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 NC General Assembly Session Law 2012-202.

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 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 and easily replicated, with all information readily available. The numerical values employed were obtained from publicly available sources and our approach is straightforward and easy to duplicate.

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

- 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 are a significant source of spatial variability in relative sea level rise rates along the North Carolina coast.
- Emphasis on the spatial variation of relative sea level rise as evidenced by the analysis of rate for the data collected by the NOAA tide gauges.
- Inclusion of scenario based global sea level rise predictions from the most recent Intergovernmental Panel on Climate Change (IPCC) Report (AR5).
- Development of a range of predictions at each of the long-term tide gauges along the North Carolina coast based on a combination of the tide gauge information and the IPCC scenarios.

Summary: Sea level is rising across the coast of North Carolina. The rate of sea level rise varies, depending on location (spatially) and the time frame for analysis (temporally). Two main factors affect the spatial variation of rate 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 subsidence north of Cape Hatteras than south of Cape Hatteras. This contributes to higher measured rates of sea level rise along the northeastern NC coast. Oceanographic research points to a link between speed and position of the Gulf Stream and sea level. This effect has been reported primarily north of Cape Hatteras, and also contributes to higher measured rates of sea level rise along the northeastern coast.

The differences in the rate of sea level rise are evident in the sea level rise trends reported by NOAA (the National Oceanographic and Atmospheric Administration) at tide gauge stations along the North

Carolina coast. Five tide gauges along the state's coast have enough data collected to have reported sea level trends. Two are located in Dare County: one at the Army Corps of Engineers Field Research Facility in Duck and another at the Oregon Inlet Marina. Another is located in Carteret County at the Duke Marine Lab dock in Beaufort. The fourth station is located in Wilmington, at the Army Corps of Engineers' maintenance yard and docks at Eagle Island. This location is in New Hanover County and immediately adjacent to Brunswick County. These stations are all continuing to record water level data. The final station was located at the Southport Fishing Pier; it is no longer active. NOAA makes available these data and an analysis of rate based on a linear regression. Data are included over the time period from the initial installation of the gauge through December 2013 for gauges at Duck, Oregon Inlet Marina, Beaufort and Wilmington and through 2006 for Southport. NOAA reports a high, a low, and a mean value for the relative rate of sea level rise using a 95% confidence level. In Table ES1, rate is converted to elevation by multiplying by 30 years–the time frame specified by the CRC for the projections in this update.

In order to determine the local effect due to geologic and oceanographic processes, the global rate of sea level rise of 1.7 ± 0.2 mm/yr is multiplied by 30 years and the difference between the gauge projection and the global effect is computed. Results are shown in Table ES1. In summary, at existing rates of sea level rise, over a 30 year time frame, sea level rise across the North Carolina coast would range from approximately 2 to 3 inches (at Wilmington and Southport) to approximately 4 to 6 inches (at Duck). At present, 2 inches is estimated to be due to global effects and the remaining due to local effects.

Table ES1. Sea level rise over 30 years at existing published rates of sea level rise. Magnitude of rise was determined by multiplying the rate ± the confidence interval (for the high/low estimates respectively) by 30 years.

Station	Gauge Projections			Local Effects			Global Effects		
	RSLR in 30 years, inches			RSLR in 30 years, inches			SLR in 30 years, inches		
	Mean	High	Low	Mean	High	Low	Mean	High	Low
Duck	**5.4**	**6.4**	**4.4**	3.4	4.2	2.6	2.0	2.2	1.8
Oregon Inlet Marina	**4.3**	**5.9**	**2.7**	2.3	3.7	0.9	2.0	2.2	1.8
Beaufort	**3.2**	**3.6**	**2.8**	1.2	1.4	1.0	2.0	2.2	1.8
Wilmington	**2.4**	**2.8**	**2.0**	0.4	0.6	0.2	2.0	2.2	1.8
Southport	**2.4**	**2.8**	**1.9**	0.4	0.6	0.1	2.0	2.2	1.8

The Intergovernmental Panel on Climate Change's most recent report (AR5) provides scenario based global sea level rise projections. The scenarios chosen to model sea level rise in the next 30 years are the low greenhouse gas emissions scenario (RCP 2.6) and the high greenhouse gas emissions scenario (RCP 8.5). (All other scenario projections fall within the range of these values). Assuming that the local effects will be constant during the next 30 years, the spatially varying relative sea level rise expected based on the projections of the IPCC scenarios is determined by adding the 30-year local effects from Table 1 to the IPCC global projections. Table ES2 provides the sea level rise projections over 30 years for the low emissions scenario; Table ES3 provides the projections for the higher emissions scenario. The additional impact of including the IPCC projections as compared with tide gauge projections only is 3 inches with a range from 2 to 5 inches.

Table ES2. Sea level rise by 2045 considering potential increased rates of sea level rise (IPCC 2013 for RCP 2.6 which is the lowest greenhouse gas emission scenario).

Station	Local Effects			Future Global Effects (Scenario Contribution)			Tide Gauge + Future Global Effects		
	RSLR by 2045, inches			SLR by 2045, inches			RSLR by 2045, inches		
	Mean	High	Low	Mean	High	Low	Mean	High	Low
Duck	3.4	4.2	2.6	5.3	6.9	3.9	**8.7**	**11.1**	**6.5**
Oregon Inlet Marina	2.3	3.7	0.9	5.3	6.9	3.9	**7.6**	**10.6**	**4.8**
Beaufort	1.2	1.4	1.0	5.3	6.9	3.9	**6.5**	**8.3**	**4.9**
Wilmington	0.4	0.6	0.2	5.3	6.9	3.9	**5.7**	**7.5**	**4.1**
Southport	0.4	0.6	0.1	5.3	6.9	3.9	**5.7**	**7.5**	**4.0**

Table ES3. Sea level rise by 2045 considering potential increased rates of sea level rise (IPCC 2013 for RCP 8.5 which is the highest greenhouse gas emission scenario).

Station	Local Effects			Future Global Effects (Scenario Contribution)			Tide Gauge + Future Global Effects		
	RSLR by 2045, inches			SLR by 2045, inches			RSLR by 2045, inches		
	Mean	High	Low	Mean	High	Low	Mean	High	Low
Duck	3.4	4.2	2.6	6.3	8.1	4.7	**9.7**	**12.3**	**7.3**
Oregon Inlet Marina	2.3	3.7	0.9	6.3	8.1	4.7	**8.6**	**11.8**	**5.6**
Beaufort	1.2	1.4	1.0	6.3	8.1	4.7	**7.5**	**9.5**	**5.7**
Wilmington	0.4	0.6	0.2	6.3	8.1	4.7	**6.7**	**8.7**	**4.9**
Southport	0.4	0.6	0.1	6.3	8.1	4.7	**6.7**	**8.7**	**4.8**

Using the Projections: The range of sea level values (from 5 to 12 inches) reported in Table ES3 reflects both the uncertainty in the predictions and the spatially varying nature of sea level. 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 involved in planning along the North Carolina coast must determine acceptable levels of risk and from that determination, select appropriate planning numbers. Planning objectives spanning longer time frames (greater than 30 years) will require a re-assessment of the numbers provided in Tables ES1 through ES3.

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

- sustain water level and land movement measurements and establish additional gauges to provide more complete spatial coverage,
- 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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1. Introduction

In 1954, Hurricane Hazel made landfall at the North Carolina, South Carolina border 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 5 or 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 6 inches higher (~10 inches north of Cape Hatteras). As reported here, 30 years from now it may be 9 inches higher (~15 inches north of Cape Hatteras), maybe more. 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 overtime it "exacerbates existing coastal hazards such as flooding from rain or tide, erosion, and storm surge" (Ruppert 2014). Over time rising waters also increase the occurrence of minor or *nuisance* flooding during lesser events (Sweet et al. 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 SL 2012-202 from the NC legislature, requested the first 5-year update using the latest science to estimate future sea level over the next 30 years, to 2045 (see Appendix A for the charge from the CRC and Appendix B for SL 2012-202).

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 International Panel on Climate Change (IPCC 2013a, 2013b). 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.

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 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 which control sea level change;

2) Provide and explain how sea level change varies across coastal North Carolina and the factors which 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;

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 at the Relative Sea Level or RSL, which is the combination of three main factors including the *Global Sea Level* (GSL), *Vertical Land Movement* (VLM) and *Oceanographic Effects* (OE), such that:

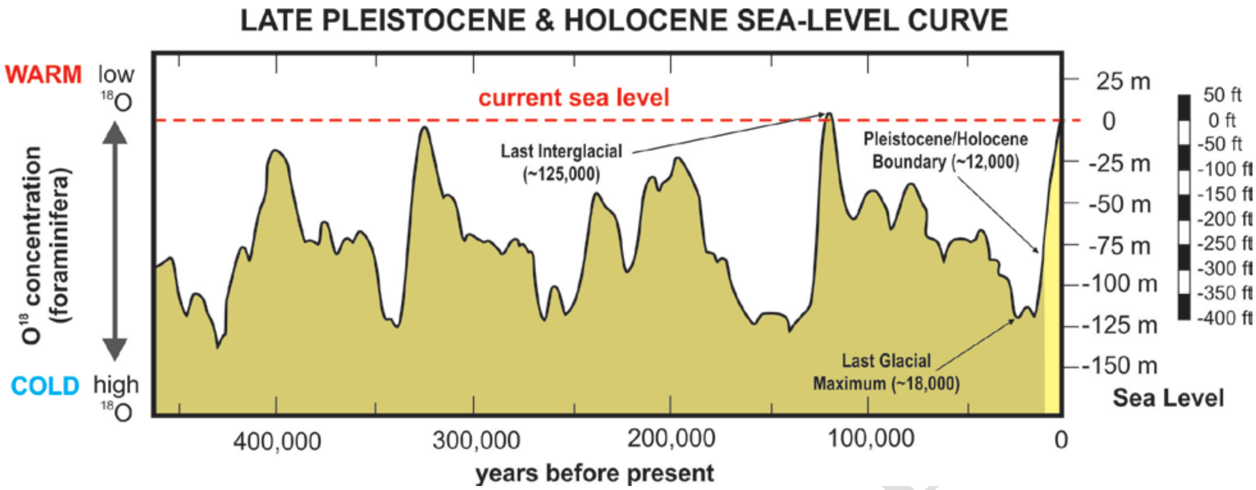
RSL = GSL + VLM + OE

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 rate of 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 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., carbon dioxide concentration in ice cores, oxygen isotopes in calcium carbonate fossils, coral reef terraces, marsh peat elevation and geochemistry, paleo-shorelines, etc. (Cohen and Gibbard 2011; NOAA 2014]. The cyclicity of the "Ice Ages" has been used to signify the geologic period of the Quaternary, which includes both the Pleistocene and Holocene Epochs.

As depicted in **Figure 1** (Imbrie et al. 1984) the most previous interglacial (warm) period was approximately 125,000 years ago where sea level was ~16 feet above present, which was subsequently followed by a period of glaciation that reached a maximum of ~18,000 years ago where sea level was ~400 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). 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 over the last 2000 years, (**Figures 2 and 3**; Kemp et al. 2009).



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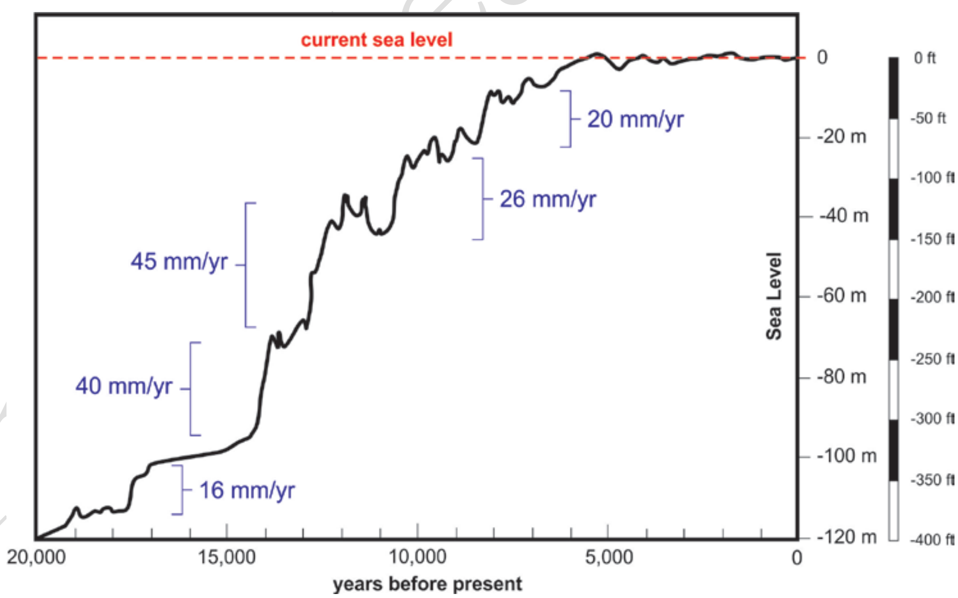

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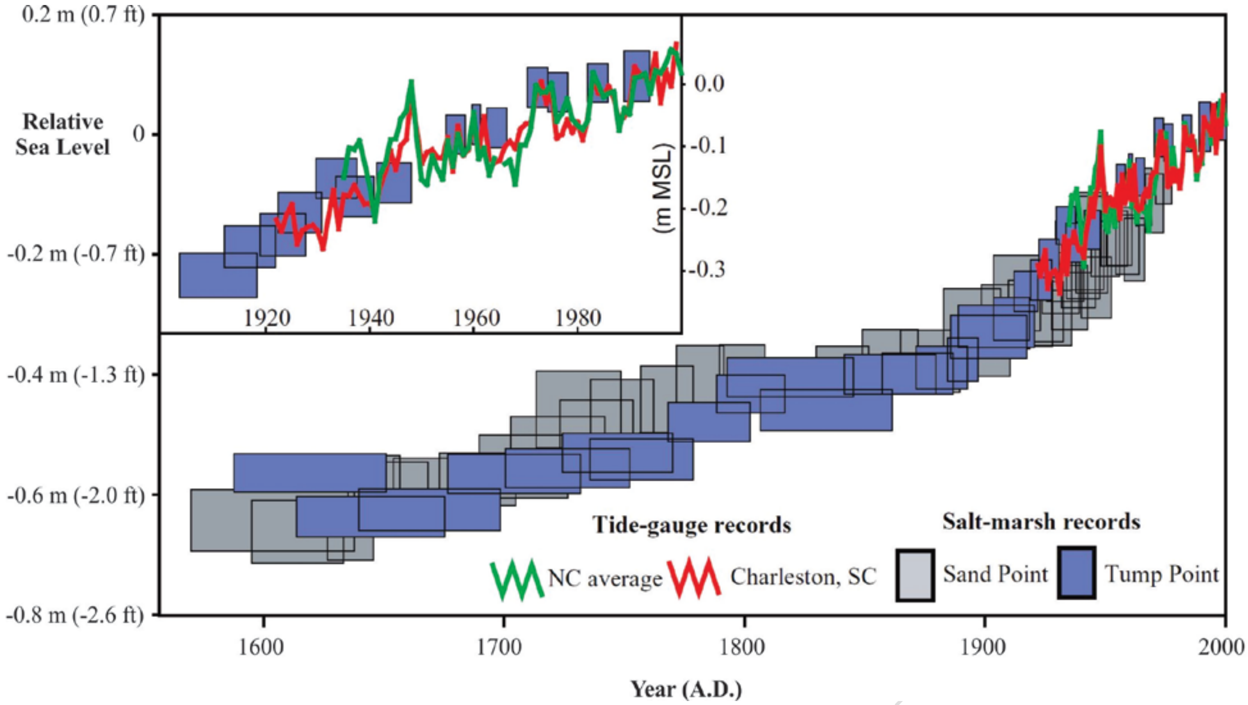

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2.2 Global or Eustatic Sea Level (GSL)

Sea level movement attributable to changes in the volume of water in the world's ocean basins, in general response to cooling and warming, is referred to as eustatic or Global Sea Level (GSL). There are many forces driving changes in water volume (**Table 1**, Church et al. 2013a) 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 (approximately 2 mm/yr from 1971-2010).

FACTORS CONTRIBUTING TO GLOBAL SEA LEVEL (GSL) FROM 1971-2010	
Thermal Expansion (+) or Contraction (-)	40%
Glaciers (non Greenland and Antarctica)	31%
Greenland and Antarctic ice sheets	20%
Land water storage	6%
Glaciers in Greenland	3%

2.3 Relative Sea Level (RSL)

Relative sea level is the measurement of the sea surface 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), El Niño Southern Oscillation (ENSO), and other non-climatic local effects. (**Table 2,** Church et al. 2013a). Importantly, relative sea level is what is recorded in measurements by tide gauges and satellites. For instance, in areas where mountain building is occurring, the land may be rising at a rate close to that of the global sea level. Therefore, the measured rate of sea level rise is close to zero. Conversely, in areas where land is subsiding (sinking), sea level measurements will record sea level rise at a higher rate because eustatic sea level/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) defined as the measurement between the sea surface and a moving datum.

FACTORS CONTRIBUTING TO CHANGES IN THE EARTH & SEA SURFACES	
LAND	**SEA**
Plate Tectonics	**Ocean-Atmospheric Oscillations**
Faults	*El Niño* Southern Oscillation
Volcanic-isostasy	Atlantic Multidecadal Oscillation
Earthquakes	Pacific Decadal Oscillation
Glacial Isostatic Adjustment	**River run-off/floods**
Subsidence	**Astronomical Tides**
Structural deformation	**Wind Tides**
Compaction	**Sea Surface Topography**
Loss of interstitial fluids	(changes in water density & currents)
(hydrocarbon and/or water)	

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)

There are two primary regional elements impacting vertical land motion that have a long-term overprint on the relative sea-level record – structural deformation of the bedrock underlying the coastal plain and Glacial Isostatic Adjustment in response to the retreat of glacial ice sheets. These factors segregate the North Carolina Coastal Plain into different zones of anticipated relative sea-level change.

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 shape of the NC Coastal Plain and Continental Shelf. The resulting deformation of the crystalline rock (bedrock) created structural lows (synclines) providing basins for subsequent sediment/rock accumulation, and also created structural highs (anticlines) that limited opportunities for sediment/rock accumulation. The rates of subsidence and uplift are related to the processes still at work that created the highs and lows of the bedrock surface and importantly, are based upon the thickness of sediment/rock accumulation, lack of accumulation, or the erosion and loss of sediments/rocks. In general, there's a greater probability of subsiding in the structural lows that correspond to areas of thick sediment/rock accumulation and conversely, less probability of subsiding, or a greater probability of uplifting in the structural highs and low sediment/rock accumulation areas. This produces the fundamental differences between the southeastern and northeastern North Carolina coastal systems, which are characterized by stability/uplift and subsidence, respectively (refer to Appendix C for an extensive list of references on structural framework, subsidence, and sea-level rise for the North Carolina coastal zone).

Glacial Isostatic Adjustment (GIA)

GIA describes the rebound of the Earth, both positively and negatively, from the melting of kilometers-thick ice sheets that covered much of North America and Europe at the last glacial maximum (~18,000 years ago). Accumulation and melting of vast ice masses cause the depression and release, respectively of the earth's surface beneath the ice sheet and develops fore-bulge ripples of the earth's surface out in front of the ice sheet. The ongoing rates of GIA rebound are measured 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, the northeastern North Carolina coastal system was part of a fore-bulge ripple that lifted the Earth's surface upward during the last glacial maximum, but which has been collapsing (subsiding) since and continues today (refer to Appendix C).

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 (e.g., Southern Chesapeake Bay, Va.; Houston, TX; etc.; see Eggleston et al. 2013; Coplin and Galloway 1999) but presently there is no evidence this is a factor in eastern North Carolina, even in the coast's major *Capacity Use Areas* where high levels of fresh-water aquifer pumping occurs (i.e., the Central Coastal Plain Capacity Use Area or the former Capacity Use Area #1; NCDENR 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; however, on the basis of existing data it is extremely difficult to separate the effects of structural deformation versus GIA processes. Both processes are ongoing and differentially impact the North Carolina coast. 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. It is important to note that the lines generally represent the location of divisions in geologic characteristics and are not to be interpreted as policy representation.

> **<u>Zone 1: Carolina Platform</u>:** 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; broad, shallow, rock-floored continental shelf; and a coastal system of narrow barrier islands and estuaries. This zone is characterized by a relative rate of uplift of 0.24 mm/yr ±0.15 mm (van de Plassche 2014).
>
> **<u>Zone 2: Albemarle Embayment</u>**: 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 young marine sediments. This results in very low land topography; narrow, deep, sediment-floored continental shelf; and a coastal system dominated by broad, embayed estuaries and high energy barrier islands. This zone is characterized by a high rate of relative subsidence of 1.00 ± 0.10 mm/yr (Englehart et al. 2009; Engelhart et al. 2011; Kemp et al. 2009; Kemp et al. 2011).
>
> **<u>Zone 3: Cape Lookout Transition Zone</u>**: 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). The resulting coastal system contains sediment rich barrier islands with extensive beach ridges, dune fields, and moderate size shore-parallel estuaries. 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 is likely 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). 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 which grade westward and upslope into the riverine systems of the stable upper Coastal Plain. 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 expected in this zone, with a value between zero and approximately 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 to 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 ripple is also not uniform across the northern provenance of the state and subsidence rates across Zone 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 for only that 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.

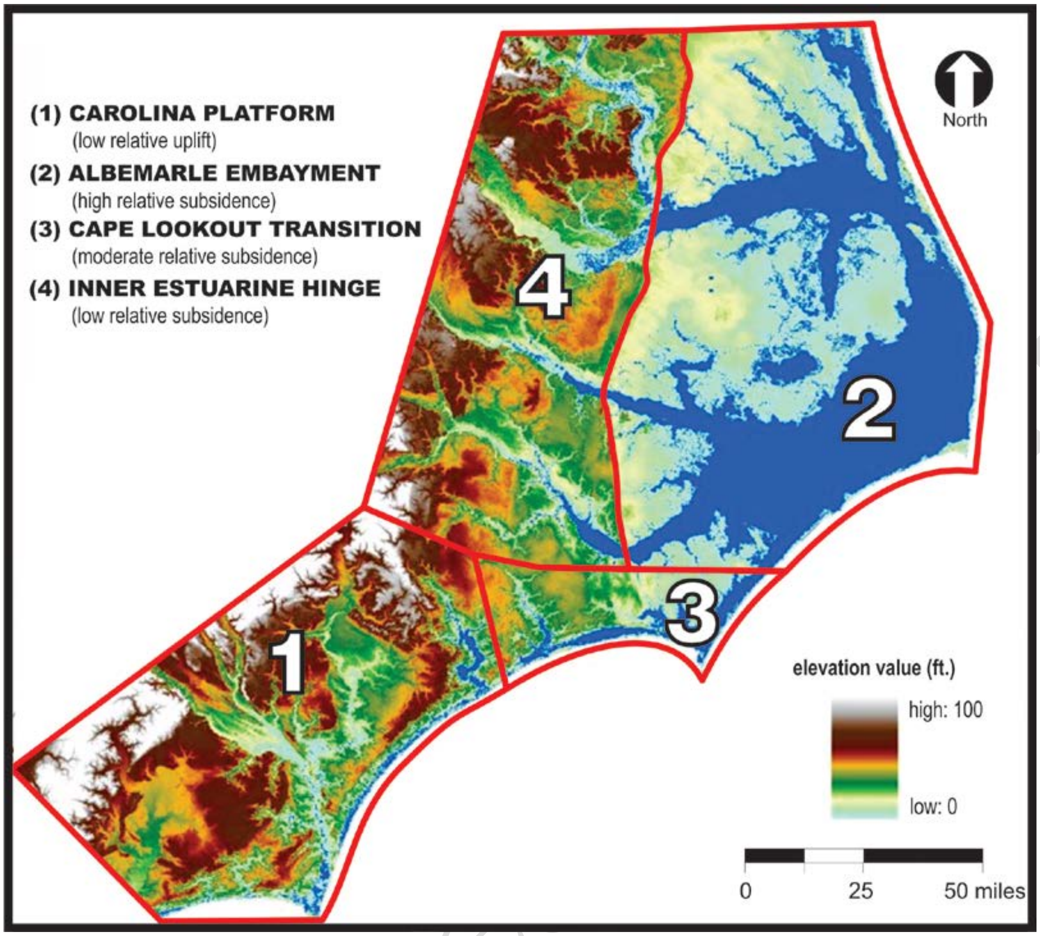

Figure 4. Zones of uplift and subsidence across Coastal North Carolina based on major differences in structure, composition, and thickness of the underlying geologic framework.

3.2 Oceanographic Effects

Data observed from tide gauges (NOAA 2014) show sea level rise rates along the mid-Atlantic coast of more than twice the global sea level rise average 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 Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), and velocity changes and shifting of the Gulf Stream (GS). 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" along 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 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 a different analysis technique, the Empirical Mode Decomposition/Hilbert-Huang Transformation (EMD/HHT) to remove the quasi-periodic variations from the trend allowing the direct computation of the acceleration in the record. They found similar findings to those of Sallenger et al. (2012) with marked differences north and south of Cape Hatteras (see **Figure 5**). 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 US 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.

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) show that water level exceedance above an elevation threshold for “minor” coastal flooding, established by the local NOAA National Weather Service forecast office, 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, NC and from natural oceanographic variation. These factors were less important at Wilmington, NC but the frequency of nuisance flooding has also increased there because of the low elevation threshold established by the local forecast office. As mean sea level rises, the frequency of flooding will increase at all locations. Ezer and Atkinson (2014) and Boon (2012) have both examined nuisance flooding using available tide station data. Spanger-Siegfried et al. (2014) used the predictions from the 2014 National Climate Assessment (Melillo 2014) along with tide data and historic flood frequencies to forecast future flooding frequency in 2030 and 2045 finding significant increases for North Carolina locations by 2045.

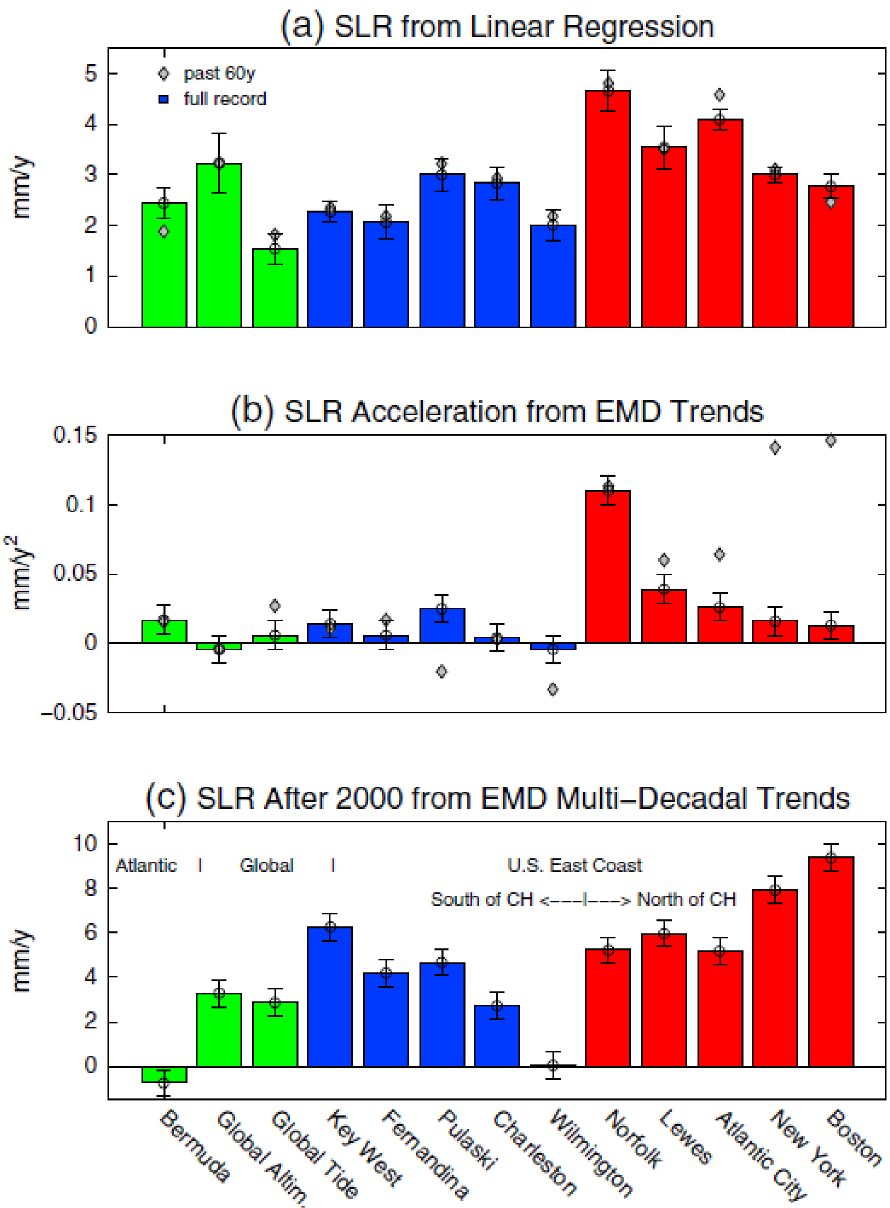

Figure 5. (a) SLR rates obtained from linear regression of the tide gauge record. (b) Average SLR acceleration from the trend of the EMD/HHT analysis of the tide gauge record. Note the difference from Norfolk north and Wilmington south. (c) SLR after 2000 obtained from the multidecadal trend from the EMD/HHT analysis. Red/blue – north/south of Cape Hatteras; green – Atlantic Ocean (Bermuda); global. From Ezer(2013)

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 greater north of Cape Hatteras than it is to the south and that oceanographic effects at times can greatly influence RSL along the coast.

The variability of both the vertical land motion and oceanographic effects along the North Carolina coast are examined further in the following section, using data measured at tide gauges.

4. Tide Gauge Data in North Carolina

Relative sea level change refers to the change in mean water level at a specific location and is generally measured by tide gauges, and the measurements include the influence of GSL, VLM and OE. In North Carolina, rates of relative sea level change measured by tide gauges vary along the coastline, with the highest rates measured in Dare County in the northeast and lowest along New Hanover and Brunswick counties to the south.

4.1 Measured Historical Local Sea Level Rise in North Carolina

In order to accurately determine historical trends, Zervas (2001, 2009) used National Water Level Observation Network (NWLON) 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 2014) through calendar year 2013 for five stations along the North Carolina coast, see **Figure 6**. 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.

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 uncertainties suspected to be caused by dredging that 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 as the deeper channel efficiently circulated more water. (Yelverton and Hackney 1990). 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 degree 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 but found an increase in the Wilmington tide range of 15 cm. Zervas (pers. comm., October 16, 2014) updated the tidal analysis for Wilmington including the relative changes in mean high water and mean low water.

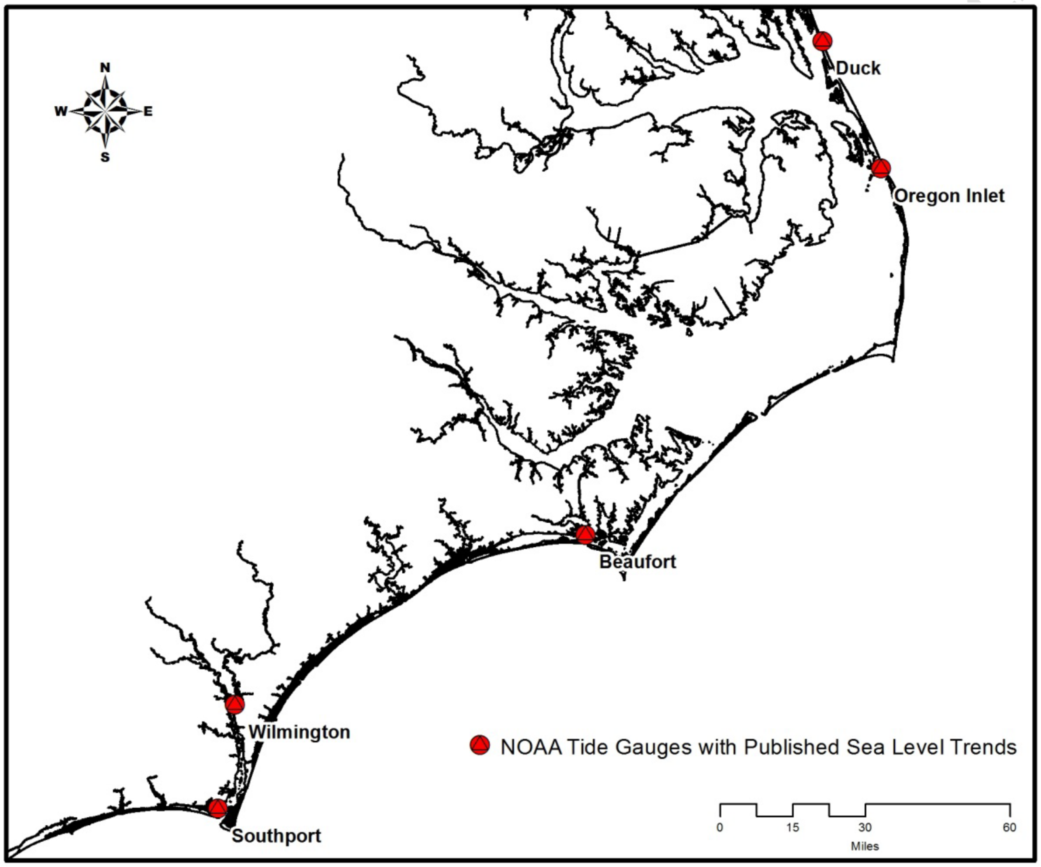

Figure 6. Location of NOAA tide gauges with published sea level trends in North Carolina.

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

Station (North to South)	Sea Level Change Trend, mm/yr (NOAA 2014)	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	2.0 ± 0.41	1933-2006	74

The monthly mean sea level trend plots from NOAA for each location are shown for reference in **Figure 7.** 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 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).

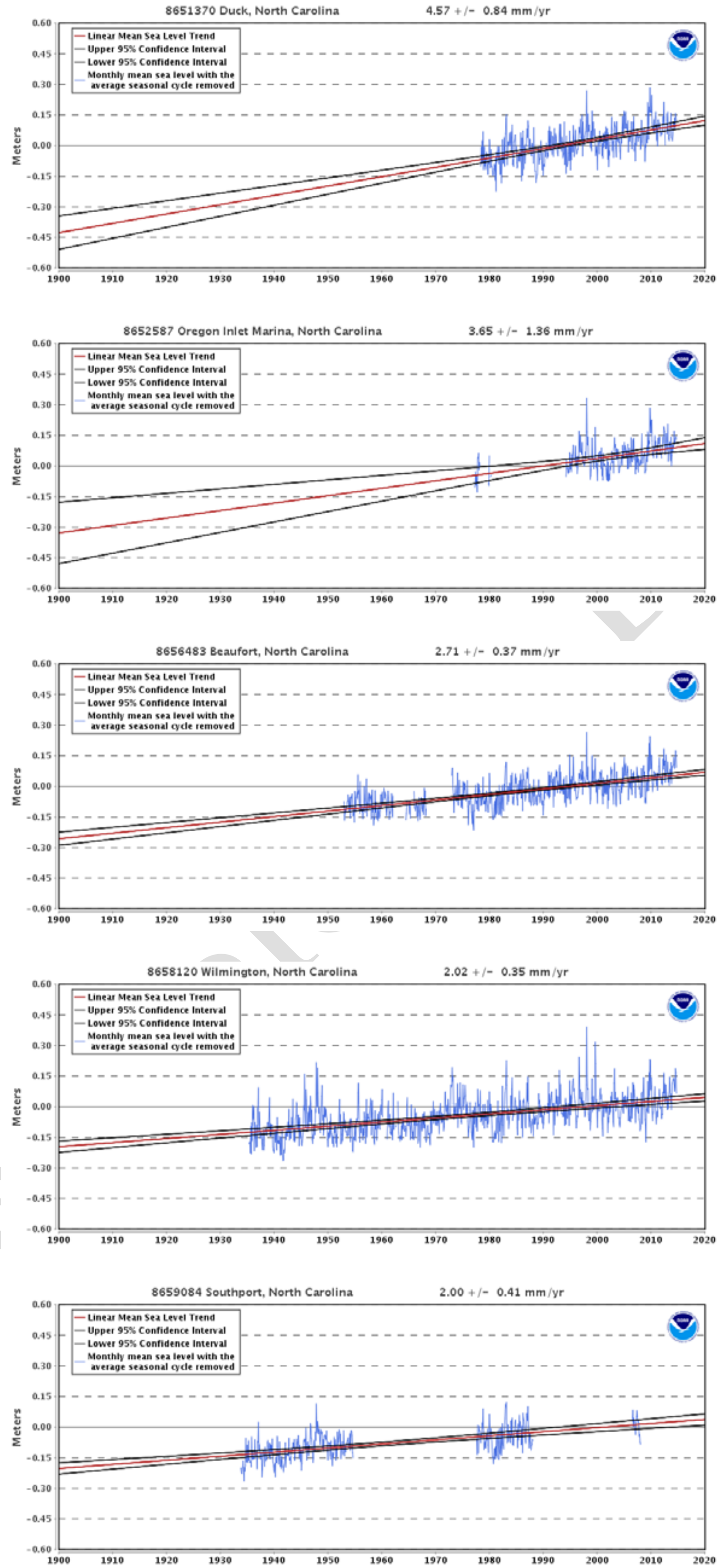

Figure 7. Monthly mean sea levels with seasonal trends removed, for each station with published sea level trends. The long-term linear trend is also shown, including its 95% confidence interval. (NOAA 2014)

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 US 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) 20th century global sea level trend of 1.7 mm/yr (Church and White 2011). 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 updated through 2006 for consistency with previously published sea level trends. 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. 21 Oct. 2014) are presented in **Table 4**. From this analysis, the highest rates of subsidence were found at Duck and the lowest at Wilmington. While the numbers in **Table 4** 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. It is noted that 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 4. Vertical Land Movement Trends Determined from Tide Gauge Data in North Carolina (Zervas, pers. comm. 2014).

Station (North to South)	Vertical Land Movement Trend, mm/yr (Zervas pers. comm. 21 October 2014)	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	1933-2006	74

4.3 Determination of Local Effects

In order to consider the relationship of global sea level trends to North Carolina, the effects of both vertical land motion and oceanographic effects must be assessed. This can be done simply by subtracting the 20th century global sea level rise trend of 1.7 ± 0.2 mm/yr from the reported trend at each individual gauge. The remaining amount is the local effect on sea level change, *including both oceanographic effects and vertical land movement*. To provide a range of values, the low rate of global change (1.5 mm/yr) was subtracted from the lowest sea level change rate at each gauge (i.e., the low end of the uncertainty interval); similarly the high rate of global change (1.9 mm/yr) was subtracted from the high end of the uncertainty interval at each gauge. Results are presented in **Table 5**. As shown in **Table 5**, local effects are much greater north of Cape Hatteras than south of the cape.

We note that this straightforward approach uses published, publicly available rates of sea level rise, including all measured data at each gauge, and is replicable by anyone with internet access. As with all time-series analysis, the rates computed may vary depending on the time span of data used to compute the trend, and in this case higher rates are associated with the shortest period of coverage. However, the short record length is reflected in the greater range of uncertainty. As these records grow with time, that uncertainty will decrease. An alternative approach that the Science Panel considered was to extend the record length of the Duck gauge using the nearby Sewells Point gauge in Virginia. However, Sewells Point is located in a different geologic setting, on the edge of the Chesapeake Bay Impact Crater and is an interior gauge, while the gauge at Duck is an open ocean gauge. Consequently the Science Panel decided to use just actual data along with their uncertainties. Should the CRC wish to investigate others ways to work with the varying time spans of the data, the Science Panel recommend that work be contracted to experts in analysis of tide gauge data.

Table 5 Local sea level change trends, global sea level change trends, and local effects assessed at North Carolina tide gauges.

Station (North to South)	Sea Level Change Trend, mm/yr (NOAA 2014)	Global Sea Level Change Trend, mm/yr (Church and White 2011)	Local Effects (Gauge Trend–Global Trend), mm/yr
Duck	4.57 ± 0.84	1.7 ± 0.2	2.87 [2.23 to 3.51]
Oregon Inlet	3.65 ± 1.36	1.7 ± 0.2	1.95 [0.79 to 3.11]
Beaufort	2.71 ± 0.37	1.7 ± 0.2	1.01 [0.84 to 1.18]
Wilmington	2.02 ± 0.35	1.7 ± 0.2	0.32 [0.17 to 0.47]
Southport	2.0 ± 0.41	1.7 ± 0.2	0.30 [0.09 to 0.51]

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 in the legislative mandate 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 NC coast using the published sea level rise (SLR) rates given in **Table 3** (NOAA 2014). Global mean sea level (GMSL), taken to be 1.7 ± 0.2 mm/yr (Church and White 2011), would amount to approximately 2 inches over 30 years. This was subtracted from the total amount of rise expected at current rates (obtained by multiplying the current rate by 30 years) to estimate local vertical land movement and oceanographic effects (see Section 3). 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, due to the local effects.

Table 6. Sea level rise over 30 years at existing published rates of sea level rise. Magnitude of rise was determined by multiplying the rate ± the confidence interval (for the high/low estimates respectively) by 30 years.

Station	Gauge Projections			Local Effects			Global Effects		
	RSLR in 30 years, inches			RSLR in 30 years, inches			SLR in 30 years, inches		
	Mean	High	Low	Mean	High	Low	Mean	High	Low
Duck	**5.4**	**6.4**	**4.4**	3.4	4.2	2.6	2.0	2.2	1.8
Oregon Inlet Marina	**4.3**	**5.9**	**2.7**	2.3	3.7	0.9	2.0	2.2	1.8
Beaufort	**3.2**	**3.6**	**2.8**	1.2	1.4	1.0	2.0	2.2	1.8
Wilmington	**2.4**	**2.8**	**2.0**	0.4	0.6	0.2	2.0	2.2	1.8
Southport	**2.4**	**2.8**	**1.9**	0.4	0.6	0.1	2.0	2.2	1.8

5.2 Global Mean Sea Level through 2045

Potential Decrease in Sea Level Rise

The Science Panel researched the possibility of including a deceleration of sea level rise, meaning a rate lower than existing published global rates of sea level rise, over the next 30 years. There are few studies that have examined the tide gauge record and found a deceleration trend – regardless of the time interval selected. Houston and Dean (2011) did postulate a deceleration but concluded that the deceleration was quite small (essentially stable). The Science Panel considers deceleration of future rates of sea level rise unlikely and no projections have been made using decreased rates of sea level rise.

Potential Increase in Sea Level Rise

The IPCC is the leading international body for the assessment of climate change. 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. 2013a), which was released in draft form on 30 September 2013, and published in final form 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.

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, due 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. 2013a). The results correspond to the scenarios, each with a possible representative concentration pathway (RCP) of greenhouse gases. RCP2.6 is the "best case" scenario in which greenhouse gases are in the lowest concentration, and RCP 8.5 is the "worst case" with the highest concentration. This table was developed by converting the original table in the IPCC report from meters to inches.

Table 7. Range of global mean sea level rise projections (inches) with respect to 1986-2005 at 1 January on the years indicated, with uncertainty ranges (modified from Table AII.7.7, IPCC 2013a).

Year	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
2010	1.6 [1.2 to 2.0]	1.6 [1.2 to 2.0]	1.6 [1.2 to 2.0]	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]

In addition to the process-based models, the IPCC (2013a) 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. 2013a). 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 (RCP2.6) and high greenhouse gases (RCP8.5) model scenarios are presented as upper and lower bounds of the potential range of sea level rise. 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 range in 2015 and 2045.
2) Subtract 2015 value from 2045 value to obtain magnitude of projected rise over the 30-year time frame.

Table 8. Global Sea level rise from 2015 to 2045 as predicted by IPCC Scenarios, shown in inches.

Predicted Amount of Sea Level Rise by Year	Scenario RCP2.6 (SLR in inches)	Scenario RCP8.5 (SLR in inches)
2015	2.4 [1.8 to 3.0]	2.3 [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 [3.9 to 6.9]	6.3 [4.7 to 7.9]

Note that the range of values for the two scenarios overlap and differ only by 1 inch, reflecting the fact that most of the increase in the rate of sea level rise forecast by these scenarios Is forecast to occur later than 2045.

5.3 Potential Increased Sea Level Rise with Local Effects

In order to make the global sea level rise values from **Table 8** relevant for North Carolina, local effects must be included. This was done by adding in the 30 year local effects presented in **Table 6**. 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 for scenarios RCP 2.6 and RCP 8. 5. For comparison with **Table 6,** values were rounded to the nearest tenth of an inch. Results are presented in **Tables 9 and 10**.

Table 9. Sea level rise by 2045 considering potential increased rates of sea level rise (IPCC 2013 for RCP 2.6 which is the lowest greenhouse gas emission scenario.

Station	Local Effects			Future Global Effects (Scenario Contribution)			Tide Gauge + Future Global Effects		
	RSLR by 2045, inches			SLR by 2045, inches			RSLR by 2045, inches		
	Mean	High	Low	Mean	High	Low	Mean	High	Low
Duck	3.4	4.2	2.6	5.3	6.9	3.9	**8.7**	**11.1**	**6.5**
Oregon Inlet Marina	2.3	3.7	0.9	5.3	6.9	3.9	**7.6**	**10.6**	**4.8**
Beaufort	1.2	1.4	1.0	5.3	6.9	3.9	**6.5**	**8.3**	**4.9**
Wilmington	0.4	0.6	0.2	5.3	6.9	3.9	**5.7**	**7.5**	**4.1**
Southport	0.4	0.6	0.1	5.3	6.9	3.9	**5.7**	**7.5**	**4.0**

Table 10. Sea level rise by 2045 considering potential increased rates of sea level rise (IPCC 2013 for RCP 8.5 which is the highest greenhouse gas emission scenario.

Station	Local Effects			Future Global Effects (Scenario Contribution)			Tide Gauge + Future Global Effects		
	RSLR by 2045, inches			SLR by 2045, inches			RSLR by 2045, inches		
	Mean	High	Low	Mean	High	Low	Mean	High	Low
Duck	3.4	4.2	2.6	6.3	8.1	4.7	**9.7**	**12.3**	**7.3**
Oregon Inlet Marina	2.3	3.7	0.9	6.3	8.1	4.7	**8.6**	**11.8**	**5.6**
Beaufort	1.2	1.4	1.0	6.3	8.1	4.7	**7.5**	**9.5**	**5.7**
Wilmington	0.4	0.6	0.2	6.3	8.1	4.7	**6.7**	**8.7**	**4.9**
Southport	0.4	0.6	0.1	6.3	8.1	4.7	**6.7**	**8.7**	**4.8**

As shown, under potential increases due to varying emissions scenarios, sea level could rise from a low estimate of 4 inches to high of approximately 12 inches by 2045, depending on location, with the highest sea level projections north of Cape Hatteras, due to local effects.

5.4 Future Sea Level Rise across North Carolina

Preparing a map with estimated sea level rise across the state of North Carolina is difficult, because the local effects are quantified only at the tide gauge locations. The geologic regions presented in **Figure 4** provide an indication of where effects due to vertical land movement are expected to be similar. Oceanographic effects have generally been shown to be most significant north of Cape Hatteras, see Section 3.2. In Session Law 2012-202 (Appendix B), the four regions presented in the April 2011 report entitled "North Carolina Beach and Inlet Management Plan" published by the Department of Environment and Natural Resources are specified for consideration by the Science Panel in making sea level rise assessments. Those regions are shown in **Figure 8.**

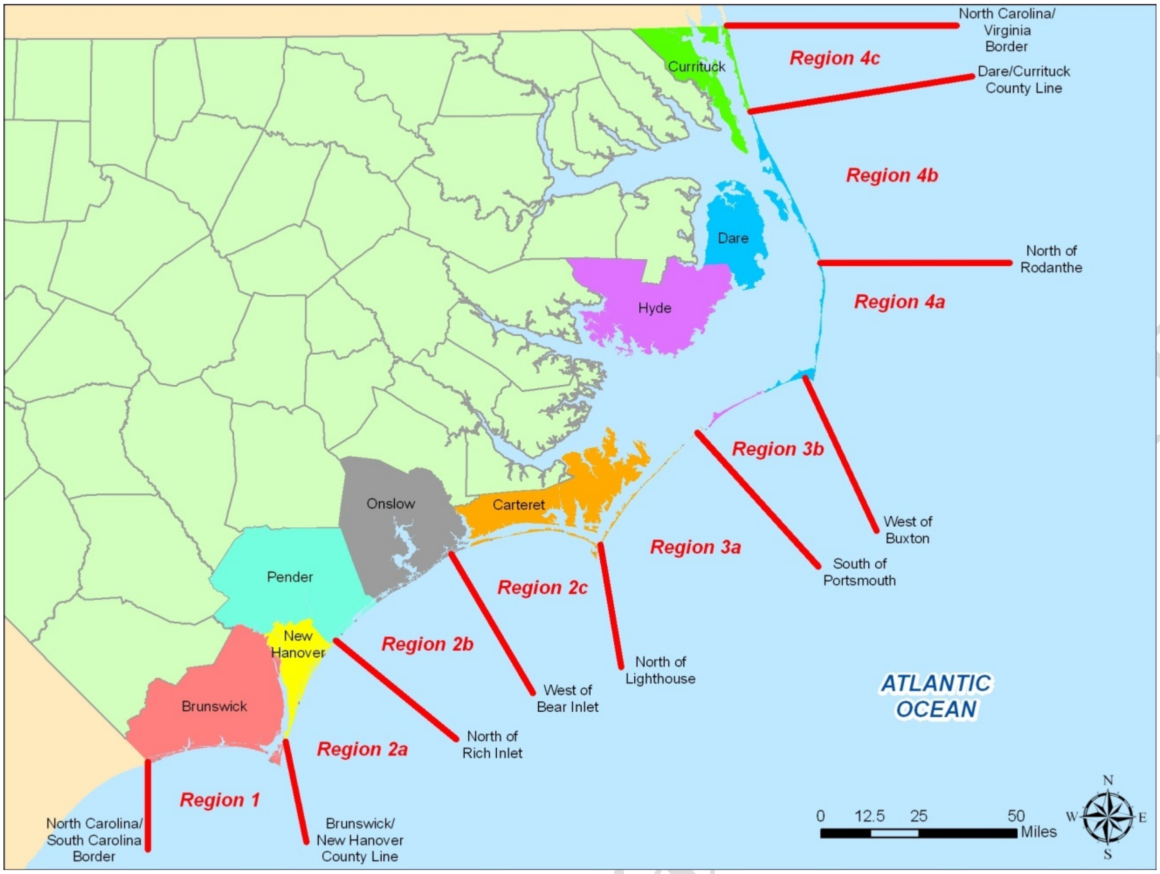

Figure 8. Beach and Inlet Management Plan (BIMP) Regions referenced in SL 2012-202.

Region 1 (Carolina Platform) in **Figure 4** corresponds roughly to Regions 1 and 2a, as well as part of Region 2b, in the BIMP (**Figure 8**). The gauges in that part of North Carolina are the Wilmington and Southport gauges, which are very similar in characteristics, with identical future increased sea level rise predictions. Region 2 (Albermarle Embayment) in **Figure 4** encompasses Regions 3b, 4a, 4b, and 4c, as well as a portion of Region 3a in the BIMP (**Figure 8**). Both the Oregon Inlet and Duck tide gauges are located in this area. These gauges have the highest expected sea level rise by 2045 across the state, with the projections at Duck slightly higher than those at Oregon Inlet. 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 a slightly higher expected sea level rise by 2045 than the Wilmington and Southport gauges. 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

We have purposely presented a range of sea level values that may occur by 2045 across North Carolina. Providing a range of values reflects both the uncertainty in the predictions and the varying nature of sea level. What's more important are the implications of these numbers relative to their use. From a planning perspective, the risk of flooding decreases by selecting a higher elevation within the expected range of sea levels. Choosing an elevation above the expected range would, theoretically reduce the risk of flooding to zero. 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 US 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 flooding and if it's not 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 and lowest potential increased sea level is just 8 inches, reflecting 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's cumulative and rising, areas of NC will be impacted. 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.

Since 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), the 2014 United States National Climate Assessment (Melillo et al. 2014), the USACE guidance (2014), including their online sea level calculator (http://www.corpsclimate.us/ccaceslcurves.cfm), or the interactive map at ClimateCentral.org (http://sealevel.climatecentral.org/ssrf/north-carolina).

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 would start to fill gaps in knowledge of behavior across the North Carolina coast.

Since 2007 the NC Geodetic Survey has been installing Continuously Operating Reference

Stations (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 4 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 and to provide a finer grid of local sea level rise measurements and predictions. The state should also consider augmenting the existing CORS GPS stations to provide coverage in all the regional zones in order to quantify and refine land subsidence and uplift on the coastal plain. 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 this 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 5 years, knowledge in climate science and forecast models is rapidly advancing—improving predictions and reducing uncertainty. The Panel again recommends a general reassessment of sea level rise in North Carolina every five years. Additional information from future analyses of CORS GPS stations should be considered to provide additional information on vertical land movement across the state. 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

These key points summarize the results of this report:

- Sea level is rising across the coast of North Carolina.
- The rate of sea level rise varies, depending on location. Two main factors affect the rate of sea level rise: (1) vertical movement of the Earth's surface, and (2) effects of ocean dynamics.
- There is evidence from both geological data and tide gauges that there is more subsidence north of Cape Hatteras than south of Cape Hatteras. This contributes to higher measured rates of sea level rise along the northeastern NC 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, and also contributes to higher measured rates of sea level rise along the northeastern coast.

- At existing rates of sea level rise, over a 30 year time frame, sea level rise across the North Carolina coast would range from approximately 2 inches (at Wilmington and Southport) to approximately 6 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 4 inches at Wilmington and Southport to a high estimate at Duck of 11 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 5 inches at Wilmington and Southport to a high estimate at Duck of 12 inches (1 foot).
- Because the science is changing rapidly, it is recommended that this assessment be updated every five years, and that water level and land movement measurements be sustained and additional gauges placed where necessary.

10. References

Boon, J. D., 2012 Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic coast, North America, *J. Coast. Res.*, *28*(6), 1437–1445, doi:10.2112/jcoastres-d-12-00102.1.

Boon, J. D., J. M. Brubaker, and D. R. Forrest (2010), Chesapeake Bay land subsidence and sea level change, in *App. Mar. Sci. and Ocean Eng.*, *Rep. No. 425*, Va. Inst. of Marine Sci., Gloucester Point, Va. http://www.vims.edu/GreyLit/VIMS/sramsoe425.pdf

Calafat, F. M., and D. P. Chambers, 2013. Quantifying recent acceleration in sea level unrelated to internal climate variability, *Geophys. Res. Lett.,* 40, 3661–3666, doi:10.1002/grl.50731.

Chambers, D. P., M. A. Merrifield, and R. S. Nerem, 2012. Is there a 60-year oscillation in global mean sea level?, *Geophys. Res. Lett*., 39, L18607, doi:10.1029/2012GL052885.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013a: *Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013b. Comment on R. Kerr, "Sea Level Rise by 2100", *Science*, 342:6165, p. 1445, DOI: 10.1126/science.342.6165.1445-a, http://www.sciencemag.org/content/342/6165/1445.1.full

Church, J. A., and N.J. White, 2011. Sea-level rise from the late 19th to the early 21st century *Surveys in Geophysics* , 32(4-5), 585–602. doi:10.1007/s10712-011-9119-1.

Cohen K.M. and Gibbard, P. 2011. Global chronostratigraphical correlation table for the last 2.7 million years. Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy), Cambridge, England.

Coplin, L.S., and Galloway, D.L., 1999, Houston-Galveston, Texas—Managing coastal subsidence: in *Land Subsidence in the United States*, Galloway, D.L., Jones, D.R., and Ingebritsen, S.E., eds., U.S. Geological Survey Circular 1182, p. 35-48

Donoghue, J.F., 2011. Sea-level history of the northern Gulf of Mexico and sea-level rise scenarios for the near future. *Climatic Change*, 107:17-33,doi:10.1007/s10584-011-0077-x, http://www.gly.fsu.edu/~donoghue/pdf/donoghue-climatic-change.pdf

Eggleston, Jack, and J. Pope, 2013. Land subsidence and relative sea-level rise in the southern Chesapeake Bay region: U.S. Geological Survey Circular 1392, 30 p.

Engelhart, S.E., B.P. Horton, B.C. Douglas, W.R. Peltier, and T.E. Törnqvist, 2009. Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic coast of the United States. *Geology*, 37, 1115-1118.

Engelhart, S.E., Horton, B.P., and A.C. Kemp, 2011. Holocene sea level changes along the United States Atlantic Coast. *Oceanography*, v. 24, no. 2, p. 70-79.

Ezer, T., 2013. Sea level rise, spatially uneven and temporally unsteady: Why the US East Coast, the global tide gauge record, and the global altimeter data show different trends. *Geophys. Res. Lett.*, 40. 5439-5444 doi:10.1002/2013GL057952.

Ezer, T., L. P. Atkinson, W. B. Corlett and J. L. Blanco, 2013. Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast, *J. Geophys. Res. Oceans*, 118, 685–697, doi:10.1002/jgrc.20091.

Ezer, T., and W. B. Corlett (2012), Is sea level rise accelerating in the Chesapeake Bay? A demonstration of a novel new approach for analyzing sea level data, *Geophys. Res. Lett.*, *39*, L19605, doi:10.1029/2012GL053435.

Hackney, C.T. and G.F. Yelverton. 1990. Effects of human activities and sea level rise on wetland ecosystems in the Cape Fear River estuary, North Carolina, USA. In: D.F. Whigham et al. (eds.), Wetland Ecology and Management: Case Studies, Kluwer Academic Publishers, the Netherlands. pp. 55-61.

Houston, J.R. and Dean, R.G., 2011. Sea-level acceleration based on U.S. tide gauges and extensions of previous global-gauge analyses*. J. Coastal Res.*, 27(3), p. 409–417.

Horton, B.P., W.R. Peltier, S.J. Culver, R. Drummond, S.E. Engelhart, A.C. Kemp, D. Mallinson, E.R. Thieler, S.R. Riggs, D.V. Ames, and K.H. Thomson, 2009. Holocene sea-level changes along the North Carolina Coastline and their implications for glacial isostatic adjustment models. *Quaternary Science Reviews*, Volume 28, Issues 17–18, August 2009, Pages 1725-1736, ISSN 0277-3791, http://dx.doi.org/10.1016/j.quascirev.2009.02.002.

Imbrie, J., Hays, J. D., Martinson, D. G., McIntyre, A., Mix, A. C., Morley, J. J., Pisias, N. G., Prell, W. L., and Shackleton, N. J., 1984. The Orbital Theory of Pleistocene Climate: Support from a Revised Chronology of the Marine Delta18O Record. In A.L. Berger et al. (eds.), *Milankovitch and Climate*, Part 1, D. Reidel Publishing Company, p. 269-305.

Intergovernmental Panel on Climate Change (IPCC), 2013a. Annex II: Climate System Scenario Tables [Prather, M., G. Flato, P. Friedlingstein, C. Jones, J.-F. Lamarque, H. Liao and P. Rasch (eds.)]. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.ipcc.ch/report/ar5/

Intergovernmental Panel on Climate Change (IPCC), 2013b. Summary for Policymakers. *In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.ipcc.ch/report/ar5/

Intergovernmental Panel on Climate Change (IPCC), 2013c. IPCC Factsheet: What is the IPCC? 30 August 2013. http://www.climatechange2013.org/images/uploads/FS_what_ipcc.pdf

Intergovernmental Panel on Climate Change (IPCC), 2013d. IPCC Factsheet: How does the IPCC review process work? 30 August 2013. http://www.ipcc.ch/news_and_events/docs/factsheets/FS_review_process.pdf

Kemp, A.C., Horton, B.P., Culver, S.J., Corbett, D.R., van de Plassche, O., Gehrels, W.R., Douglas, B.C., and Parnell, A.C. 2009. Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States). *Geology*, v. 37, no. 11, p. 1035-1038.

Kemp, A.C., Horton, B.P., Donnelly J.P., Mann, M.E., Vermeer, M., and Rahmstorf, S. 2011. Climate related sea-level variations over the past two millennia. *Proc. National Academy of Sciences of the United States of America*. v. 108 no. 27, 11017-11022.

Kopp, R. E. (2013), Does the mid-Atlantic United States sea-level acceleration hot spot reflect ocean dynamic variability?, *Geophys. Res. Lett.*, *40*, 3981–3985, doi:10.1002/GRL.50781.

Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2., http://nca2014.globalchange.gov/report

National Oceanographic and Atmospheric Administration (NOAA), 2014. World Data Center for Paleoclimatology. http://www.ncdc.noaa.gov/paleo/datalist.html

NC Science Panel, 2010. North Carolina Sea Level Rise Assessment Report http://portal.ncdenr.org/c/document_library/get_file?uuid=724b16de-ef9f-4487-bddf-e1cb20e79ea0&groupId=38319

NC Department of Environment and Natural Resources, 2014. Central Coastal Plain Capacity Use Area, Division of Water Resources http://www.ncwater.org/?page=49

National Oceanic and Atmospheric Administration (NOAA), 2014. Sea Level Trends. http://tidesandcurrents.noaa.gov/sltrends/. Last accessed 24 Nov. 2014.

Ruppert, T., 2014. Sea-Level Rise in Florida—the Facts and Science, Florida Sea Grant College Program, 7 p., http://www.flseagrant.org/wp-content/uploads/2012/02/SLR-Fact-Sheet_dual-column-letterhead_8.2.13_pdf.pdf

Sallenger, A.H., Doran K.S., and P.A. Howd, 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nature Climate Change 2, 884-888. doi:10.1038/nclimate1597

Smeed, D. A., McCarthy, G. D., Cunningham, S. A., Frajka-Williams, E., Rayner, D., Johns, W. E., Meinen, C. S., Baringer, M. O., Moat, B. I., Duchez, A., and Bryden, H. L. 2014. Observed decline of the Atlantic meridional overturning circulation 2004–2012, *Ocean Sci*., 10, 29-38, doi:10.5194/os-10-29-2014.

Smith, P., 2014. Hurricane Hazel, Fast and Furious. *Coastwatch*, 4., 6-15. http://ncseagrant.ncsu.edu/coastwatch/previous-issues/2014-2/autumn-2014/hurricane-hazel-fast-and-furious/

Spanger-Siegfried, M. Fitzpatrick and K. Dahl. 2014. "Encroaching Tides, Union of Concerned Scientists, 76. http://www.ucsusa.org/sites/default/files/attach/2014/10/encroaching-tides-full-report.pdf

Sweet, W., J. Park, J. Marra, C. Zervas, and S. Gill, 2014. Sea Level Rise and Nuisance Flood Frequency Changes around the United States, *NOAA Tech. Rep. No. NOS CO-OPS 073*, 66 pp., NOAA National Ocean Service, Silver Spring, Md. http://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.pdf

U.S. Army Corps of Engineers, 2014. *Procedures to Evaluate Sea Level Change Impacts, Responses, and Adaptation,* ETL 1100-2-1. Washington, DC: U.S. Army Corps of Engineers. http://www.publications.usace.army.mil/LinkClick.aspx?fileticket=K2PCg5mvLB8%3d&tabid=16442&portalid=76&mid=43547

van de Plassche, O., Wright, A. J., Horton, B. J., Engelhart, S. E., Kemp, A. C., Mallinson, D., Kopp, R. E. 2014. Estimating tectonic uplift of the Cape Fear Arch (south-eastern United States) using reconstructions of Holocene relative sea level. *J. Quaternary Science* 29, 749-759. DOI: 10.1002/jqs.2746

Wright, H.E., Jr., 1989. The Quaternary, in Bally, A.W. and Palmer, A.R., eds. *The Geology of North America – An Overview*: Boulder, Colorado Geological Society of America.

Yin J, Goddard PB (2013) Oceanic control of sea level rise patterns along the east coast of the United States. *Geophys. Res. Lett.*, 40:5514–5520, DOI 10.1002/2013GL057992

Zervas, C. 2001. NOS Technical Report 036 NOS-CO-OPS 053 Sea Level Variations of the United States 1854-1999. NOAA, July, 2001 http://tidesandcurrents.noaa.gov/publications/techrpt36doc.pdf

Zervas, C. 2009. NOS Technical Report NOS-CO-OPS 053 Sea Level Variations of the United States 1854-2006. NOAA, December 2009. http://tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf

Zervas, C., Gill, S., and W. Sweet. 2013 NOS Technical Report NOS CO-OPS 065. Estimating Vertical Land Motion from Long-Term Tide Gauge Records. http://tidesandcurrents.noaa.gov/publications/Technical_Report_NOS_CO-OPS_065.pdf

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.

Appendix C: References for Structural Framework, Subsidence, and Sea-Level Rise for the North Carolina Coastal Zone

Brown, P.M., Miller, J.A., and Swain, F.M. 1972. Structural and stratigraphic framework, and spatial distribution of permeability of Atlantic Coastal Plain, North Carolina to New York, U.S. Geological Survey Prof. Paper, vo. 796, 79 p.

Dillon, W.P., and Popenoe, P. 1988. The Blake Plateau Basin and Carolina Trough; *in* The Atlantic Continental Margin, *eds*. R.E. Sheridan and J.A. Grow; Geological Society of America Pub: The Geology of North America, v. I-2, p.291-328.

Engelhart, S.E., Horton, B.P., Douglas, B.C., Peltier, W.R., and Tornqvist, T.E. 2009. Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic coast of the United States. Geology, v. 37, no. 12, p. 1115-1118.

Engelhart, S.E., Horton, B.P., and Kemp, A.C. 2011. Holocene sea level changes along the United States Atlantic Coast. Oceanography, v. 24, no. 2, p. 70-79.

Gohn,G.S. 1988. Late Mesozoic and early Cenozoic geology of the Atlantic Coastal Plain: North Carolina to Florida; *in* The Atlantic Continental Margin, *eds*. R.E. Sheridan and J.A. Grow; Geological Society of America Pub: The Geology of North America, v. I-2, p.107-130.

Grow, J.A., and Sheridan, R.E. 1988. U.S. Atlantic Continental Margin; A typical Atlantic-type passive continental margin; *in* The Atlantic Continental Margin, *eds*. R.E. Sheridan and J.A. Grow; Geological Society of America Pub: The Geology of North America, v. I-2, p.1-8.

Kemp, A.C., Horton, B.P., Culver, S.J., Corbett, D.R., van de Plassche, O., Gehrels, W.R., Douglas, B.C., and Parnell, A.C. 2009. Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States). Geology, v. 37, no. 11, p. 1035-1038.

Kemp, A.C., Horton, B.P., Donnelly J.P., Mann, M.E., Vermeer, M., and Rahmstorf, S. 2011. Climate related sea-level variations over the past two millennia. 6 p. (www.pnas.org/cgi/doi/10.1073/pnas.1015619108).

Klitgord, K.D., and Hutchinson, D.R. 1988. U.S. Atlantic continental margin; structural and tectonic framework; *in* The Atlantic Continental Margin, *eds*. R.E. Sheridan and J.A. Grow; Geological Society of America Pub: The Geology of North America, v. I-2, p.1-8.

Horton, B.P., Peltier, W.R., Culver, S.J., Drummond, R., Engelhart, S.E., Kemp, A.C.,

Mallinson, D., Thieler, E.R., Riggs, S.R., Ames, D.V., and Thomson, K.H. 2009. Holocene sea-level changes along the North Carolina coastline and their implications for glacial isostatic adjustment models. Quaternary Science Reviews, v. 28, p. 1725-1736.

Mallinson, D.J., Culver, S.J., Riggs, S.R., Thieler, E.R., Foster, D., Wehmiller, J., Farrel, K.M., and Pierson, J. 2009. Regional seismic stratigraphy and controls on the Quaternary evolution of the Cape Hatteras region of the Atlantic passive margin, USA. Marine Geology, v. 268, p. 16-33.

NCGS. 1991. Generalized geologic map of North Carolina.

Parham, Peter R., 2009. Quaternary stratigraphy and geologic history of the Albemarle embayment, northeastern North Carolina. Coastal Resource Management PhD Program, East Carolina University, Greenville, NC, 290 p.

Popenoe, P. 1990. Paleoceanography and paleogeography of the Miocene of the southeastern United States; *in* Phosphate Deposits of the World: Neogene to Modern Phosphorites; *eds*. W.C. Burnett and S.R. Riggs; Cambridge University Press, v. 3, p. 352-372.

Riggs, S.R. 1984. Paleoceanographic model of Neogene phosphorite deposition, U.S. Atlantic continental margin. Science, v. 233, no. 4632, p. 123-132.

Riggs, S.R., & Belknap, D.F. 1988. Upper Cenezoic processes and environments of continental margin sedimentation: eastern United States; *in* The Atlantic Continental Margin, *eds*. R.E. Sheridan and J.A. Grow; Geological Society of America Pub: The Geology of North America, v. I-2, p.131-376.

Riggs, S.R., and Manheim, F.T. 1988. Mineral resources of the U.S. Atlantic continental margin; *in* The Atlantic Continental Margin, *eds*. R.E. Sheridan and J.A. Grow; Geological Society of America Pub: The Geology of North America, v. I-2, p.501-520.

Riggs, S.R., Snyder, S.W., Ames, D.V., & Stille, P. 2000. Chronostratigraphy of Upper Cenozoic phosphorites on the North Carolina continental margin and the oceanographic implications for phosphogenesis; in Marine Authigenesis: From Global to Microbial. SEPM Special Publication No 66, p. 369-385.

Riggs, S.R., Snyder, S.W., Snyder, S.W., & Hine, A.C. 1990. Carolina continental margin: Part I—stratigraphic framework for cyclical deposition of Miocene sediments in the Carolina Phosphogenic Province; *in* Phosphate Deposits of the World: Neogene to Modern Phosphorites; *eds*. W.C. Burnett and S.R. Riggs; Cambridge University Press, v. 3, p. 381-395.

Riggs, S.R., Snyder, S.W., Hine, A.C., Snyder, S.W., Ellington, M.D., & Mallette, P. 1985. Geologic framework of phosphate resources in Onslow Bay, North Carolina continental shelf; Economic Geology, v. 80, p. 716-738.

Riggs, S.R., Cleary, W.J., and Snyder, S.W., 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. Marine Geology, Volume 126, Issues 1–4, 213-234.

Schlee, J.S., Manspeizer, W., & Riggs, S.R. 1988. Paleoenvironments: Offshore Atlantic U.S. Margin; *in* The Atlantic Continental Margin, *eds*. R.E. Sheridan and J.A. Grow; Geological Society of America Pub: The Geology of North America, v. I-2, p.365-385.

Snyder, S.W., Hine, A.C., & Riggs, S.R. 1990. Carolina continental margin: Part II—The seismic stratigrphic record of shifting Gulf Stream flow paths in response to Miocene glacio-eustacy: implications for phosphogenesis along the North Carolina continental margin; *in* Phosphate Deposits of the World: Neogene to Modern Phosphorites; *eds*. W.C. Burnett and S.R. Riggs; Cambridge University Press, v. 3, p. 396-423.

Snyder, S.W., Hine, A.C., Riggs, S.R., & Snyder, S.W. 1993. Miocene geology of the continental shelf: Onslow Bay, North Carolina; North Carolina Geological Survey, Map No. 3.

USGS. 1996. United States Geological Survey Fact Sheet, FS-033-96.

van de Plassche, O., Wright, A. J., Horton, B. J., Engelhart, S. E., Kemp, A. C., Mallinson, D., Kopp, R. E. 2014. Estimating tectonic uplift of the Cape Fear Arch (south-eastern United States) using reconstructions of Holocene relative sea level. Journal of Quaternary Science 29, 749-759. DOI: 10.1002/jqs.2746

Zervas, C.E. 2004. North Carolina bathymetry/topography sea level rise project: determination of sea level trends. NOAA Technical Report NOS CO-OPS 041, 31 p.