications/CEC-500-2009-024/CEC-500-2009-024-F.PDF
- Perez, P. 2009. *Potential Impacts of Climate Change on California's Energy Infrastructure and Identification of Adaptation Measures.* California Energy Commission. http://www.energy.ca.gov/2009publications/CEC-150-2009-001/CEC-150-2009-001.PDF