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NORTH CAROLINA

Sea Level Rise

Assessment Report

2015 Update to the 2010 Report
and 2012 Addendum

Prepared by the N.C. Coastal Resources Commission Science Panel



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Executive Summary: 2015 Science Panel Update to 2010 Report and 2012 Addendum

Charge: This report has been written by the members of the Science Panel as a public service in response to a charge from the Coastal Resources Commission (CRC) and the N.C. General Assembly Session Law 2012-202. The CRC charge specified that sea level rise projections be developed for a 30-year timeframe.

Background: The Science Panel, along with six additional contributors, issued a report in March 2010 titled “North Carolina Sea Level Rise Assessment Report.” In response to a series of questions by the CRC, in April 2012 the panel issued a follow up Addendum to the report. As stated in these documents, the Science Panel recommendation was for re-assessments to be completed every five years. The present document serves as the 2015 update of the 2010 report.

Approach: It is critical to the Science Panel that our process be transparent. Therefore all numerical values used in this report, as well as the corresponding sources, are presented. In addition, mathematical calculations and formulas employed are described in detail.

What’s New: This document expands on the 2010 report and 2012 addendum in a number of important ways, including the following:

- Inclusion of scenario based global sea level rise predictions from the most recent Intergovernmental Panel on Climate Change (IPCC) Report (AR5).
- Emphasis on the spatial variation of relative sea level rise rates as evidenced by the analysis of data collected by NOAA tide gauges along the North Carolina coast.
- Additional discussion of the expected spatial variability in relative sea level rise rates along the North Carolina coast due to geologic factors.
- Review of recent research indicating that ocean dynamics effects may be a significant source of spatial variability in existing relative sea level rise rates along the North Carolina coast.
- Discussion of recent research into the impacts of sea level rise on the frequency of relatively minor coastal flooding not necessarily associated with storms (*nuisance flooding*).
- Examination of dredging effects on tide range and sea level signal.
- Consideration of a 30-year time frame for sea level rise projections as requested by the CRC.
- Development of a range of predictions at each of the long-term tide gauges along the North Carolina coast based on a combination of local vertical land motion information and the IPCC scenarios.

Summary: Sea level is rising across the coast of North Carolina. The rate of local sea level rise varies, depending on location (spatially) and the time frame for analysis (temporally). Two main factors affect the spatial variation of rates of sea level rise along the North Carolina coast: (1) vertical movement of the Earth’s surface, and (2) effects of water movement in the oceans (including the shifting position and changing speed of the Gulf Stream). There is evidence from both geological data and tide gauges that there is more land subsidence north of Cape Lookout than south of Cape Lookout. This contributes to higher measured rates of sea level rise along the northeastern N.C. coast. Oceanographic research reveals a strong link between speed and position of the Gulf Stream and sea level. This effect has been

observed to increase sea level primarily north of Cape Hatteras. The differences in the rates of relative sea level rise (meaning, the rate of sea level rise at a specific location including local effects, and distinct from the global average rate of sea level rise) at different locations along the North Carolina coast are evident in the sea level trends reported by the National Oceanic and Atmospheric Administration (NOAA) at tide gauge stations along the North Carolina coast. Five tide gauges along the state's coast have collected water level data for long enough to have reported sea level trends. Two are located in Dare County: one of those at the U.S. Army Corps of Engineers' Field Research Facility in Duck and another at the Oregon Inlet Marina. A third is located in Carteret County at the Duke University Marine Lab dock in Beaufort. The fourth station is located in Wilmington, at the U.S. Army Corps of Engineers' maintenance yard and docks at Eagle Island. This location is in New Hanover County, immediately adjacent to Brunswick County. These stations still continue to record water level data. The fifth station was located at the Southport Fishing Pier, but is no longer active.

NOAA makes available these data and an analysis of rate based on linear regression. Data span the time period from the initial installation of the gauge through December 2013 for the gauges at Duck, Oregon Inlet Marina, Beaufort and Wilmington and through 2008 for the gauge at Southport. NOAA reports a high, a low, and a mean value for the rate of relative sea level rise using a 95% confidence interval for each gauge. The Science Panel worked closely with Dr. Chris Zervas (*e.g.*, Zervas 2001, Zervas 2009, Zervas et al. 2013) at the NOAA National Ocean Service Center for Operational Oceanographic Products and Services, who provided additional analyses of tide gauge data for this report. The existing published rate of sea level rise is converted to a future elevation by multiplying the rate plus or minus the 95% confidence interval (for the high/low estimates respectively) by 30 years – the time frame specified by the CRC for the projections in this update.

Since tide gauges only measure past sea levels, the Science Panel used the most recent report of the Intergovernmental Panel on Climate Change (AR5) to provide scenario-based global sea level rise projections. The scenarios chosen to model sea level rise over the next 30 years are the IPCC's low greenhouse gas emissions scenario (RCP 2.6) and the high greenhouse gas emissions scenario (RCP 8.5), as all other scenario projections fall within the range of these two. These values were combined with rates of vertical land movement (subsidence) determined by the analysis of tide gauge records and provided by NOAA (Zervas et al. 2013; Zervas, pers. comm. 2014) to develop a range of values across the North Carolina coast.

Table ES1 summarizes the results. Using existing gauge rates, sea level rise across North Carolina by 2045 would vary from a low estimate of 2.4 inches (with a range between 1.9 and 2.8 inches) at Southport to a high estimate of 5.4 inches (with a range between 4.4 and 6.4 inches) at Duck. Considering the IPCC scenario RCP 2.6 combined with vertical land movement, sea level rise would vary from a low estimate of 5.8 inches (with a range between 3.5 and 8.0 inches) at Wilmington to a high estimate at Duck of 7.1 inches (with a range between 4.8 and 9.4 inches). Considering IPCC scenario RCP 8.5 with vertical land movement, sea level rise would vary from a low estimate of 6.8 inches (with a range between 4.3 and 9.3 inches) at Wilmington to a high estimate at Duck of 8.1 inches (with a range between 5.5 and 10.6 inches).

Table ES1. Three relative sea level rise (RSLR) scenarios by 2045 using published tide gauge rates (NOAA 2014a), and IPCC scenario projections RCP 2.6 and RCP 8.5 (Church et al. 2013) representing the lowest and highest greenhouse gas emission scenarios, combined with local vertical land movement (VLM) at each tide gauge.*

Station	Tide Gauge Projections		IPCC RCP 2.6 + VLM		IPCC RCP 8.5 + VLM	
	RSLR in 30 years (inches)		RSLR in 30 years (inches)		RSLR in 30 years (inches)	
	Mean	Range	Mean	Range	Mean	Range
Duck	5.4	4.4-6.4	7.1	4.8-9.4	8.1	5.5-10.6
Oregon Inlet	4.3	2.7-5.9	6.3	3.9-8.7	7.3	4.7-9.9
Beaufort	3.2	2.8-3.6	6.5	4.2-8.7	7.5	5.0-10.0
Wilmington	2.4	2.0-2.8	5.8	3.5-8.0	6.8	4.3-9.3
Southport	2.4	1.9-2.8	5.9	3.7-8.2	6.9	4.4-9.4

*Note: Projections were rounded to the nearest tenth of an inch.

Using the Projections: The range of sea level values (from 1.9 to 10.6 inches) reported in **Table ES1** reflects both the uncertainty in the predictions and the spatially varying nature of sea level in North Carolina. Economic, social and environmental sustainability in the coastal region of North Carolina will, in part, be dependent on how this information is used. Agency groups should work in an open and informed manner with the scientific community, local landowners and political bodies, and other affected stakeholders to consider acceptable levels of risk. Planning objectives that span longer time frames (greater than 30 years) will require looking at the IPCC results directly as the IPCC scenarios begin to differ significantly beyond 30 years.

Table ES1 reflects change in mean sea level. Recent research into the frequency of coastal flooding has shown that, regardless of the rate of rise, as the mean sea level increases, North Carolinians should expect more frequent flooding of low-lying areas.

Future Data Collection, Data Analysis and Reporting: Recommendations are made to:

- continue to monitor oceanographic research with regards to the effect of ocean-atmospheric oscillations and regional ocean currents (*e.g.*, the Gulf Stream) on sea level,
- sustain existing water level recording stations and land movement measurements and establish additional gauges to provide more complete spatial coverage,
- review updated satellite sea level data as the record is extended and consider use of these data in the future,
- consider additional analysis of the tide gauge data to standardize the time period covered using the NOAA analysis of rate procedures, and
- update the assessment every five years to include the rapidly changing science of projecting sea level rise.

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Terms and Acronyms

BIMP: Beach and Inlet Management Plan –a joint project by the North Carolina Division of Water Resources and the North Carolina Division of Coastal Management to manage the state's inlets and beaches

AR5: Fifth Assessment Report – the most recent report (2013) on climate change from the Intergovernmental Panel on Climate Change

CORS: Continuously Operating Reference Stations – ground based reference stations that continuously collect and record GPS data

Eustatic Sea Level – the global sea level; eustatic sea level changes affect all areas across the globe and include changes in the volume of water in the ocean or changes in ocean basins that affect the volume of water they can hold

GIA: Glacial Isostatic Adjustment – describes the Earth’s rebound, both positively and negatively, from the melting of kilometers-thick ice sheets that covered much of North America and Europe during the last glacial maximum approximately 20,000 years ago

GPS: Global Positioning System – a satellite based navigation system that provides location and time information anywhere on or near Earth where there is an unobstructed line of sight to four or more GPS satellites

GSL: Global Sea Level – the global average sea level

IPCC: Intergovernmental Panel on Climate Change – the leading international body for the assessment of climate change. It operates under the auspices of the United Nations (UN)

Nuisance flooding – flooding events not necessarily associated with storms

OE: Oceanographic effects – changes in sea level due to movement of the ocean waters, including effects of ocean-atmospheric oscillations and changes in ocean currents

RCP: Representative Concentration Pathways – four greenhouse gas concentration trajectories adopted by the IPCC for AR5; these scenarios are used for climate modeling and research and represent possible climate futures depending on the amounts of greenhouse gases emitted in the years to come

RSL: Relative Sea Level – the sea level at any location and time

Thermal expansion of ocean water – increase in ocean water volume due to a corresponding increase in water temperature

VLM: Vertical land movement or vertical land motion –sinking or rising of the Earth’s surface (*i.e.*, subsidence or uplift, respectively)

1. Introduction

In 1954, Hurricane Hazel made landfall at the border of North Carolina and South Carolina as a category 4 hurricane arriving at spring high tide and packing 140 mph winds (Smith 2014). Her winds, waves and 18-ft storm surge swept across the barrier islands causing wide-spread destruction along the coast. In North Carolina, 19 people died; on Long Beach only five of 357 homes survived. Hurricane Hazel was one of the most damaging storms in North Carolina history. Because of the sea level change that has occurred since, a storm of similar intensity today, 60 years later, would have a storm surge approximately 5 inches higher (~10 inches higher north of Cape Hatteras). In low lying areas of the coast, a few inches may be the difference between the ground floor of a house staying dry or being underwater. Sea Level change is not a new coastal hazard, but over time it “exacerbates existing coastal hazards such as flooding from rain or tide, erosion, and storm surge” (Ruppert 2014). Over time, rising water levels also increase the occurrence of *nuisance flooding* (flooding events not necessarily associated with storms) during more frequent events (like monthly spring tides) (Sweet et al. 2014, Sweet and Park 2014, Ezer and Atkinson 2014).

Because of the potential impact of future sea levels to coastal North Carolina, in 2009 the Coastal Resources Commission (CRC) asked the Science Panel on Coastal Hazards to develop an assessment of future sea levels for NC. The first assessment was published in March 2010 (NC Science Panel 2010). Because climate and sea level science is advancing rapidly, the 2010 report recommended an update every five years. In 2013 the CRC, responding to Session Law 2012-202 from the N.C. General Assembly, requested the first 5-year update using the latest science to estimate future sea levels. The CRC requested that the update consider only the next 30 years, from 2015 to 2045 (see Appendix A for the charge from the CRC and Appendix B for S.L. 2012-202) rather than the 90-year timeframe used in the original report.

Since our original report, there have been significant advances in climate science and the publication of several major reports, including the 2013 report of Working Group I (WG1) to the Fifth Assessment (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2013b, 2013c). That report is a thorough and updated analysis of climate and sea level prediction. It represents a 5-year effort by 250 authors and their conclusions were based on 9,200 published papers and were finalized after fielding 50,000 comments.

Because the IPCC report is based on peer-reviewed research and is itself peer-reviewed science, it is the most widely used and vetted climate document. We make use of their projections in the present report. The AR5 scenarios are currently also being used in recent efforts by New York State (New York State Energy Research and Development Authority 2014) and the Canadian coast (Zhai et al. 2014).

Also published since our 2010 report are the 2014 update to the United States National Climate Assessment, which includes sea level predictions (Melillo et al. 2014) and a series of studies of sea level along the Atlantic coast which are relevant to North Carolina and are discussed in this report.

In this update, we:

- 1) Introduce the concept of sea level and the variables that control sea level change;
- 2) Provide and explain how sea level change varies across coastal North Carolina and the factors that control that variation;
- 3) Present a range of sea level values appropriate for different areas of North Carolina, which may occur by 2045 based on the IPCC scenarios as well as local geologic and oceanographic variations;
- 4) Provide guidance as to how to interpret and make use of these values.

2. Sea Level Change: What influences ocean water levels?

The sea level at any location and time is known as the Relative Sea Level or RSL, which is the combination of three primary factors including the *Global Sea Level* (GSL), *Vertical Land Movement* (VLM) and *Oceanographic Effects* (OE). GSL and RSL are discussed in this section; VLM and OE are discussed in **Section 3**. These parameters are usually discussed in terms of their rates of temporal change, commonly expressed in mm/year.

2.1 Historical Sea Level Change

Over the scale of 10,000s to 100,000s of years, climate has oscillated between extensive periods of cold and warm phases, triggering the uptake of seawater in glacial ice during cold stages of global climate and the release of this water during warm episodes (Wright 1989). Periods of glaciation and interglaciation, and the corresponding fall and rise of sea level respectively have been well documented in the geologic record using an array of indicators [e.g., oxygen isotopes in calcium carbonate fossils, coral reef terraces, marsh peat elevation and geochemistry, paleo-shorelines, etc. (Cohen and Gibbard 2011; Blanchon and Shaw 2005; NOAA 2014b)]. The cyclicity of the “Ice Ages” has been used to signify the Quaternary geologic period, which includes both the Pleistocene and Holocene Epochs.

As depicted in **Figure 1** (Imbrie et al. 1984) the most recent previous interglacial (warm) period was approximately 125,000 years ago when sea level was ~16 to 20 feet above present, which was subsequently followed by a period of glaciation that reached a maximum at ~20,000 years ago when sea level was ~425 feet below present. Currently, we are in a warm phase that was first marked by rapid de-glaciation and rising sea level, which also represents the demarcation

of the Pleistocene/Holocene boundary (**Figure 2**, Donoghue 2011; Fairbanks 1989; Peltier and Fairbanks 2006; Bard et al. 2010). Climate and sea level have relatively plateaued over the past 5,000 years and sea level is estimated to have risen on the order of 3 feet during this timeframe (**Figures 2 and 3**; Kemp et al. 2011).

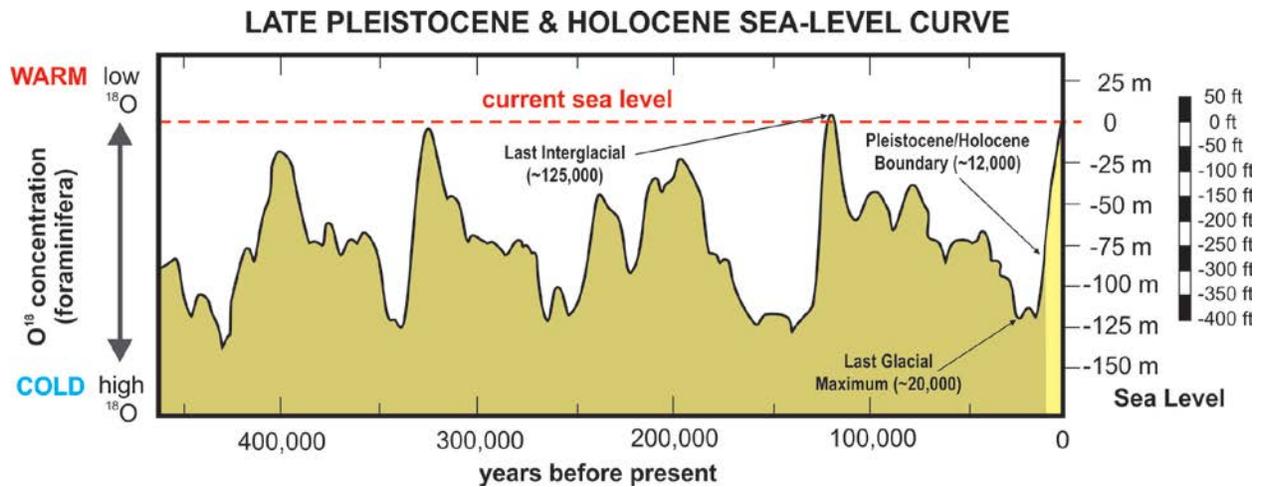


Figure 1. Global sea level curve over the scale of 100,000s of years developed from the marine delta ^{18}O record, which also depicts the last interglacial highstand and glacial maximum. (Modified from Imbrie et al. 1984)

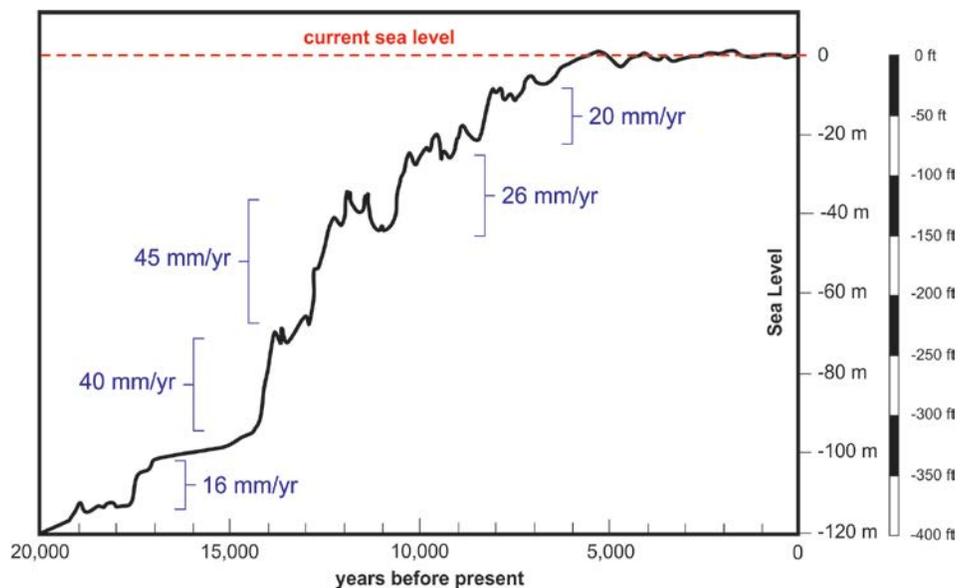


Figure 2. Global sea level curve over the scale of the past 10,000s of years based on radiocarbon-dated reef corals and paleoshoreline indicators constraining sea level movement since the last glacial maximum. (Adapted from Donoghue 2011).

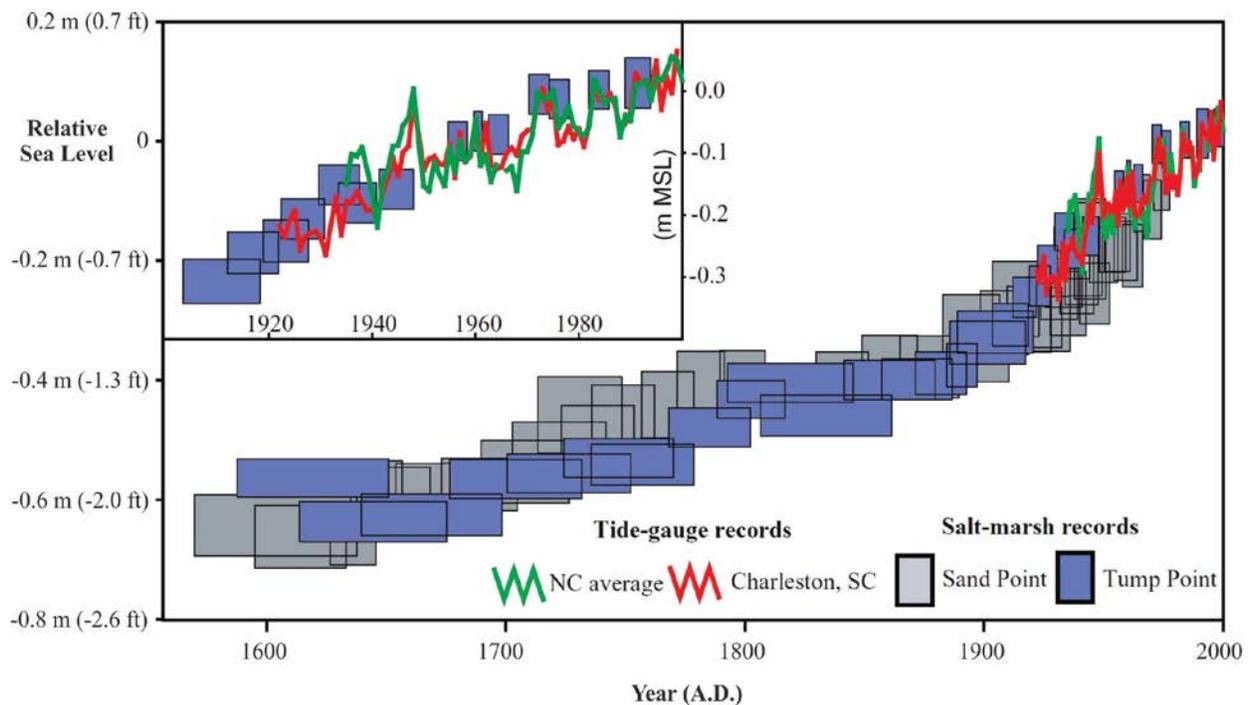


Figure 3. Sea level curve over the scale of the past decades or centuries of years based on N.C. salt marsh records, presented along with the N.C. and S.C. tide gauge records superimposed upon the latter portion of the salt marsh data. The rate of sea level rise has ranged from approximately 0–2 mm/year during the timeframe shown. (Adapted from Kemp et al. 2009)

2.2 Global or Eustatic Sea Level (GSL)

Sea level movement attributable to changes in the volume of water in the world’s ocean basins, in general responding to cooling and warming, is referred to as eustatic or Global Sea Level (GSL) change. There are many forces driving changes in water volume (Table 1, Church et al. 2013) and future GSL is anticipated to be controlled predominantly by the thermal expansion of ocean water and mass loss from glaciers, ice caps, and ice sheets on the Earth’s surface.

Table 1. Major factors contributing to Global Sea Level (GSL), representing the volume change of water in the world’s ocean basins; and their respective inputs to the present rate of GSL change. (Adapted from Church et al. 2013.)

FACTORS CONTRIBUTING TO GLOBAL SEA LEVEL (GSL) FROM 1993-2010	
Thermal Expansion (+) or Contraction (-)	39%
Glaciers (non Greenland and Antarctica)	27%
Greenland and Antarctic ice sheets	21%
Land water storage	13%

2.3 Relative Sea Level (RSL)

Relative sea level is the measurement of the sea surface elevation relative to a local datum incorporating both the global rate of rise and other dynamics affecting land and/or sea movement such as tectonic uplift, land subsidence, glacial isostatic adjustment (GIA), ocean-atmospheric oscillations, and other non-climatic local oceanographic effects (**Table 2**, Church et al. 2013). Importantly, tide gauges and satellites record relative sea level changes at particular locations. For instance, in areas where mountain building is occurring, the land may be rising at a rate close to that of GSL. Therefore, the measured rate of sea level rise would be close to zero. Conversely, in areas where land is subsiding (sinking), sea level measurements will record sea level rise at a higher rate than global sea level rise because GSL is rising and the land is sinking, producing an additive effect.

Table 2. Major factors contributing to positive and negative changes to the surface of the Earth and sea. These changes affect Relative Sea Level (RSL). (Adapted from Church et al. 2013.)

FACTORS CONTRIBUTING TO CHANGES IN THE EARTH & SEA SURFACES	
LAND	SEA
Plate Tectonics	Ocean-Atmospheric Oscillations
Faults	<i>El Niño</i> Southern Oscillation
Volcanic-isostasy Earthquakes	Atlantic Multi-decadal Oscillation Pacific Decadal Oscillation
Glacial Isostatic Adjustment	Oceanographic effects on western boundary currents like the Gulf Stream
Subsidence	River run-off/floods
Structural deformation	Astronomical Tides
Compaction	Wind driven pile up
Loss of interstitial fluids	Sea Surface Topography
(hydrocarbon and/or water)	(changes in water density & currents)

3. Relative Sea Level Change: What causes variation across North Carolina?

Along the North Carolina coast, sea level is rising. The rate of rise varies depending on the location. There are two primary reasons for this variation: vertical land motion (VLM) and the effects of ocean dynamics. These are discussed in this section.

3.1 Vertical Land Motion (VLM)

Two primary regional elements impact vertical land motion that have long-term overprints on North Carolina's relative sea level record – structural deformation of the bedrock underlying the coastal plain (Grow and Sheridan 1988; Klitgord and Hutchinson 1988; N.C. Geological Survey 1991; Snyder et al. 1993) and glacial isostatic adjustment in response to the retreat of glacial ice sheets in North America (Horton et al. 2009; Peltier 2004). These factors segregate the North Carolina Coastal Plain into different zones of relative sea level change.

Tectonic Structural Deformation Resulting in Subsidence and Uplift

The rifting of the supercontinent Pangea and formation of the Atlantic Ocean that began 180 million years ago had (and continues to have) a pronounced impact on the spatial geometry and physical dynamics of the N.C. Coastal Plain and Continental Shelf (Dillon and Popenoe 1988; Gohn 1988; Klitgord and Hutchinson 1988; Riggs et al. 2011). The resulting deformation of the crystalline rock (bedrock) created structural lows providing basins for subsequent deposition of thick sequences of sediment/rock, and structural highs that limited the amount of sediment/rock accumulation. The rates of modern subsidence and uplift are related to the processes still at work that created the highs and lows of the bedrock surface and determined the thickness of sediment/rock accumulation, as well as the subsequent erosion and loss of sediments/rocks. In general, there is a greater amount of subsidence associated with the structural lows that correspond to areas of thick sediment/rock accumulation and conversely, less subsidence, or a greater likelihood of uplift associated with the structural highs and areas of low sediment/rock accumulation areas. This produces the fundamental differences between the southeastern and northeastern North Carolina coastal systems, which are characterized by stability to slight uplift and subsidence, respectively (Riggs 1984; Poponoe 1990; Riggs and Belknap 1988; Schlee et al. 1988; Riggs et al. 1990, 1995; Snyder et al. 1990).

Glacial Isostatic Adjustment (GIA)

GIA describes the Earth's rebound, both positively and negatively, from the melting of kilometers-thick ice sheets that covered much of North America and Europe during the last glacial maximum approximately 20,000 years ago (Peltier 2004). Accumulation and subsequent melting of vast ice masses caused the depression and release, respectively, of the Earth's surface beneath the ice sheet and developed fore-bulges of the surface out in front of the ice sheet. The ongoing rates of GIA rebound are measured directly in the northern portions of the U.S., but are primarily estimated based upon model studies within the southern portions of the country, including North Carolina. More specifically, models for the northeastern North Carolina coastal system demonstrate the region was part of a fore-bulge that lifted the Earth's surface upward during the last glacial maximum, but which has been collapsing (subsiding) since and continues today (Engelhart et al. 2009, 2011; Horton et al. 2009). This phenomenon

also causes some ocean basins to be subsiding as mantle material moves from under the oceans into previously glaciated regions on land.

Other Factors Influencing Vertical Land Motion

The extraction of fluids such as water and fossil fuels from subsurface sediments by extensive pumping is also known to increase regional land subsidence as evidenced in southern Chesapeake Bay, Va.; Houston, TX; etc. (Eggleston and Pope 2013; Coplin and Galloway 1999). However no studies have been conducted citing fluid extraction as a factor in eastern North Carolina, even in the coast's major water *Capacity Use Areas* where high levels of fresh-water aquifer pumping occurs; specifically the Central Coastal Plain Capacity Use Area or in the Capacity Use Area #1 region near the Aurora phosphate mine and Pamlico River Estuary (NC Department of Environment and Natural Resources 2014).

Geological Zonation of the North Carolina Coastal Plain

Studies demonstrate there is a regional effect of uplift and subsidence on RSL rise in North Carolina (Engelhart et al. 2009, 2011; Kemp et al. 2009, 2011; van de Plassche et al. 2014). However on the basis of existing data, it is extremely difficult to separate the effects of structural deformation from GIA processes. Consequently, the Science Panel assumes for the purpose of this analysis that both processes are ongoing and differentially impact the North Carolina coastal system. Because no data are available to constrain the precise inputs of the two processes, they are considered together as a net influence on vertical land motion. Regions with substantial variations in the rate of vertical land motion have been delineated for coastal North Carolina and are described below and graphically depicted in **Figure 4**. The figure was developed by members of the Science Panel and it is important to note the lines represent the general location of divisions in geologic characteristics and are not to be interpreted as delineation for policy implementation.

Zone 1: Carolina Platform: Old crystalline basement rocks form a high platform within this zone that is capped by a relatively thin layer of younger marine sediment units. This results in higher land topography; a broad, shallow, rock-floored continental shelf; and a coastal system of narrow barrier islands and estuaries (Riggs et al. 1995, 2011). This zone is characterized by a relative rate of uplift of 0.24 mm/yr \pm 0.15 mm (van de Plassche et al. 2014).

Zone 2: Albemarle Embayment: The old crystalline basement rocks slope downward to the north forming a deep basin which has been buried through time with a very thick layer of younger marine sediments (Mallinson et al. 2009). This results in very low land topography; a narrow and deep sediment-floored continental shelf; and a coastal system dominated by broad, embayed estuaries and high wave energy barrier islands (Riggs et al. 1995, 2011). This zone is characterized by a high rate of relative subsidence of 1.00 \pm 0.10 mm/yr (Engelhart et al. 2009, 2011; Kemp et al. 2009, 2011).

Zone 3: Cape Lookout Transition Zone: This intermediate zone occurs in the region where the crystalline basement rocks of the Carolina Platform (Zone 1) dip gradually into the deeper basin of the Albemarle Embayment (Zone 2) (Snyder et al. 1990, 1993). The resulting coastal system contains sediment rich barrier islands with extensive beach ridges, dune fields, and moderate sized shore-parallel estuaries (Riggs et al. 1995, 2011). Since there is a general northward slope of both the basement rocks and the younger sequence of marine deposits between the uplift of Zone 1 and the subsidence of Zone 2, the vertical land movement in this area likely falls in a range between those two zones.

Zone 4: Inner Estuarine Hinge Zone: This is an intermediate zone that generally constitutes the central Coastal Plain in northeastern NC. It represents the transition from the upper Coastal Plain to the west and the lower Coastal Plain to the east which is dominated by the Albemarle Embayment (Zone 2) (Brown et al. 1972; Riggs 1984). The crystalline bedrock occurs at intermediate depths and is covered by a moderately thick sequence of older marine sediments. The coastal system within this hinge zone consists of the inner or western portions of the drowned river estuaries that grade westward and upslope into the riverine systems of the stable upper Coastal Plain (Riggs et al. 1995, 2011). Since the Inner Estuarine Hinge Zone occurs between the stable region of the upper Coastal Plain to the west and the subsiding Albemarle Embayment (Zone 2) to the east, subsidence is estimated to have an approximate value between zero and 1 mm/yr (as measured in Zone 2).

The information presented for Zones 1 through 4 is intended to be utilized as estimates of the VLM contribution characterizing the difference between the GSL and the different RSL values observed along the North Carolina coast. This assumption is predicated by the following: (1) the geographic area of each zone is large and therefore the underlying geology is spatially heterogeneous, resulting in different rates of VLM within each zone; (2) similarly, the collapse of the deglaciation fore-bulge is also not uniform across the northern provenance of the state and subsidence rates across Zones 2 and 4 most notably will be different; (3) the VLM numbers were obtained from sediment studies at two discrete locations in two of the four zones—the VLM calculation therefore is applicable to only the specific sampling location(s) and again may not represent the entire zone; and (4) no exact VLM numbers are provided for Zones 3 and 4, rather, the values are expected to be in a range between known values in adjacent zones.

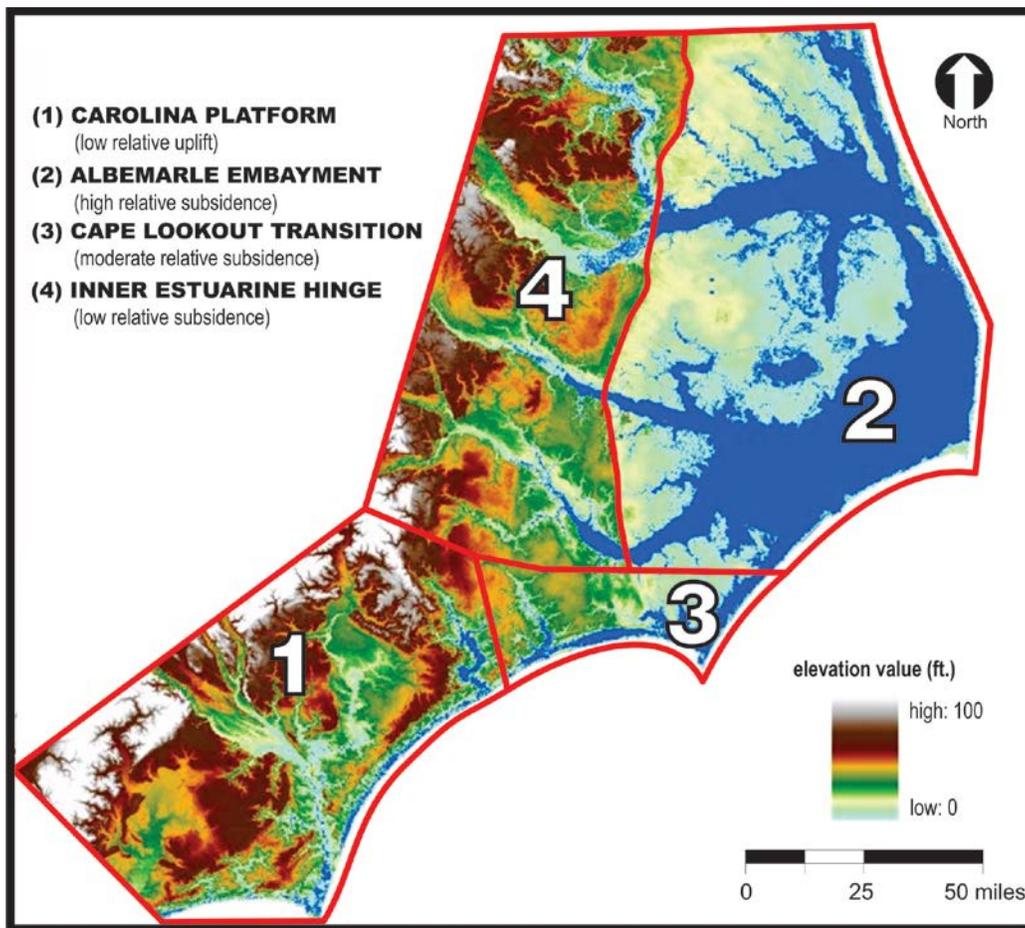


Figure 4. Zones of uplift and subsidence across coastal North Carolina based on major differences in structure, composition, and thickness of the underlying geologic framework.

3.2 Oceanographic Effects

Data observed from tide gauges (NOAA 2014a) show sea level rise rates along the mid-Atlantic coast of more than twice the global sea level rise average rate from 1900 to 2009 of 1.7 mm/yr determined by Church and White (2011). Some of that difference is attributed to vertical land movement, discussed in the previous section, and the remainder to short and longer term oceanographic effects (see **Table 2**). Examples relevant to the N.C. coast include sea level response to the Atlantic Multi-decadal Oscillation (AMO), North Atlantic Oscillation (NAO), and velocity changes and position shifting of the Gulf Stream (Ezer et al. 2013). The signature of these is imprinted in the sea level record (both satellite and tide gauge measurements) and considerable recent research has looked at separating out temporal, local, and global effects.

Sallenger et al. (2012) identified a “hotspot” approximately 600 miles north of Cape Hatteras where the sea level rise rate increase was 3 to 4 times the global rate, while south of Cape Hatteras there was no increase. Houston and Dean (2013) examined the tide gauge analysis of Sallenger et al. (2012) and pointed out that because of long-term quasi-periodic variations in

the record up to 60 years (see Chambers et al. 2012), the records used for computing acceleration were too short. Most studies use a linear (or quadratic) regression analysis to compute the sea level trend and acceleration which is sensitive to both record length and the variation included in the period of coverage. Ezer (2013), and Ezer and Corlett (2012) used an Empirical Mode Decomposition/Hilbert-Huang Transformation (EMD/HHT) to remove the quasi-periodic variations from the trend, thereby allowing the direct computation of the acceleration in the record. They found similar findings to those of Sallenger et al. (2012) and Boon (2012) with marked differences north and south of Cape Hatteras. There is evidence that the Atlantic Ocean circulation is slowing down (Smeed et al. 2014), resulting in a weakening of the Gulf Stream. Ezer et al. (2013) and Ezer (2013) hypothesize that variations in the Gulf Stream location and strength change the sea surface height gradient, raising sea level along the U.S. East Coast north of Cape Hatteras and lowering sea level in the open ocean southeast of the Gulf Stream. They correlate observational data to Gulf Stream changes in support of this hypothesis.

Kopp (2013) examined the findings in the mid-Atlantic of Boon (2012), Sallenger et al. (2012), and Ezer and Corlett (2012) using a different technique, a Gaussian Process model. He confirmed a recent shift toward higher than global sea level rise rates in the mid-Atlantic, but noted that the rates were not unprecedented within the available record and would need to continue for two more decades before they would exceed the range of past variability. Yin and Goddard (2013) and Calafat and Chambers (2013) also examine the relationship between variation in oceanographic observations and sea level change along the Atlantic coast and obtained similar patterns as in Ezer (2013).

Along with these studies of the change in RSL along the Atlantic coast are new studies into the increased frequency of minor flooding. Flooding occurs when sea level, typically during a storm or during high tide, exceeds land elevation. Sweet et al. (2014), Sweet and Park (2014) and Ezer and Atkinson (2014) show that water level exceedance above an elevation threshold for “minor” (meaning, not necessarily associated with a storm event) coastal flooding, established by the local NOAA National Weather Service forecast offices, has increased over time, and that minor, nuisance flooding event frequencies are accelerating at many East and Gulf Coast gauges. They found that some of the increased frequency of flooding resulted both from high rates of VLM at locations like Duck, N.C. and from natural oceanographic variation. These factors were less important at Wilmington, N.C. but the frequency of nuisance flooding has also increased there because of the low elevation threshold established by the local forecast office. Ezer and Atkinson (2014) and Boon (2012) have both examined nuisance flooding using available tide station data. All of these studies strongly indicate that, as mean sea level rises, the frequencies of flooding will increase at all locations.

The studies discussed above, all published in just the past two years, represent the interest and focus on the mid-Atlantic and the challenge of separating naturally varying ocean dynamics

from GSL changes. Relevant to North Carolina is the growing evidence that sea level change is currently greater north of Cape Hatteras (after the Gulf Stream separates from the coast) than it is to the south and that oceanographic effects at times can greatly influence RSL along the coast. At this stage, it is unknown whether oceanographic effects on RSL will persist into the future; however, this is an important area of current oceanographic research which should be followed closely in future sea level rise assessment reports.

The variability of relative sea level change along the North Carolina coast is examined further in the following section, using data measured at tide gauges.

4. Tide Gauge Data in North Carolina

In North Carolina there are five NOAA tide gauges with published rates of sea level change. The measured rates vary along the coastline, with the highest in Dare County in the northeast and the lowest along New Hanover and Brunswick counties to the south. The Science Panel worked closely with Dr. Chris Zervas (*e.g.*, Zervas 2001, Zervas 2009, Zervas et al. 2013) at the NOAA National Ocean Service Center for Operational Oceanographic Products and Services, who provided additional analyses of the tide gauge data for this report.

4.1 Measured Historical Local Sea Level Rise in North Carolina

In order to accurately determine historical sea level change trends nationwide, Zervas (2001, 2009) used National Water Level Observation Network stations with a minimum of a 30-year record, because trends computed with shorter data ranges have wide error bars and in some cases differ noticeably from longer-term stations nearby. The data analyzed are monthly mean sea levels, which are the arithmetic average of all of the hourly data for each complete calendar month. The monthly data are characterized as an autoregressive time series of order 1 and processed such that the monthly seasonal trend is identified and removed and a linear long-term trend is determined (Zervas 2001, 2009). This method accounts for the fact that consecutive monthly mean water levels are not independent variables, and it provides an estimate of the uncertainty associated with the long-term trend.

Published sea level trends are available (NOAA 2014a) through calendar year 2013 for five stations along the North Carolina coast (see **Figure 5**). These long term trends are presented in **Table 3**. In general, the sea level trends from the stations north of Cape Hatteras (Duck, Oregon Inlet) are substantially higher than those from the stations south of Cape Hatteras, with the highest sea level rise in North Carolina measured at Duck.

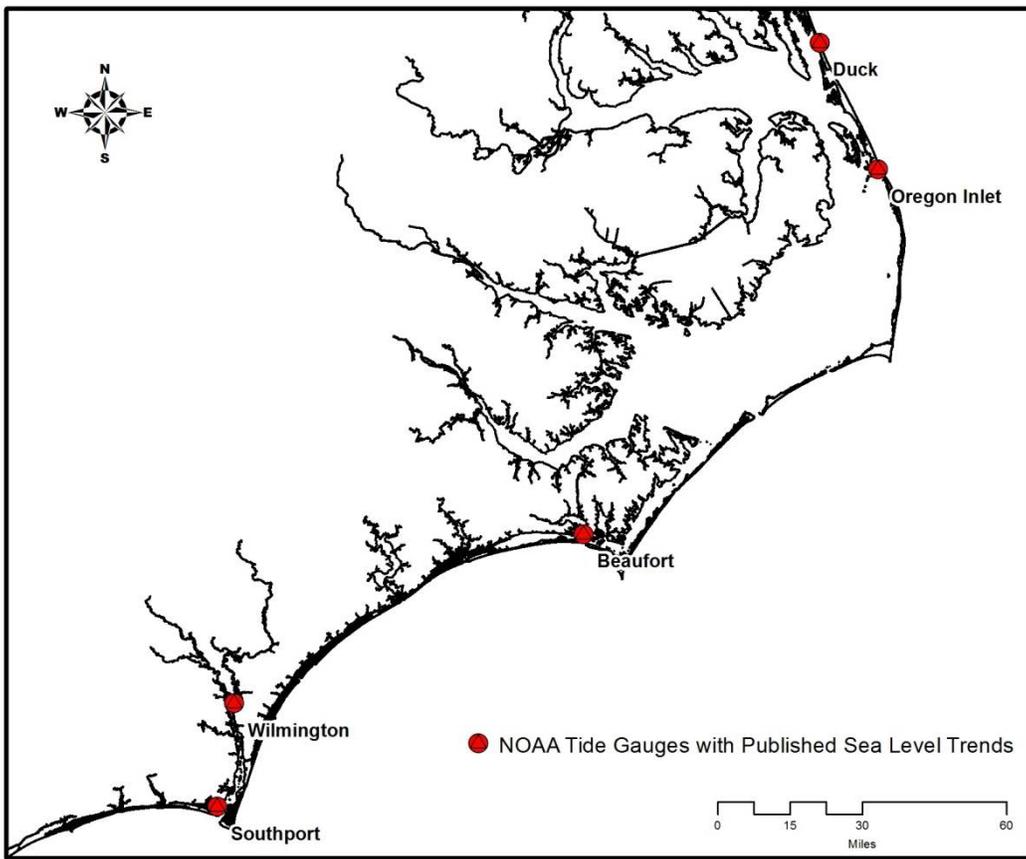


Figure 5. Location of NOAA tide gauges with published sea level trends in North Carolina.

Table 3. Long Term Sea Level Change Trends in North Carolina (NOAA 2014a).

Station (North to South)	Sea Level Change Trend, mm/yr (NOAA 2014a)	Coverage Dates	Time Span of the Data (years)
Duck	4.57 ± 0.84	1978-2013	36
Oregon Inlet	3.65 ± 1.36	1977-2013	37
Beaufort	2.71 ± 0.37	1953-2013	61
Wilmington	2.02 ± 0.35	1935-2013	79
Southport	2.00 ± 0.41	1933-2008	76

The monthly mean sea level trend plots from NOAA for each location are shown for reference in **Figure 6**. It is noted that the Oregon Inlet and Southport gauges have some discontinuity in their records. Zervas (2001, 2009) notes that at some locations where sea level trends were determined, there are long data gaps. However, it is stated that the existing discontinuous data can still provide good estimates of linear mean sea level trends because the vertical datums have been carefully maintained through periodic leveling to stable benchmarks with respect to the adjacent landmass (Zervas 2001, 2009).

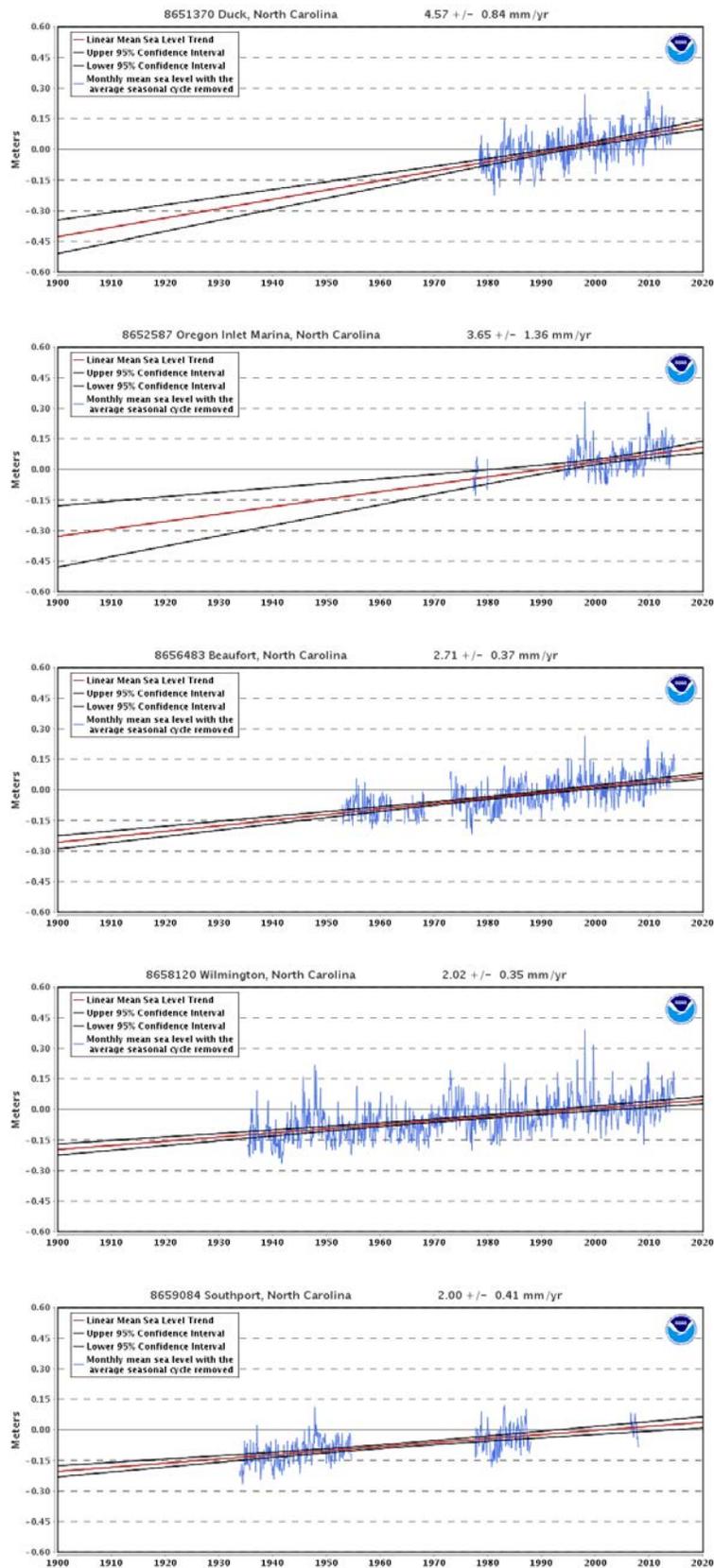


Figure 6. Monthly mean sea levels with seasonal trends removed, for each station with published sea level trends. The long-term linear trend is also shown, including its 95% confidence interval. (NOAA 2014a)

The 2010 Sea Level Rise Assessment Report based its projections on the Duck gauge, the only ocean gauge with a long-term record. The other gauges were not used due to concern that dredging could have altered the tide range and the sea level trend. On the Cape Fear River, mean high water, as recorded by the Wilmington tide gauge, had been found to have risen significantly after the deepened channel efficiently circulated more water (Hackney and Yelverton 1990). Dredging events and corresponding depths of the Cape Fear channel are shown in **Table 4**. The impact of increasing the tide range on sea level depends on how mean low water is altered relative to mean high water. If mean low water goes down the same amount that mean high water goes up, the change is symmetrical and the sea level record is not altered by the dredging.

Dredging impacts have since been analyzed using two methods — numerical modeling and more detailed analysis of the water level records. The North Carolina Flood Mapping Program is upgrading the coastal flood maps using a storm surge model that is initially verified by modeling the daily tides. The present Wilmington and Beaufort tides were compared to the results obtained using the shallower channel depths in place at the beginning of the tidal record (R. Luettich, pers. comm. 2013). The modeling found no significant dredging impacts for the Beaufort gauge. However, the modeling found an increase in the Wilmington tide range of 15 cm since the tide gauge was installed in 1935. Because the model resets mean sea level for each channel condition, assessment of the impact of the tide range changes on sea level measurements was inconclusive.

Table 4. Cape Fear River Channel Deepening Progression. The Wilmington tide gauge was installed in 1935.

Dredging Completion Date	River Channel Depth (feet)
1829-1889	16
1907	20
1913	26
1930	30
1949	32
1958	34
1970	38
2002	42

Zervas (pers. comm., Oct. 16, 2014) updated the tidal analysis for Wilmington including the relative changes in mean high water and mean low water for the 1935 to 2013 period. While changes in the tide range have been observed, there do not appear to be obvious shifts in the monthly mean water levels following the dredging events detailed in **Table 4** (refer to **Figure 6**). For these reasons, dredging impacts on mean sea level are not considered to substantially affect sea level changes measured at the Wilmington tide gauge.

4.2 Vertical Land Movement Estimated from Tide Gauge Data

Because local sea level change measurements include the vertical land movement (subsidence and/or uplift), tide gauge data can be used to assess the magnitude of this movement. Zervas et al. (2013) used tide gauge records to estimate vertical land movement at stations across the U.S. coasts. Long-term gauge records were analyzed with linear mean sea level trends through 2006 as presented in Zervas (2009). Seasonal and regional oceanographic signals were removed as well as an approximated global (eustatic) sea level trend. A linear trend was then fit to the resultant data to estimate vertical land movement at the gauge station. Results were reported in Zervas et al. (2013) for gauges at Oregon Inlet Marina, Beaufort, Wilmington, and Southport. These published results were computed through 2006 for consistency with previously published sea level trends in Zervas (2009). The Science Panel contacted Zervas, who at our request updated the vertical land movement trends through 2013 and included an analysis of the vertical land movement at the Duck gauge. These results (Zervas, pers. comm. Oct. 21, 2014) are presented in **Table 5**. From this analysis, the highest rates of subsidence were found at Duck and the lowest at Wilmington. While the numbers in **Table 5** are not exactly the same as those reported in **Section 3**, the trends are the same as those determined from geologic evidence. It is noted that geological data indicate a small amount of uplift in the Wilmington/Southport area, and tide gauge determined land motion shows a small amount of subsidence. Similar to the published values reported for vertical land motion in **Section 3**, these values are also obtained at discrete locations along the coast, which differ from those precise locations where the geologic data were obtained. This likely explains some of the differences in the exact numerical values. *Most important is the fact that both data sources indicate that subsidence has more influence on relative sea level rise in the northeastern portion of North Carolina than in the southeastern counties.*

Table 5. Vertical Land Movement Trends Determined from Tide Gauge Data in North Carolina.

Station (North to South)	Vertical Land Movement Trend*, (mm/yr)	Coverage Dates	Time Span of the Data (years)
Duck	-1.49 ± 0.39	1978-2013	36
Oregon Inlet	-0.84 ± 0.65	1977-2013	37
Beaufort	-0.99 ± 0.17	1953-2013	61
Wilmington	-0.39 ± 0.19	1935-2013	79
Southport	-0.51 ± 0.15	1933-2008	76
*Zervas pers. comm. Oct. 21, 2014			

5. Future Sea Level in North Carolina

The Science Panel considered three scenarios for future sea level in North Carolina: (1) sea level rise will continue at existing rates as measured at tide gauges, (2) sea level rise will decelerate, and (3) sea level rise will increase in response to changes in the climate. These scenarios are discussed in this section for the 2015-2045 timeframe (30 years, specified by the N.C. Coastal Resources Commission's charge for this report).

5.1 Existing Rates of Sea Level Rise

Table 6 presents the amount of future sea level rise that would occur over 30 years at the tide gauges along the N.C. coast using the published sea level rise (SLR) rates given in **Table 3** (NOAA 2014a). As shown, if existing conditions continue for the next 30 years, sea level would be expected to rise between approximately 2 and 6 inches across the North Carolina coast, with the highest sea levels expected north of Cape Hatteras. This computation assumes that the trends at each gauge will remain the same as historical trends over the 30-year time frame.

Table 6. Relative sea level rise over 30 years at existing published rates (NOAA 2014a) of sea level rise. Magnitude of rise was determined by multiplying the rate \pm the confidence interval (for the high/low estimates respectively) by 30 years.*

Station	Tide Gauge Projections		
	RSLR in 30 years, inches		
	Mean	Low	High
Duck	5.4	4.4	6.4
Oregon Inlet	4.3	2.7	5.9
Beaufort	3.2	2.8	3.6
Wilmington	2.4	2.0	2.8
Southport	2.4	1.9	2.8

*Note: Sea level rise over 30 years was rounded to the nearest tenth of an inch.

5.2 Potential Decrease in Sea Level Rise

The Science Panel examined the scientific research regarding deceleration of sea level rise, meaning a rate lower than existing published global rates of sea level rise, over the next 30 years. There have been many efforts to detect acceleration or deceleration in the past sea level record. AR5 (Rhein et al. 2013) discusses these studies and concludes, as have others (Houston and Dean 2011, 2013; Houston 2013, Chambers et al. 2012), that strong multi-decadal variations in the tide gauge record make it difficult to detect whether there is a long-term

acceleration or deceleration using record lengths less than 60 years (see also **Section 3.2**). While researchers using both tide data and altimetry data have reported analyses that observe deceleration in sea level records (*e.g.*, Houston and Dean 2011, 2013; Ezer 2013), the signal is small and indicative of cyclic or multi-decadal variations. Houston (2013) summarizes the existing studies and concludes that the range of acceleration in the existing record is from -0.01 to 0.01 mm/yr², or just ± 0.18 inches over 30 years, so not a significant factor. There is therefore no justification to apply a global deceleration factor to existing gauge rate projections for the next 30 years.

5.3 Potential Increase in Sea Level Rise

Global Mean Sea Level through 2045

The IPCC is the leading international body for the assessment of climate change and for predicting future global sea level. It operates under the auspices of the United Nations (UN), and reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. Thousands of scientists from all over the world contribute to the work of the IPCC on a voluntary basis (IPCC 2013c). Multiple stages of review are an essential part of the IPCC process to ensure a comprehensive, objective, and transparent assessment of the current state of knowledge of the science related to climate change. The review process includes wide participation, with hundreds of reviewers critiquing the accuracy and completeness of the scientific assessment contained in the drafts (IPCC 2013d). The IPCC's most recent publication is the Fifth Assessment Report (AR5, Church et al. 2013), which was released in draft form on Sept. 30, 2013, and published in final form in March 2014. For the 30-year time frame requested by the CRC, the panel considers the IPCC scenarios to be the most scientifically vetted predictions to use for global sea level rise.

Future climate predictions require assumptions about activities that may alter the climate. Accordingly the IPCC has developed a series of scenarios or *Representative Concentration Pathways* (RCPs), each defined by a specific mix of emissions, concentrations and land use. RCP 2.6 is the "best case" scenario in which greenhouse gases are lowest in concentration, and RCP 8.5 is the "worst case" with the highest concentration.

AR5 states that it is very likely that the rate of global mean sea level rise during the 21st century will exceed that observed in the 20th, in response to increased ocean warming and loss of mass from glaciers and ice sheets. **Table 7** presents the range of sea level rise predictions through the year 2050 from a variety of process-based model scenarios (Church et al. 2013). This table was developed by converting the original table in the IPCC report (Table AII.7.7) from meters to inches, rounded to the nearest tenth of an inch.

Table 7. Global mean sea level rise projections with respect to 1986-2005 at Jan. 1 on the years indicated, with uncertainty ranges for the four IPCC Representative Concentration Pathways (modified from Table AII.7.7, IPCC 2013a).*

Year	RCP 2.6 (inches)	RCP 4.5 (inches)	RCP 6.0 (inches)	RCP 8.5 (inches)
2010	1.6 [1.2 to 2.0]			
2020	3.1 [2.4 to 3.9]	3.1 [2.4 to 3.9]	3.1 [2.4 to 3.9]	3.1 [2.4 to 4.3]
2030	5.1 [3.5 to 6.3]	5.1 [3.5 to 6.3]	4.7 [3.5 to 6.3]	5.1 [3.9 to 6.7]
2040	6.7 [5.1 to 8.7]	6.7 [5.1 to 8.7]	6.7 [4.7 to 8.3]	7.5 [5.5 to 9.4]
2050	8.7 [6.3 to 11.0]	9.1 [6.7 to 11.4]	8.7 [6.3 to 11.0]	9.8 [7.5 to 12.6]
*Note: Projections were rounded to the nearest tenth of an inch.				

In addition to the process-based models, the IPCC (Church et al. 2013) also reviewed other approaches to sea level projections including semi-empirical models, paleo-records of sea level change, and ice sheet dynamics. They state that of the approaches examined, they have greater confidence in the process-based projections, and that the global mean sea level rise during the 21st century is likely to lie within the 5-95% uncertainty ranges given by the process-based projections and shown in **Table 7** (Church et al. 2013). For completeness, all scenarios are presented in **Table 7**. However, to provide a range of potential effects across the North Carolina coast, the low greenhouse gases (RCP 2.6) and high greenhouse gases (RCP 8.5) model scenarios are presented as upper and lower bounds of the potential range of future sea level rise. The endpoints of the range of global sea level rise scenarios for this report were computed as follows:

- 1) Use linear interpolation of **Table 7** values to estimate sea level and its uncertainty range in 2015 and 2045.
- 2) Subtract each 2015 value from the corresponding 2045 value to obtain magnitude of the projected rise over the 30-year time frame.

When values with quantified uncertainties are added and subtracted, the uncertainties associated with those values are added in quadrature (*i.e.*, added as the square root of the sum of squares). The uncertainties in **Table 8** have been added in quadrature to obtain the uncertainty of the change in SLR from 2015 to 2045. This provides a better estimate of the confidence interval than simply adding or subtracting the uncertainty values. In the case of **Table 8** where there are uneven confidence intervals, the larger of the two was used to obtain the quadrature uncertainty.

Table 8. Global sea level rise from 2015 to 2045 as predicted by IPCC Scenarios.*

Predicted Amount of Sea Level Rise by Year	Scenario RCP 2.6 (inches)	Scenario RCP 8.5 (inches)
2015	2.4 [1.8 to 3.0]	2.4 [1.8 to 3.1]
2045	7.7 [5.7 to 9.8]	8.7 [6.5 to 11.0]
Change in SLR (2015 to 2045)	5.3 [3.1 to 7.6]	6.3 [3.8 to 8.8]
<i>*Note: Projections were rounded to the nearest tenth of an inch.</i>		

Note that the range of values for the two scenarios overlap and differ only by approximately 1 inch, reflecting the fact that these scenarios are similar initially and begin to differ significantly after 2045.

Linking Global Sea Level Rise Projections to Local RSL

In order to consider the relationship of global sea level rise projections to those in North Carolina, factors causing variability in sea level trends across the state must be quantified. As discussed in **Section 4.2**, vertical land movement has been quantified using tide gauge data; additional information on vertical land movement is presented in **Section 3.1** based on geologic studies. The VLM trends are dependent upon long-term geologic factors; therefore they are considered to be likely to persist into the future.

While considerable study has been devoted to identifying oceanographic effects on relative sea level rise (**Section 3.2**), it is unknown whether these effects will persist in the 30-year time period considered for sea level rise projections in this report. Therefore, for the present report, no quantification of oceanographic effects has been included in the sea level projections. Should continued research suggest that these effects may be persisting, future reports may incorporate these factors.

In order to make the global sea level rise values from **Table 8** relevant for North Carolina, VLM was used as a proxy for local effects. This was done by adding 30-year VLM projections (30 years times the values presented in **Table 4**) to the global sea level projections in **Table 8**. As discussed previously, the confidence intervals on the VLM and global projections were added in quadrature to assess uncertainty associated with the projections.

To provide a range of potential increase scenarios, the 30-year projection values were computed for the low and high values of the projected sea level rise from 2015 to 2045 using scenarios RCP 2.6 and RCP 8.5. For comparison with **Table 6**, values were rounded to the nearest tenth of an inch. Results, including the 95% confidence intervals, are presented in **Tables 9 and 10**. The low value in each table is the 95% confidence interval subtracted from the mean, and the high is the mean plus the confidence interval.

Table 9. Relative sea level rise by 2045 considering potential increased rates of sea level rise (RCP 2.6 which is the lowest greenhouse gas emission scenario, combined with vertical land movement at each tide gauge).*

Station	RCP 2.6 + VLM			
	RSLR in 30 years, inches			
	Mean	Low	High	95% CI
Duck	7.1	4.8	9.4	2.3
Oregon Inlet	6.3	3.9	8.7	2.4
Beaufort	6.5	4.2	8.7	2.3
Wilmington	5.8	3.5	8.0	2.3
Southport	5.9	3.7	8.2	2.3
*Note: Projections were rounded to the nearest tenth of an inch.				

Table 10. Relative sea level rise by 2045 considering potential increased rates of sea level rise (RCP 8.5 which is the highest greenhouse gas emission scenario, combined with vertical land movement at each tide gauge).

Station	RCP 8.5 + VLM			
	RSLR in 30 years, inches			
	Mean	Low	High	95% CI
Duck	8.1	5.5	10.6	2.5
Oregon Inlet	7.3	4.7	9.9	2.6
Beaufort	7.5	5.0	10.0	2.5
Wilmington	6.8	4.3	9.3	2.5
Southport	6.9	4.4	9.4	2.5
*Note: Projections were rounded to the nearest tenth of an inch.				

As shown, under alternative rates of increase in sea level rise as a function of varying emissions scenarios, sea level could rise from a low estimate of 3.5 inches to high of 10.6 inches by 2045, depending on location. Locations with higher rates of subsidence have correspondingly higher relative sea level rise projections.

5.4 Future Sea Level Rise across North Carolina

Preparing a map depicting varying sea level rise estimates across the state of North Carolina is difficult, because the local effects are quantified only at the tide gauge locations. The four

geologic regions presented in **Figure 4** indicate areas within which effects driven by local vertical land movement are expected to be similar based on the geologic data. Further, Session Law 2012-202 (Appendix B), specifies that the Coastal Resources Commission consider the four regions presented in the N.C. Dept. of Environment and Natural Resources' April 2011 report entitled "North Carolina Beach and Inlet Management Plan" (BIMP) in making geographically variable sea level rise assessments. Therefore the following discussion to address similarities and differences of the regions provided in the geologic map in **Figure 4** compared with the BIMP map (shown in **Figure 7**) is provided.



Figure 7. Beach and Inlet Management Plan (BIMP) Regions referenced in S.L. 2012-202.

Region 1 (Carolina Platform) in **Figure 4** corresponds roughly to Regions 1 and 2a, plus part of Region 2b, as drawn in the BIMP (**Figure 7**). The gauges in that part of North Carolina are the Wilmington and Southport gauges, which are very similar in characteristics, with similar future increased sea level rise predictions. Region 2 (Albemarle Embayment) in **Figure 4** encompasses Regions 3b, 4a, 4b, and 4c, as well as a portion of Region 3a as drawn in the BIMP (**Figure 7**). Both the Oregon Inlet and Duck tide gauges are located in this area. The Duck gauge has the highest expected sea level rise by 2045 across the state, with the projections at Oregon Inlet slightly lower. Region 3 in **Figure 4** (Cape Lookout Transition) corresponds approximately to BIMP Region 2c, with parts of Region 2b and 3a included as well. This region contains the

Beaufort tide gauge, which has an expected sea level rise by 2045 similar to the Oregon Inlet gauge. Region 4 (Inner Estuarine Hinge) in **Figure 4** does not correspond to any of the BIMP regions, and contains no tide gauges.

For any management decisions, the CRC will have to evaluate the potential division of the state by region. Additional monitoring and data will facilitate this type of decision.

6. Making Sense of the Predictions

The report presents a range of sea level values that may occur by 2045 across the North Carolina coast. Providing a range of values reflects both the uncertainty in the predictions with regards to future climate and the varying nature of sea level. From a planning perspective, the *risk* of flooding decreases by selecting a higher elevation within the expected range of sea levels. The goal in planning is to match the selected elevation with a level of *acceptable risk* for a particular project (road, bridge, hospital, etc.) based on the expected range of water levels. The U.S. Army Corps of Engineers (USACE 2014) has adopted a planning process similar to this, requiring that every coastal project be evaluated using three sea level scenarios. Doing so allows the project planner to estimate the risk of any impacts of sea level rise, and if the potential impact is found to not be acceptable, require a change to the project design. The adoption of this planning guidance by the USACE is relevant to North Carolina as it is required on every federal coastal project.

We also note that the difference between the highest (**Table 10**) and lowest (**Table 6**) potential increase in mean sea level varies from just 2.7 inches at Duck to 4.5 inches at Southport. This small change reflects the short 30-year time span of the projection. This small amount adds to, but is inconsequential relative to, the extreme water levels experienced in a storm surge and is small relative to the twice daily excursion of the tide. But since it is cumulative and rising, areas of N.C. will be impacted. Recent research into the frequency of coastal flooding has shown that, regardless of the rate of rise, as sea level increases North Carolinians should expect more frequent flooding of low-lying areas. These impacts are already being observed in North Carolina (Sweet et al. 2014; Sweet and Park 2014; Ezer and Atkinson 2014).

The short 30-year period also allows increased confidence in the forecast, relative to a 60- or 100-year forecast during which more rapid climate change is expected. One of the major sources of uncertainty in estimates of sea level rise is the behavior of ice sheets. However, the IPCC states that only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the likely predicted range during the 21st century (Church et al. 2013). As research evolves with more data and our understanding of these phenomena improves, forecasts will be updated. This is one of the many reasons that the panel recommends updating this report every five years.

Because our focus is on the next 30 years, people whose planning requirements extend beyond that should consult other reports on sea level such as the IPCC (2013b) or the USACE guidance (2014) and their online sea level calculator (<http://www.corpsclimate.us/ccaceslcurves.cfm>).

7. Recommendations for Improved Sea Level Rise Monitoring in North Carolina

Tide gauges provide a critical and permanent record of sea level in North Carolina. Consequently, as we recommended in our 2010 report, it is important to sustain the long-term tidal observations. At a minimum, continued monitoring at the recently established gauge (2010) at Cape Hatteras and establishment of long-term tidal monitoring in the Albemarle Sound and at a location in the Pamlico Sound near the entrance to the Neuse River as well as on the innermost portion of the drowned river estuaries (*e.g.*, New Bern, Washington, and Edenton) would start to fill gaps in knowledge of not only local sea level changes but also the magnitude of tidal surge and wind set-up during storms of differing intensity and track across the North Carolina coast. Ongoing efforts by the North Carolina Division of Emergency Management include maintenance of seven new gauges in the Albemarle and Pamlico Sounds. These gauges should also be maintained long-term to augment the sea level record in North Carolina.

The state should also consider augmenting existing Continuously Operating Reference Stations (CORS) to provide coverage in all the regional zones in order to quantify and refine land subsidence and uplift on the coastal plain. Since 2007 the N.C. Geodetic Survey has been installing CORS which are used to improve the accuracy and ease of surveying using Global Position Survey (GPS) techniques. These stations use the GPS satellites to determine the exact location and elevation of the station as frequently as once a second. Thirty-three stations are presently installed in or near the four zones in **Figure 4**. With time these stations will provide detailed measurement of land elevation changes that can be used to put water level records in perspective. The collection and analysis of additional sediment cores is also desirable to compliment the CORS stations. To be useful, all new CORS and tide gauge locations will need to be sustained for decades, so the sooner they are deployed, the better.

8. Recommendations for Updating the Report

Predicting future sea level rise in North Carolina will continue to be an important topic of interest. As we have seen over the past five years, knowledge in climate science and forecast models is rapidly advancing — improving predictions and reducing uncertainty. Continued monitoring of global and regional sea levels using satellite data will improve as the record length is extended, and these data should be reviewed for consideration in future reports. The panel again recommends a general reassessment of sea level rise in North Carolina every five years. Information from future analyses of CORS GPS stations and from additional geologic research (*e.g.*, expanded regional salt marsh studies) should be considered to provide additional information on vertical land movement across the state. Continuing research on oceanographic impacts on sea level rise should be followed closely. Detailed analyses of tide gauge data and potential dredging impacts are areas of research that the CRC may wish to pursue on a contract basis with researchers in those fields.

9. Summary

Sea level is rising across the entire coast of North Carolina. This report discusses the variation in sea level rise across the state's coastline and provides projections of future sea level. The following points summarize the results of this report:

- The rate of sea level rise varies within NC, depending on location. Two main factors affect the local rate of sea level rise: (1) vertical movement of the Earth's surface, and (2) effects of ocean dynamics (oceanographic influences).
- There is evidence from both geological data and tide gauges that there is more subsidence north of Cape Lookout than south of Cape Lookout. This contributes to higher measured rates of sea level rise along the northeastern N.C. coast.
- Oceanographic research points to a link between speed and position of the Gulf Stream and local sea level. This effect has been reported primarily north of Cape Hatteras.
- At existing rates of sea level rise, over a 30-year time frame, sea level rise across the North Carolina coast would vary from a low estimate of 2.4 inches (with a range between 1.9 and 2.8 inches) at Southport to a high estimate of 5.4 inches (with a range between 4.4 and 6.4 inches) at Duck.
- In a scenario with low greenhouse gas emissions, projected potential sea level rise over a 30-year time frame would vary from a low estimate of 5.8 inches (with a range between 3.5 and 8.0 inches) at Wilmington to a high estimate at Duck of 7.1 inches (with a range between 4.8 and 9.4 inches).
- In a scenario with high greenhouse gas emissions, projected potential sea level rise over a 30-year time frame would vary from a low estimate of 6.8 inches (with a range

between 4.3 and 9.3 inches) at Wilmington to a high estimate at Duck of 8.1 inches (with a range between 5.5 and 10.6 inches).

- Recent research into the frequency of coastal flooding has shown that, regardless of the rate of rise, as sea level increases North Carolinians should expect more frequent flooding of low-lying areas.

Because the science is changing rapidly, it is recommended that this assessment be updated every five years, and that water level monitoring and land movement measurements be sustained and additional gauges placed in as yet unmonitored locations where necessary.

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Appendix A. CRC Charge to the Science Panel, June 11, 2014

The CRC has determined that the issue of potential sea-level rise is of extreme importance to the State, its policy makers and the citizens of NC. It is further noted that the periodic updates of current data are vital to help formulate future policy. The CRC therefore charges the Science Panel to conduct a comprehensive review of scientific literature and available North Carolina data that addresses the full range of global, regional, and North Carolina specific sea-level change. The CRC further determines that the scope and time period of the study and report regarding sea-level rise shall be limited to a “Rolling 30-Year Time Table”. It is the intent of the CRC that this rolling 30-year time table will be updated every five years. The CRC further directs the Science Panel to report regional ranges of sea-level rise as described in S.L. 2012-202

Timeline

S.L. 2012-202 requires the Science Panel to deliver your report to the CRC no later than March 31, 2015.

This will be the version that will be made available for public comment, and we would like this version to include the review and responses as described in the technical peer review process. In order to complete the technical peer review process we are asking you to deliver your initial draft to us by **December 31, 2014**. The technical peer review timeline is as follows:

1. CRC sends the initial draft report for Drs. Dean and Houston's review on January 1, 2015.
2. Drs. Dean and Houston write a brief review with comments and suggestions as appropriate, and forwards to the Science Panel through CRC by January 21, 2015.
3. Science Panel submits a response to Drs. Dean and Houston's comments by February 15, 2015.
4. Drs. Dean and Houston respond in writing as to whether the Science Panel has adequately addressed their comments, by February 28, 2015.

All four written documents will be publicly disseminated together without change.

Following the March 31, 2015 public release of the draft report, there will be an extended public comment period through December 31, 2015, as well as the preparation of an economic and environmental cost-benefit study. The Science Panel will not be asked to prepare the cost-benefit study. The CRC will ask the Science Panel to finalize the report in early 2016, following the close of the public comment period.

Appendix B. General Assembly of North Carolina: Session 2011, Session Law 2012-202, House Bill 819

SECTION 2.(a) Article 7 of Chapter 113A of the General Statutes is amended by adding a new section to read:

"§ 113A-107.1. Sea-level policy.

The General Assembly does not intend to mandate the development of sea-level policy or the definition of rates of sea-level change for regulatory purposes.

No rule, policy, or planning guideline that defines a rate of sea-level change for regulatory purposes shall be adopted except as provided by this section.

Nothing in this section shall be construed to prohibit a county, municipality, or other local government entity from defining rates of sea-level change for regulatory purposes.

All policies, rules, regulations, or any other product of the Commission or the Division related to rates of sea-level change shall be subject to the requirements of Chapter 150B of the General Statutes.

The Commission shall be the only State agency authorized to define rates of sea-level change for regulatory purposes. If the Commission defines rates of sea-level change for regulatory purposes, it shall do so in conjunction with the Division of Coastal Management of the Department. The Commission and Division may collaborate with other State agencies, boards, and commissions; other public entities; and other institutions when defining rates of sea-level change."

SECTION 2.(b) The Coastal Resources Commission and the Division of Coastal Management of the Department of Environment and Natural Resources shall not define rates of sea-level change for regulatory purposes prior to July 1, 2016.

SECTION 2.(c) The Coastal Resources Commission shall direct its Science Panel to deliver its five-year updated assessment to its March 2010 report entitled "North Carolina Sea Level Rise Assessment Report" to the Commission no later than March 31, 2015. The Commission shall direct the Science Panel to include in its five-year updated assessment a comprehensive review and summary of peer-reviewed scientific literature that address the full range of global, regional, and North Carolina-specific sea-level change data and hypotheses, including sea-level fall, no movement in sea level, deceleration of sea-level rise, and acceleration of sea-level rise. When summarizing research dealing with sea level, the Commission and the Science Panel shall define the assumptions and limitations of predictive modeling used to predict future sea-level scenarios. The Commission shall make this report available to the general public and allow for submittal of public comments including a public hearing at the first regularly scheduled meeting

after March 31, 2015. Prior to and upon receipt of this report, the Commission shall study the economic and environmental costs and benefits to the North Carolina coastal region of developing, or not developing, sea-level regulations and policies. The Commission shall also compare the determination of sea level based on historical calculations versus predictive models. The Commission shall also address the consideration of oceanfront and estuarine shorelines for dealing with sea-level assessment and not use one single sea-level rate for the entire coast. For oceanfront shorelines, the Commission shall use no fewer than the four regions defined in the April 2011 report entitled "North Carolina Beach and Inlet Management Plan" published by the Department of Environment and Natural Resources. In regions that may lack statistically significant data, rates from adjacent regions may be considered and modified using generally accepted scientific and statistical techniques to account for relevant geologic and hydrologic processes. The Commission shall present a draft of this report, which shall also include the Commission's Science Panel five-year assessment update, to the general public and receive comments from interested parties no later than December 31, 2015, and present these reports, including public comments and any policies the Commission has adopted or may be considering that address sea-level policies, to the General Assembly Environmental Review Commission no later than March 1, 2016.