PAT MCCRORY
Governor

DONALD R. VAN DER VAART
Secretary

MEMORANDUM

TO: ENVIRONMENTAL REVIEW COMMISSION
The Honorable Jimmy Dixon, Co-Chairman
The Honorable Chuck McGrady, Co-Chairman
The Honorable Trudy Wade, Co-Chairman

FROM: Brad Knott, Deputy Director of Legislative Affairs

SUBJECT: 2015 N.C. Sea Level Rise Assessment Report

DATE: February 19, 2016

Pursuant to Session Law 2012-202, 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 law directs the Coastal Resources Commission to "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." The Coastal Resources Commission has not adopted, and is not considering, any such policies at this time.

If you have any questions or need additional information, please contact me by phone at (919) 707-9335 or via e-mail at Brad.Knott@ncdenr.gov.

cc: Donald R. van der Vaart, Secretary, Department of Environmental Quality
Frank D. Gorham, III, Chairman, Coastal Resources Commission
Tom Reeder, Assistant Secretary, Department of Environmental Quality
Braxton Davis, Director, Division of Coastal Management

North Carolina
Coastal Resources Commission

February 15, 2016

The Coastal Resources Commission (CRC) Science Panel has completed the 2015 N.C. Sea Level Rise Assessment report. This report was prepared pursuant to Session Law 2012-202 which states in part: "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 subject of sea level rise has generated considerable public and political interest in North Carolina and beyond. When the CRC was directed to perform this study, we wanted to create a process that was as fair, objective, and credible as possible, and created a Technical Peer Review Group made up of two well-respected national experts on this subject: Drs. Robert G. Dean and James R. Houston. Drs. Dean and Houston were selected because they had previously published peer-reviewed articles challenging the some of the research findings of accelerating rates of sea level rise. We hoped that their technical review would help address claims of bias, such as those that were heard about the 2010 report. The CRC also decided that the study would be limited to a rolling 30-year time frame rather than the previous projections out to the year 2100, and that the report should be updated every five years.

After receiving their charge from the CRC, the Science Panel drafted the report between July and December 2014. Based on the recommendations of Drs. Dean and Houston, numerous changes were made to the initial draft over the next two months. In the end, both the Science Panel, and Drs. Dean and Houston, supported the final draft report. In fact, Drs. Dean and Houston's final review was highly complimentary of the final draft. The CRC then accepted public comments on the report from April to December 2015, and all comments, including the technical peer review comments and the Science Panel's responses, are attached to the final report.

In addition to the sea level rise study requirement, the session law also stated: "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 CRC decided at our April 2015 general meeting that an economic analysis should not be included with the sea level rise report, since the commission has not adopted or initiated any sea level rise rules or policies, and, consequently, has no rules or policies to analyze for potential impacts. If the CRC were to propose any rules related to sea level rise in the future, the NC Administrative Procedures Act requires a fiscal analysis that examines the expected costs and benefits; and, if a significant economic impact is anticipated, an even more detailed economic analysis of the proposed rule must be completed, including an analysis of various policy alternatives.

Division of Coastal Management
Department of Environmental Quality
400 Commerce Ave., Morehead City, North Carolina 28557
Phone 252-808-2808 FAX 919-733-1495

The Science Panel did a remarkable job in preparing this report, and Drs. Dean and Houston provided excellent technical review; we are extremely grateful to them for their generous public service and professionalism. The 2015 N.C. Sea Level rise Assessment Report is attached, in fulfillment of the Session Law 2012-202 directive to the CRC.

Frank D. Gorham, III
Chairman, Coastal Resources Commission

Division of Coastal Management
Department of Environmental Quality
400 Commerce Ave., Morehead City, North Carolina 28557
Phone 252-808-2808 FAX 919-733-1495

MARCH 31, 2015

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

This work supported by the N.C. Department of Environment and Natural Resources, Division of Coastal Management.

Disclaimer: This report was prepared by the N.C. Coastal Resources Commission's Science Panel, acting entirely in a voluntary capacity on behalf of the Coastal Resources Commission. The information contained herein is not intended to represent the views of the organizations with which the authors are otherwise affiliated.

Members of the CRC Science Panel

The Science Panel consists of the following individuals, who serve voluntarily and at the pleasure of the Coastal Resources Commission.

Dr. Margery Overton, Chair
Department of Civil, Construction, and Environmental Engineering, N.C. State University

Mr. William Birkemeier, Co-Chair
Field Research Facility, ERDC/CHL, US Army Corps of Engineers

Mr. Stephen Benton
N.C. Division of Coastal Management (Retired), Raleigh

Dr. William Cleary
Center for Marine Science, University of North Carolina at Wilmington

Mr. Tom Jarrett, P.E.
U.S. Army Corps of Engineers (Retired), Wilmington

Dr. Charles "Pete" Peterson
Institute of Marine Sciences, University of North Carolina at Chapel Hill

Dr. Stanley R. Riggs
Department of Geological Sciences, East Carolina University

Mr. Spencer Rogers
North Carolina Sea Grant, Wilmington

Mr. Greg "Rudi" Rudolph
Shore Protection Office, Carteret County

Dr. Elizabeth Judge Sciaudone, P.E.
N.C. State University, Raleigh

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 at 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).

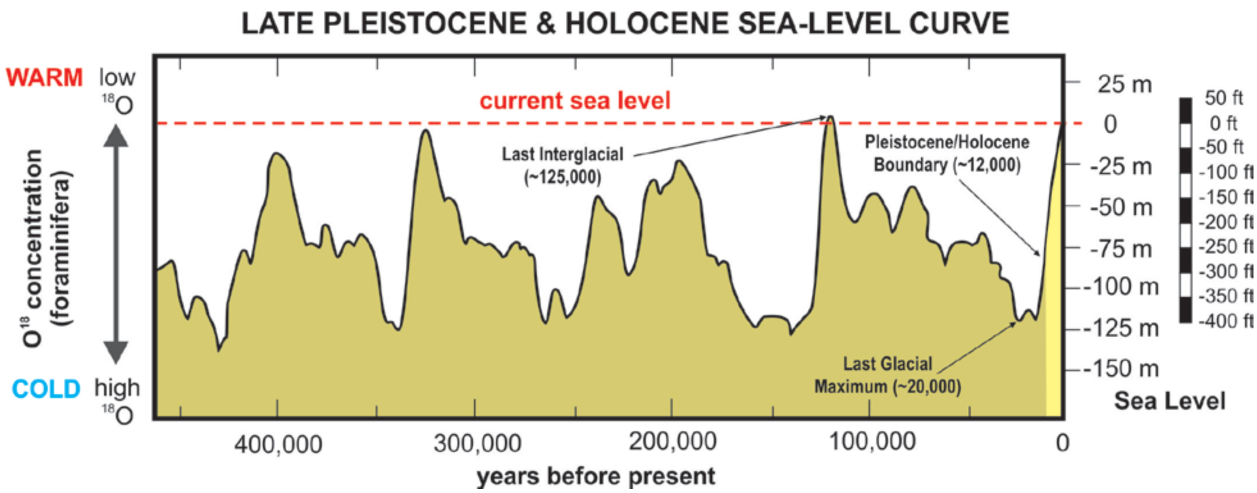

Figure 1. Global sea level curve over the scale of 100,000s of years developed from the marine delta ^{18}O record, which also depicts the last interglacial highstand and glacial maximum. (Modified from Imbrie et al. 1984)

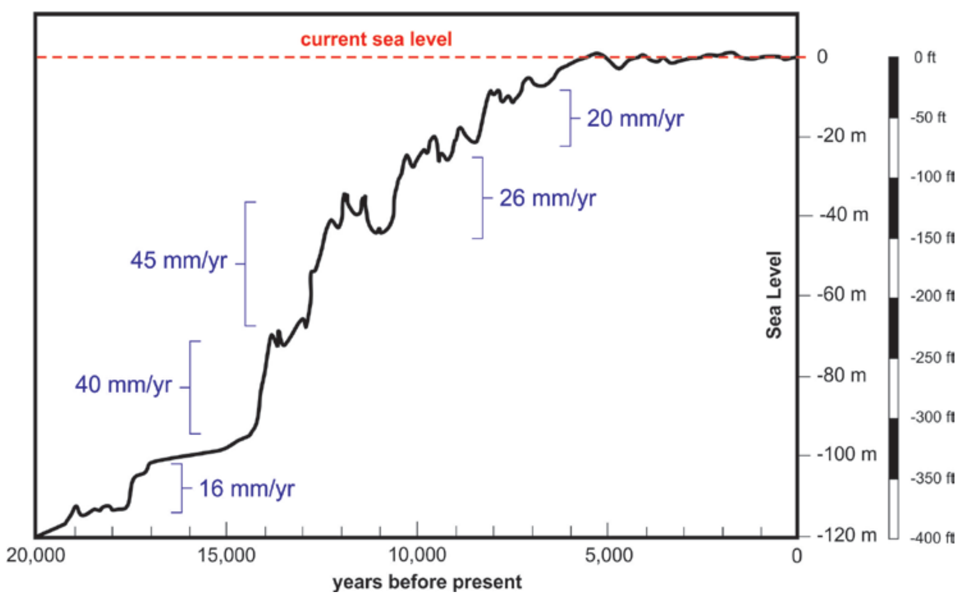

Figure 2. Global sea level curve over the scale of the past 10,000s of years based on radiocarbon-dated reef corals and paleoshoreline indicators constraining sea level movement since the last glacial maximum. (Adapted from Donoghue 2011).

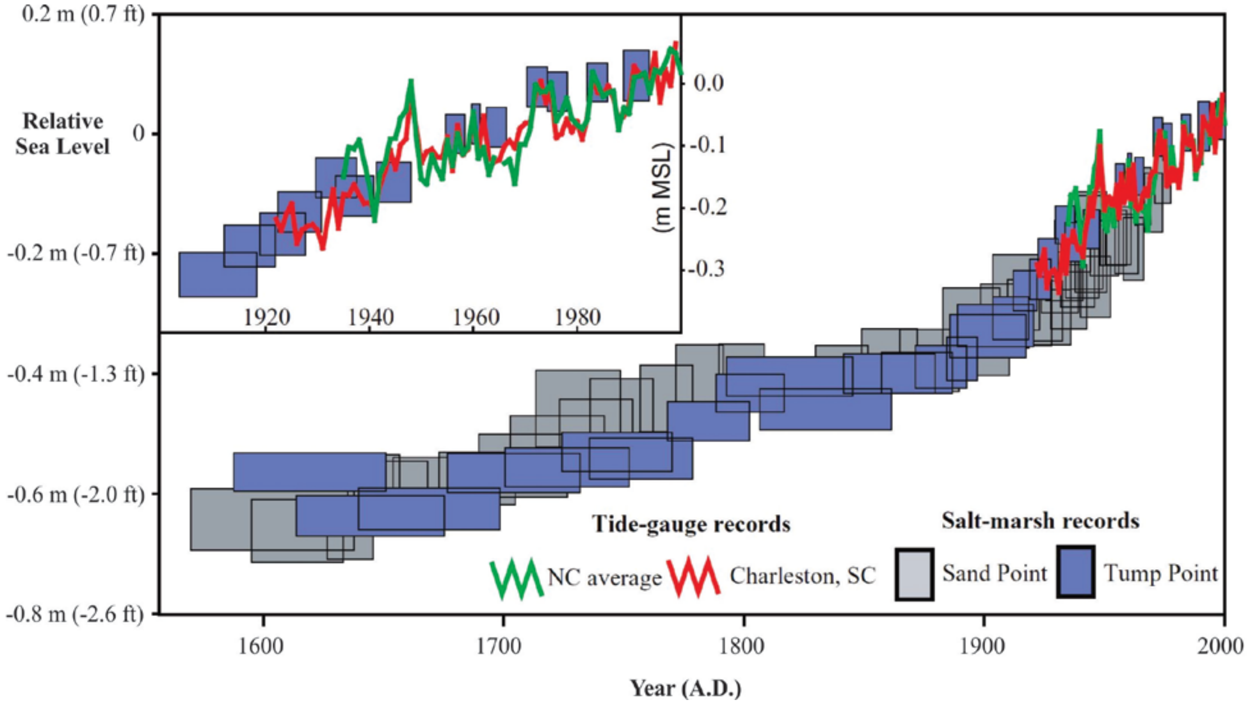

Figure 3. Sea level curve over the scale of the past decades or centuries of years based on N.C. salt marsh records, presented along with the N.C. and S.C. tide gauge records superimposed upon the latter portion of the salt marsh data. The rate of sea level rise has ranged from approximately 0–2 mm/year 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	*El Niño* 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 ±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 ± 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.

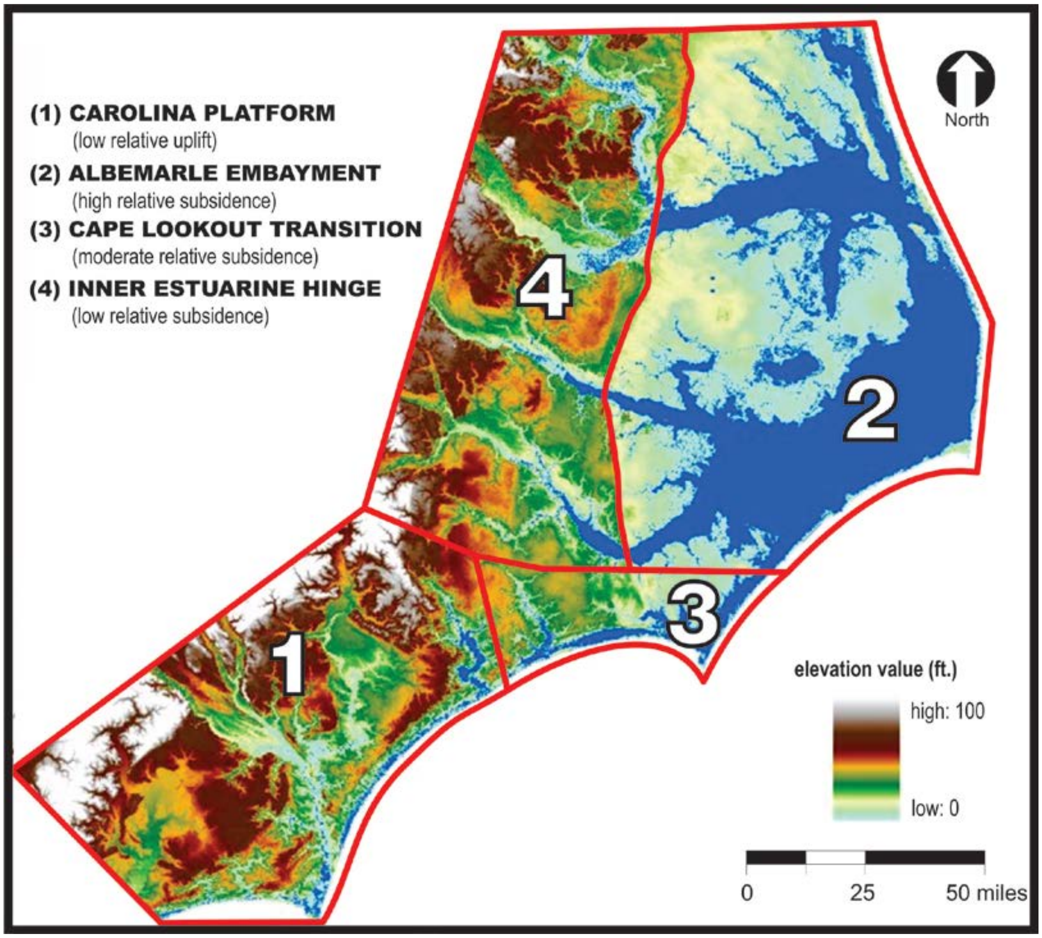

Figure 4. Zones of uplift and subsidence across coastal North Carolina based on major differences in structure, composition, and thickness of the underlying geologic framework.

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.

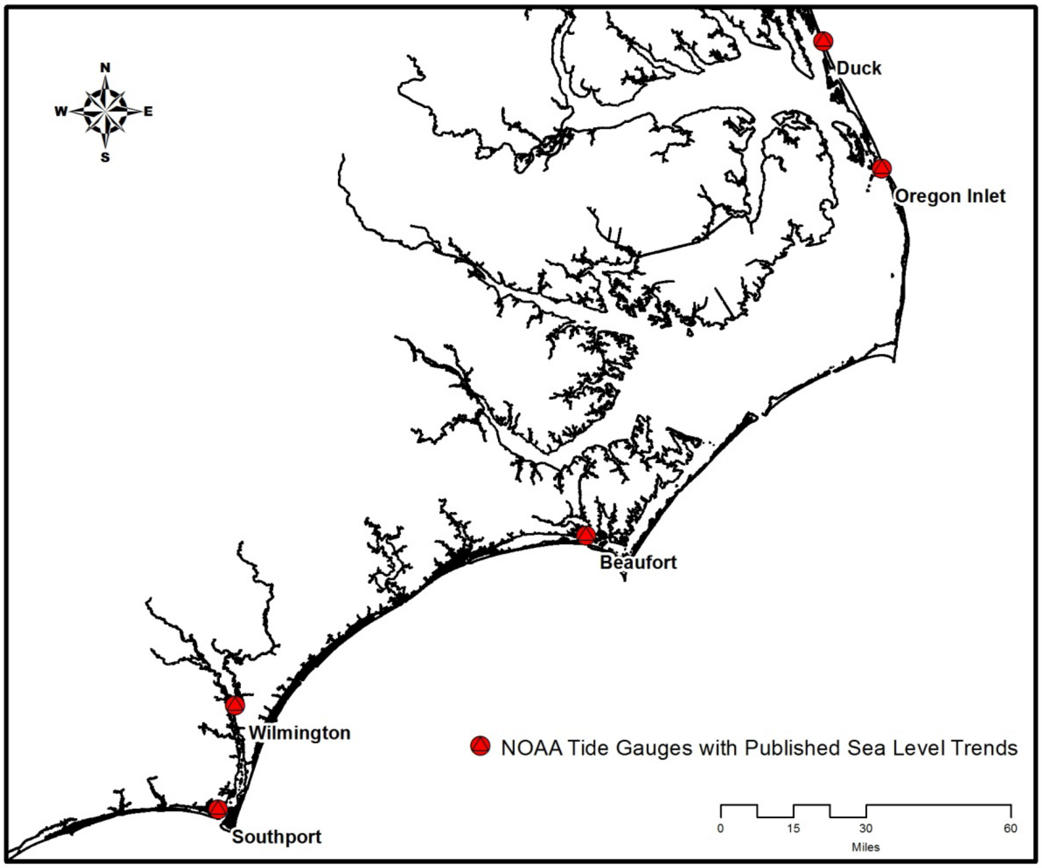

Figure 5. Location of NOAA tide gauges with published sea level trends in North Carolina.

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).

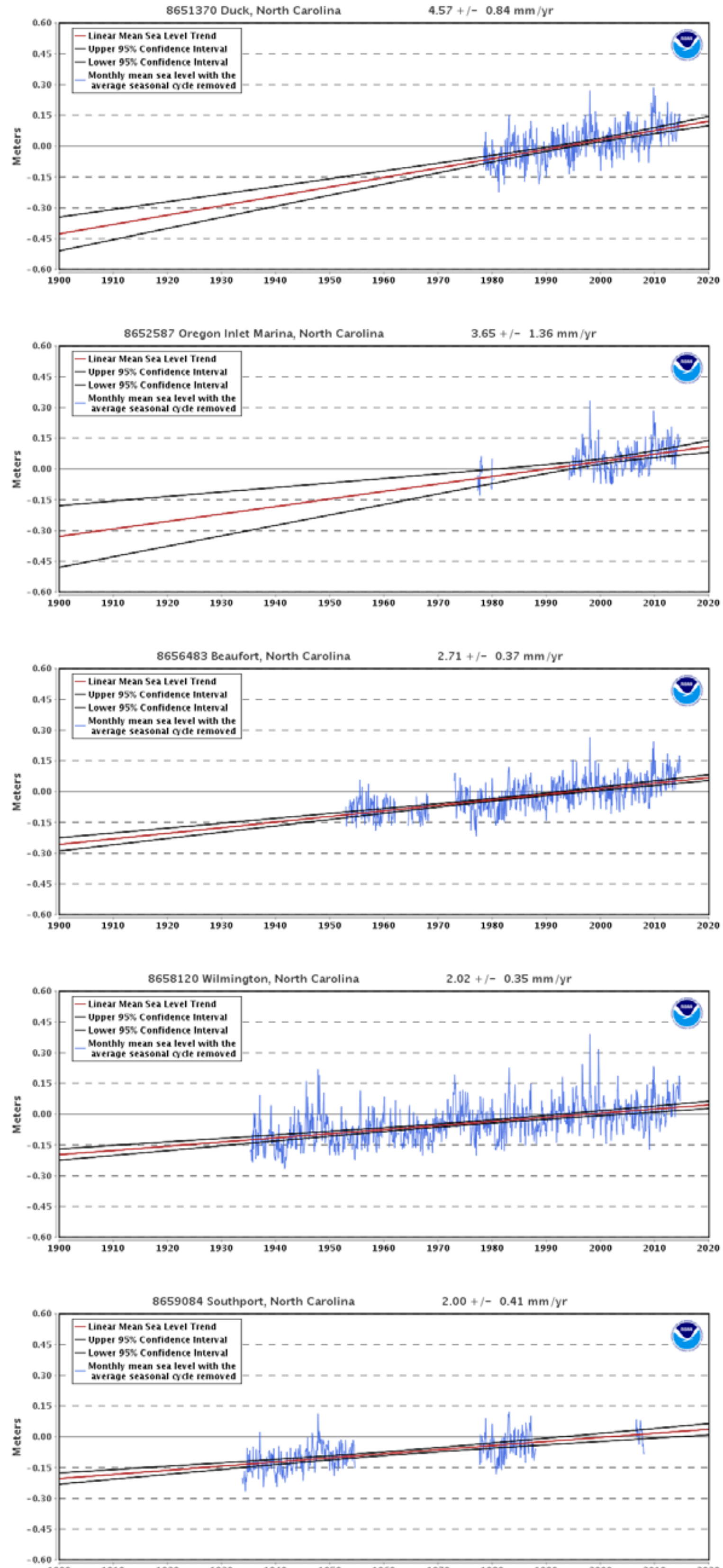

Figure 6. Monthly mean sea levels with seasonal trends removed, for each station with published sea level trends. The long-term linear trend is also shown, including its 95% confidence interval. (NOAA 2014a)

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 ± 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/yr^2, or just $\pm$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]	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]

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

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.

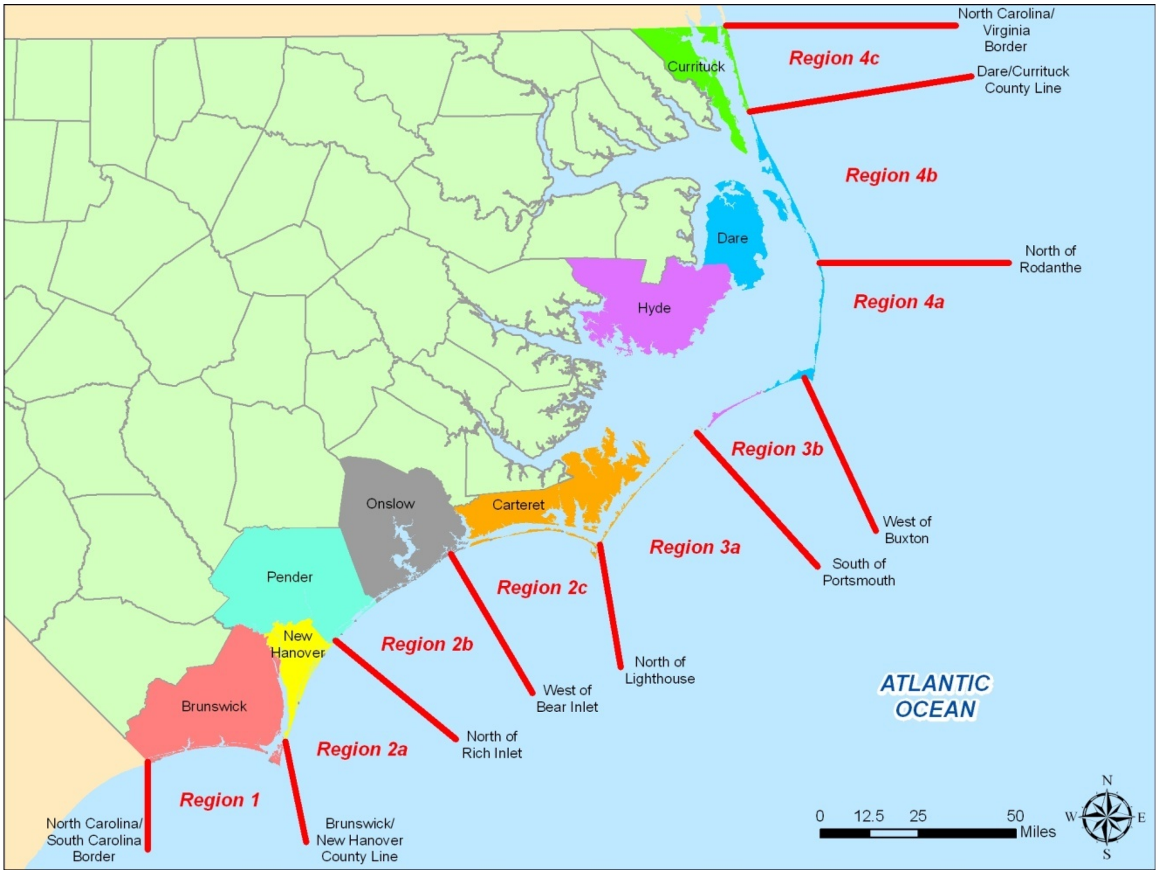

Figure 7. Beach and Inlet Management Plan (BIMP) Regions referenced in S.L. 2012-202.

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.

2015 N.C. SEA LEVEL RISE ASSESSMENT REPORT

TECHNICAL PEER REVIEW
AND
PUBLIC COMMENTS

TECHNICAL PEER REVIEW

Comments on 2015 Science Panel Update to 2010 Report and 2012 Addendum
Robert Dean & James Houston, Jan. 17, 2015

Comments on 2015 Science Panel Update to 2010 Report and 2012 Addendum

We highly commend the members of the Science Panel for volunteering their time and talents in public service to the people of North Carolina.

The 2015 Science Panel Update to 2010 Report and 2012 Addendum (referred to as SPU) presents two good approaches that use different assumptions to estimate sea level rises by 2045 at tide gauge locations in North Carolina (NC). One approach estimates rises by projecting empirical data measured by the NC tide gauges, which assumes the future reflects that past. The second approach uses sea level projections of the Intergovernmental Panel on Climate Change (IPCC 2013), which are based on IPCC global warming scenarios in which temperature rises more rapidly in the future than the past.

The SPU has two significant problems. Confidence intervals are incorrectly added and subtracted in the report, and it uses a value for global sea level rise that is appropriate for the period 1900 through 2009 but not for the periods of North Carolina tide gauge measurements, leading to projections not supported by the data.

Confidence intervals in SPU were incorrectly added and subtracted, producing errors in most tables. Averages are properly added and subtracted, but variances add for confidence intervals, meaning that confidence intervals are added in quadrature. For example (a ± c) – (b ± c) is not a - b ± 0 and (a ± c) + (b ± c) is not a + b ± 2c. In both cases the confidence interval is $\pm \sqrt{c^2 + c^2} = \pm \sqrt{2}$ c. The following website explains this:
http://ipl.physics.harvard.edu/wp-uploads/2013/03/PS3_Error_Propagation_sp13.pdf.
Note that IPCC (Church, et al, 2013) adds confidence intervals in quadrature for components of global sea level rise.

As an example of the errors caused by adding confidence intervals incorrectly, for Southport the SPU has (2.0 ± 0.41) - (1.7 ± 0.20) equal to 0.3 ± 0.21. However, the result should be 0.3 ± $\sqrt{(0.41)^2 + (0.2)^2}$ = 0.3 ± 0.46, making the range (- 0.16 to 0.76) rather than (0.09 to 0.51). Another example is in Table 8. The 2015 values for RCP2.6 and RCP8.5 are correctly given as both being about 2.4 ± 0.6 inches and the 2045 values as about 7.7 ± 2.1 inches and 8.7 ± 2.3 inches for RCP2.6 and RCP8.5 respectively. But when the 2015 values are subtracted from the 2045 values, the errors do not subtract, but add in quadrature, so the correct values are 5.3 ± 2.2 inches for RCP2 and 6.3 ± 2.4 inches for RCP8.5. Therefore, results should be 5.3 (3.1 to 7.5) for RCP2.6 and 6.3 (3.9 to 8.7) for RCP8.5 rather than 5.3 (3.9 to 6.8) and 6.3 (4.7 to 7.9) in SPU. The SPU should include a simple discussion and reference that explain how confidence intervals are added and subtracted.

It is not valid to use a global sea level rate of 1.7 ± 0.2 mm/yr over the periods of NC gauge measurements because this rate was determined for 1900 to 2009, whereas global rates during actual times of NC gauge measurements were sometimes much greater. SPU subtracts this unrepresentative low global rate along with subsidence from measured rates and calls the difference “oceanographic effects”. SPU then assumes these “oceanographic effects” continue unchanged for the next 30 years and adds them to IPCC scenarios, and this produces rises by 2045 that are not supported by the data.

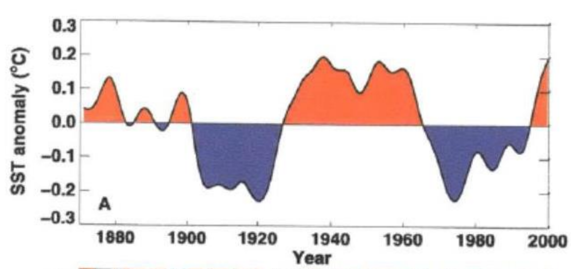
The problem of using a global rate not representative of actual rates during periods of gauge measurements is readily seen for Duck and Oregon Inlet. The Duck gauge recorded from 1978 through 2013 and the Oregon Inlet gauge from 1977 through 2013. Satellite altimeters measured a global rise rate of 3.2 ± 0.4 mm/yr from 1993 through 2013 (University of Colorado, 2014). Therefore, for about 60% of the Duck and Oregon Inlet tide gauge records the global rise rate was substantially greater than 1.7 ± 0.2 mm/yr. It is important to realize that in addition to the linear rise of 1.7 mm/yr given in Church and White (2011), they have an acceleration term so the rise rate increases with time, and this is not considered in the SPU. The linear and acceleration terms determined by Church and White could be used to estimate rise rates during periods of NC gauge measurements. However, Church and White's approach underestimates the rise rate measured by satellite altimeters. Church and White use "synthetic data" generated by combining tide gauge data with Empirical Orthogonal Functions, whereas the satellite altimeter data are measured data. Therefore, the satellite altimeter data should be used for 1993 though 2013.

We can estimate the rate from 1978 to 2013 by taking a global rate of 1.9 ± 0.4 mm/yr for 1978 through 1992 (Church and White, 2011, have a global rate of 1.9 ± 0.4 mm/yr for 1961 through 2009, which is much more representative of the time period than the rate from 1900 through 2009) and a global rate of 3.2 mm ± 0.4 mm/yr from 1993 through 2013. Combining these rates gives a global rate from 1978 to 2013 of 2.66 ± 0.4 mm/yr (Ray and Douglas, 2011, show a global rise from 1978 to 2007 of about 2.5 mm/yr that when coupled with a rise from 2007 through 2013 of 3.2 mm/yr results in a similar global rate of 2.6 mm/yr from 1978 through 2013). With subsidence of - 1.49 ± 0.39 at Duck, this gives a relative sea level rise (global rate minus subsidence) of 4.15 ± 0.56 mm/yr (confidence intervals added in quadrature). This compares with the gauge recording of 4.57 ± 0.84 mm/yr over the same period. Note the two rates are within confidence intervals of each other. The same analysis for Oregon Inlet, results in an average global rate from 1977 to 2013 of 2.64 ± 0.4 mm/yr. With a subsidence of - 0.84 ± 0.65 mm/yr, this leads to a relative rise of 3.48 ± 0.76 mm/yr versus the recorded 3.65 ± 1.36 mm/yr. Again, calculated and measured rates are within confidence intervals.

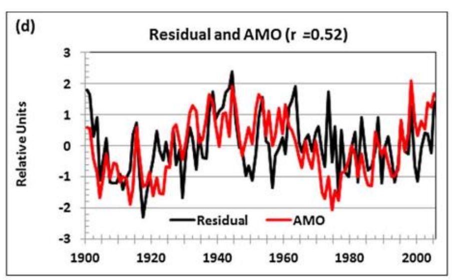
If global sea level rise rates are estimated for Beauford, Wilmington, and Southport using rates of 0.71 ± 0.4 mm/yr prior to 1935 and 1.84 ± 0.19 mm/yr from 1935 to 1961 (Church and White, 2006), 1.9 ± 0.4 mm/yr from 1961 to 1993 (Church and White, 2011), and 3.2 ± 0.4 mm/yr for 1993 through 2013 (University of Colorado, 2014); subtracting the vertical motions of Table 2 from these global rates result in relative sea level rise rates within confidence intervals of the measured rates in Table 1. For all five NC gauges, realistic global rates combined with subsidence yield relative sea level rates within confidence intervals of measured rates. Therefore, "oceanographic effects" must have relatively small magnitudes that are less than confidence intervals of measured rates.

The above method of estimating global rise rates also applies to the gauges north and south of the NC gauges. Figure 5 of the SPU presents a figure from Ezer (2013) that is shown presumably to indicate there is a significant difference in sea level rise north of Cape Hatteras. The figure shows that the Norfolk (Sewell Point) gauge recorded the greatest sea level rise rate and acceleration of the gauges from Key West to Boston, and it is the nearest gauge north of the Duck and Oregon Inlet gauges. Using the same approach as for the NC gauges yields a global rate from 1927 through 2006 of 1.99 ± 0.33 mm/yr. Zervas (2013) shows a subsidence of - 2.61 ± 0.11 mm/yr. Combining the calculated rate with subsidence yields 4.60 ± 0.33 mm/yr. Zervas shows the rise measured by the Norfolk tide gauge from 1927 through 2006 was 4.44 ± 0.27 mm/yr. The same approach applied to the Charleston gauge, the nearest long-term gauge south of NC, yields a global and subsidence relative rise of 3.14 ± 0.34 mm/yr versus the rate of 3.15 ± 0.25 mm/yr recorded by the Charleston tide gauge. As was the case for the five NC tide gauges, calculated rates for the Charleston and Norfolk gauges that are based on subsidence and realistic global sea level rates during periods of recording agree within confidence intervals of measured relative sea level rise rates. The average rise rate based on calculated global rates and subsidence for the five NC, Charleston, and Norfolk gauges is 3.15 ± 0.43 mm/yr, and this is in good agreement with the measured average rate for the seven gauges of 3.22 ± 0.55.

There certainly are oceanographic effects that affect sea level along the NC coast such as variations in the Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), and Gulf Stream as governed by the Atlantic Meridional Overturning Current (AMOC), and other factors. Indeed, Houston and Dean (2014) show that there are multi-decadal oscillations in the rate of sea level rise in every gauge recording in the world. Variations in the AMOC, AMO (see figures), and NAO can affect sea levels along the NC coast, but these variations will not remain constant over the next 30 years as is assumed in SPU ("oceanographic effects" are assumed in SPU to have a constant rate over 30 years when used with the IPCC scenarios). For example, it would not be valid to take falling sea levels on the Pacific Coast measured over the last 22 years by satellite altimeters (caused by an oscillation of the Pacific Decadal Oscillation – PDO), and project that sea level will fall on the Pacific Coast over the next 22 years. Indeed, Bromirski et al (2011) assert just the opposite will occur, the rise in sea level will be greater than the worldwide average along this coast for decades as the PDO reverses. AMO, NAO, and AMOC also have periodic reversals.



AMOC (Buckley, 2011)



AMO (Chylek et al, 2014)

SPU cites journal papers that indicate there has been acceleration in sea level rise in the mid-Atlantic area, but some of the papers also indicate the acceleration may well be a typical variation in decadal oscillations and not enduring. For example, Smeed et al (2014) say that evidence suggests that the decrease in the AMOC, "… represents decadal variability of the AMOC system rather than a response to climate change." Knopp (2013) says, "Consistent with the hypothesis that the regional 'hot spot' represents variability rather than the start of a trend, none of these indexes currently exceeds its range of historical variability. As the changes in these indices reflect the driving factors underlying the 'hot spot', the phenomenon may not prove to be enduring." Varying and non-enduring phenomenon cannot be assumed constant and projected into the future. In any case, magnitude of sea level change rates resulting from "oceanographic effects" are not apparent because relative sea level rates estimated from realistic global and subsidence rates agree within confidence intervals with measurements at all five NC gauge locations and gauges at Charleston and Norfolk.

The SPU should discuss how calculated rises as shown above agree within confidence intervals at all seven gauges, so additional factors other than subsidence should not be added to IPCC projected rises.

The error caused by using a rate of 1.7 ± 0.2 mm/yr at Duck from 1978 to 2013 and then having to postulate "oceanographic effects" that would remain constant for the next 30 year is easily shown. As shown earlier, there is a global sea level rise of 6.3 ± 2.4 in/yr for IPCC scenario RCP 8.5 (confidence intervals added incorrectly in Table 8). If we subtract the vertical motion of - 1.8 ± 0.5 in/yr at Duck, the relative sea level projection becomes 8.1 ± 2.5 in/yr (confidence intervals from adding in quadrature). The low, medium, and high values are therefore 5.6, 8.1, and 10.6 in/yr versus 7.3, 9.7, and 12.3 in/yr in Table 10.

Dropping the incorrect rate of 1.7 ± 0.2 mm/yr as representative of the global rate over the time of NC gauge measurements also simplifies results and makes them more understandable and transparent to non-technical readers. For example, one approach would just multiply measured rates by 30. The second approach would merely combine subsidence over 30 years with IPCC projections. These approaches are simple, understandable, and defensible; in contrast to the current approach in SPU 2015, which is easily criticized and, therefore, likely to be controversial.

Using three sentences to dismiss the possibility of deceleration may not satisfy critics. Satellite altimeters have made the best measurements of sea level rise in the past two decades because they measure over the globe rather than the limited locations of tide gauges and they do not have the problem of vertical land motions that tide gauges have. Satellite altimeter measurements show a decelerating sea level rise. Dean and Houston (2013) show that during the period of satellite altimeter measurements from 1993 to 2011, sea level had a deceleration of - 0.083 mm/yr^2 (deceleration also seen in Figure 5b of the SPU and Ezer, 2013, p. 5441). They analyzed all 456 tide gauges in the world with records from 1993 to 2011 and found a deceleration of - 0.041 mm/yr^2. The altimeter record (University of Colorado, 2014) analyzed from 1992.9595 through 2014.6508 still shows a deceleration of - 0.035 mm/yr^2. However, the record is relatively short and, as noted in Dean and Houston (2013), the deceleration may just be evidence of cyclic behavior - that is, caused by decadal variations. As noted earlier, uncertain and varying phenomena cannot be assumed to remain at current values and then be projected into the future.

With the Duck gauge as an example, projecting the current rate of rise at Duck for 30 years yields an average relative sea level rise of 137.1 ± 25.2 mm. Analysis of the altimeter record from 1992.9595 through 2014.6508 shows that the rise has the form $3.245x - 0.0176x^2$ with x equal to years of record. Over the next 30 years, this rise would produce a global rise of 81.5 ± 12 mm including the deceleration term. Subsidence would add 44.7 ± 11.7 mm/yr for a total of 126.2 ± 23.7 mm. This value is well within the confidence interval of the rise determined by projecting Duck rates without deceleration. Moreover, the difference in the two projections is only 10.9 mm, or 0.4 inches. Assuming the global deceleration for last 22 years will continue unchanged for the next 30 years is not justified, and its effect is small in any case.

Duck is shown in Table 4 to have a substantially greater vertical land motion than does Oregon Inlet, although the tide gauges are only about 30 miles apart. Since the Duck pier pilings are concrete, is it known whether the pier itself is sinking, so that it is not representative of land subsidence in the area? There are bench marks on the pier, in the parking lot, and along the pier access road, so the question can be settled if it has not been already. If settled, a sentence should note that there is not subsidence of the pier relative to land.

Additional comments on SPU 2015 are listed below by page section and page.

Executive Summary

We suggest a brief introductory paragraph in the Executive Summary. Something like:

"Two bases for quantifying global sea level change are reported in the scientific literature: (1) sea level as observed directly by tide gauges, and (2) volumetric changes including the best estimate of the average global subsidence of the sea floor (0.3 mm/yr) due to Glacial Isostatic Adjustment (GIA) as reported in the satellite altimeter measurements and calculations by Church and White (2006, 2011) and others. In this report, the first basis is used as the most relevant to those who will use the results."

We also suggest an expanded discussion of the above be included as an early section of the main text of the report. The 0.3 mm/yr is relevant to the SPU because IPCC projections include the GIA average global sea floor subsidence of 0.3 mm/yr. When IPCC projections are used to determine local relative rise projections, they are too large by 0.3 mm/yr because they include the effect of global sea floor subsidence. However, Zervas (2013) subtracted 1.7 mm/yr (includes the GIA value of 0.3 mm/yr) instead of 1.4 mm/yr to determine local subsidence. Therefore, subsidence values are too low by 0.3 mm/yr. The 0.3 mm/yr portions of IPCC projections and subsidence values offset, so IPCC and subsidence numbers are properly added (as done in the SPU) to determine relative sea level change at NC tide gauges.

Also, early in the main body of the report or alternatively as a table preceding the report there should be a description of terms and acronyms including: Relative Sea Rise (RSL), etc.

Page 1. Ezer and Atkinson 2014 does not appear in the references.

Page 2. Fairbanks (1989) does not appear in the references.

Page 4. Table 1 has a percentage contribution to sea level rise from the Greenland and Antarctic ice sheets for the period from 1971 to 2010, but it is based on Table 13.1 of Church et al (2013), which does not have percentage contributions for these ice sheets for the period. SPU apparently assumes the numbers must add to 100%, but contributions are so uncertain that Church et al (2013) do not give percentages for either ice sheet. We suggest instead percentages be presented for the period shown in Table 13.1 from 1993 to 2010, because Greenland and Antarctic ice sheet contributions are given (it appears the total should be 2.94 rather than 2.8 mm/yr). In addition, the 1993 to 2010 rates give a better appreciation of current contributions to sea level rise. For example, "Land water storage", which includes water impoundment and groundwater extraction, is shown in Table 1 to be only 6% of the contribution to sea level rise, whereas Table 13.1 has it contributing 13%, illustrating how important groundwater extraction has become to sea level rise.

Page 7.

Eggleston et al. 2013 should be Eggleston and Pope 2013.

The reference should be Engelhart et al. 2009 and not Englehart et al. 2009.

The acronym NCDENR appears without being defined as North Carolina Department of Environment and Natural Resources

Page 9.

Text says, “The present rate of GSL rise is 1.7 mm/yr (Church and White, 2011) …” Of course, this is not the present rate, but the average rate from 1900 to 2009. The present rate as measured by satellite altimeters from 1993 through the present is 3.2 mm/yr (University of Colorado, 2014).

Page 10.

Spanger-Siegfried et al. (2014) is a non-peer-reviewed internet article authored by an advocacy group. There are many non-peer-reviewed internet articles authored by skeptics of global warming and increased sea level rise that also could be cited, so we suggest dropping the reference. In addition, NOAA (June 2014) isn't referenced although it focuses on nuisance flooding (Sea Level Rise and Nuisance Flood Frequency Changes around the United States, NOAA Technical Report NOS CO-OPS 073,
http://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.pdf)

We recommend the reference to the 2014 National Climate Assessment (actual citation should be Melillo et al 2014 rather than Melillo 2014) be dropped because it has about a page of its 841 pages devoted to sea level rise. It has no original information, but bases its maximum projected sea level rise on the intermediate high listed in NOAA 2012. The NOAA report says the intermediate high is, “… based on an average of the high end of semi-empirical, global SLR projections.” IPCC 2013 (page 1140) said of semi-empirical modeling, “…there is no consensus in the scientific community about their reliability, and consequently low confidence in projections based on them.” A couple of authors of IPCC 2013 have used semi-empirical models and published papers, but they agreed with the IPCC statement that there is low confidence in projections based on semi-empirical modeling.

Pages 9-11.

The discussion of “oceanographic effects” is interesting, but as discussed earlier, the section should be eliminated or shortened with an emphasis on the effects having a magnitude less than confidence intervals and being oscillatory and likely non-enduring as pointed out by Smeed et al (2014) and Knopp (2013). As discussed earlier, the usefulness of Figure 5 is not apparent because subsidence combined with global rates equals measured rates within confidence intervals for the tide gauges from Charleston to Norfolk.

Page 12.

The acronym NWLON is never used.
Text says Yelverton and Hackney 1990, but references say Hackney, C.T. and G.F. Yelverton. 1990.

Page 23.

Sweet and Parker 2014 should be Sweet et al 2014.

Page 24.

The text says that, "One of the major sources of uncertainty in estimates of sea level rise even over a period as short as 30 years is introduced by our limited understanding of the rates of loss of the Greenland and West Antarctic ice shelves. The rates of melting and ice sheet loss into the sea are highly uncertain and could occur rapidly." These sentences have an element of hyperbole. The IPCC numbers in Table AII 7.7 include uncertainties in loss of ice in Greenland and West Antarctica. In 2045, even for Scenario RCP 8.5, the upper confidence level is only 2.4 inches higher than the average and only part of this uncertainty is due to uncertainty in the loss of ice in Greenland and West Antarctica. There have been a number of media releases in 2014 emphasizing studies that indicate the West Antarctic ice sheet has started to collapse and the collapse is unstoppable. Joughin et al (2014) is the only one of these studies with a projected sea level rise rate resulting from this beginning collapse. They note that losses in the 21st century due to the beginning collapse of the West Antarctic ice sheet at the Thwaites glacier (which would eventually release other glaciers – in hundreds of years) will be less than 0.25 mm/yr with a more rapid rise of greater than 1 mm/yr within the range of 200 to 900 years from now. A rise of less than 0.25 mm/yr results in a rise over the next 30 years of less than 0.3 inches, and is largely accounted for in current IPCC projections.

The reference Boon, J. D., J. M. Brubaker, and D. R. Forrest (2010) is not found in the text.

Page 27.

The reference 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 does not appear in the text.

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University of Colorado, 2014. 2014_rel5: Global Mean Sea Level Time Series (seasonal signals removed). http://sealevel.colorado.edu/

Science Panel response to January 17th comments from Robert Dean and James Houston
Feb. 19, 2015

We first extend our appreciation to our reviewers for their time and careful consideration of this report and methodology. Two issues that impact the calculation of the range of future sea level rise projections are the primary focus of the review comments. They are 1) how the confidence interval or range of projections for each component is treated mathematically as elements are combined in the methodology and 2) the assessment of local effects and how these are used in combination with the IPCC projections. The Panel has considered these comments and a synthesis of our discussions are provided below. The additional comments were more editorial in nature and will be considered in our revised draft in March.

1) The Panel discussed possible inclusion of 'quadrature' in assessing limits or ranges of estimates in our November meeting and is revisiting our proposed methodology based on the reviewers' comments. Because of the expression of range of estimates in the Table ll.7.7 of Annex ll: Climate System Scenario Tables is not a confidence interval, we have asked for additional review from statistics at NC State on our methodology and will not have their input until later this month. At that time we plan to update our calculations and will communicate with the reviewers on the outcome.

2) The reviewers note that the length of record for the gauge at Duck is not consistent with the time period used to establish a global SLR of 1.7 mm/yr and conclude that therefore the computed local effect at Duck is in error. Further, they suggest an alternative computation which would result in a conclusion that the local effect can be explained by the local VLM (vertical land motion) only.

The Panel recognizes the issues with respect to length of record of the tide gauges and the time period of the record relative to assessment of global sea level rise and in the November meeting considered using different rates for different gages. The primary tide gauge that has spurred this discussion is the Duck gauge. The time frame of operation of this gauge and the Oregon Inlet gauge are the shortest in North Carolina, spanning the late 1970s to present time frame (data through the end of 2013 were employed for the report). The panel spent considerable time discussing the issue of the different time periods of measurement for each of the gauges including an analysis offered by Tom Jarrett that could simulate the extension of the time series at Duck in order to be more consistent with the time frame for the use of 1.7 mm/yr. As a result of this discussion the Panel recommended that the time series issue should be dealt with as a special project outside the work of the Panel.

In response to the reviewers' comments we offer the following discussion. The time frame of operation of the Duck gauge coincides with a measured increase in the rates of sea level rise along the mid-Atlantic region (consistent with the reviewers' analysis). The question at hand is whether this measured increase reflects a global increase or is local. In addition, if local, will the effect persist for the 30 year response period requested by the CRC or is it other (i.e., cyclic or not persisting). In our draft, the Panel made the assumption that the local effect was separate from the global and would persist into the future. This assumption is clearly stated and the numbers reflect that approach. The Panel felt that it was responsible to acknowledge the possibility that local effects including oceanographic factors could persist and to bring this information to the attention those making management decisions. After discussion in the January meeting, the Panel decided to keep this analysis in the report.

Because it is an assumption and we recognize it as such, we can compute and present the alternative formulation (considering the IPCC projections in combination with the VLM numbers) in order to communicate the magnitude of the difference in the projections by making this assumption. Using VLM directly eliminates the step of assuming a global sea level rise rate in the proposed methodology. Using the updated 2013 VLM values as computed by Zervas essentially reduces the local effects at Duck and Oregon Inlet 1-2 inches in the 30 year projection since these gauges have the shorter temporal records and are located north of Cape Hatteras where the increase in the mid-Atlantic rates has been observed. Projections for the Beaufort gauge remain the same and Wilmington and Southport differ by less than 1 inch. (see table below). Note, the magnitude of the high and the low of the local effect and the difference may change when procedures for error analysis are finalized.

Station	Local Effects			VLM Effects			Difference		
	Relative Sea Level Rise by 2045, inches			Relative Sea Level Rise by 2045, inches			Relative Sea Level Rise by 2045, inches		
	Mean	High	Low	Mean	High	Low	Mean	High	Low
Duck	3.4	4.2	2.6	1.8	2.2	1.3	-1.6	-2.0	-1.3
Oregon Inlet Marina	2.3	3.7	0.9	1.0	1.8	0.2	-1.3	-1.9	-0.7
Beaufort	1.2	1.4	1.0	1.2	1.4	1.0	0.0	0.0	0.0
Wilmington	0.4	0.6	0.2	0.5	0.7	0.2	0.1	0.1	0.0
Southport	0.4	0.6	0.1	0.6	0.8	0.4	0.2	0.2	0.3

The issue of the impact of the length of record and time period of the record of the tide gauges on the computations (including VLM) is important as the state considers how to use the information and our recommendation for further analysis will likely remain in the report.

Robert Dean and James Houston reply to Science Panel's Feb. 19, 2015 response
Feb. 20, 2015

The Science Panel has not adequately addressed our comments on the Science Panel Update (SPU), and, therefore, in its present form the SPU is not publishable as we expected in a referred journal. The Panel did not rebut our criticisms of assumptions underlying one of its key approaches. Instead it merely said the assumptions were clearly stated. However, these assumptions were not justified in the SPU or in a rebuttal of our criticisms. Assumptions must be clearly justified, not merely clearly stated.

The Panel's one action that was responsive was to indicate it would include in one part of a table sea level rises based on the standard approach of adding IPCC projections and vertical ground. We recommended this approach because local and global data presented in the SPU provided no evidence of a persistent local effect other than ground motion that would cause an extra increase in sea level rise on the NC coast over the next 30 years.

The Panel did not address our comments relating to adding and subtracting errors. The approach used in the SPU is embarrassingly incorrect, and the Panel should have simply admitted so and made corrections. It is good the Panel will be seeking help from NC State. However, it is important to provide NC State with correct information. For example, the Panel's response says, "…the expression of range of estimates in the Table ll.7.7 of Annex ll: Climate System Scenario Tables is not a confidence interval." This is incorrect. Table II.7.7 of Annex II uses the term "likely range" and says to go to Section 13.5.1 of "Sea Level Change" of IPCC (2013) to see what this means. On page 1184 of Section 13.5.1 (entitled "Confidence in Likely Ranges and Bounds"), it says "The AR5 5 to 95% process-based model range is interpreted as a likely range". The IPCC numbers all have 95% confidence intervals.

Even if the Panel was not sure about the IPCC numbers, it should have been clear that the NOAA sea level rise rates, vertical land motion, and global rates from Church and White (2011) all had confidence intervals, so it is inexplicable that the Panel did not agree with our comments and correct the SPU. The NOAA (2014) sea level rise rates have confidence intervals as can be seen in Table ES1 of the SPU report itself, which has the caption, "Sea level rise over 30 years at existing published rates of sea level rise (NOAA 2014). Magnitude of rise was determined by multiplying the rate ± the 95% confidence interval…" VLM numbers from Zervas (2013) have confidence intervals as noted in the following from Zervas, "Table 1 lists the published relative NOAA sea level trend for each station (along with the 95% Confidence Interval of the trend) and the estimated rate of VLM (along with the 95% Confidence Interval) using the methodology described above." The projections of Church and White (2011) have standard deviation confidence intervals.

Had the errors been simple average errors rather than confidence intervals, the absolute value of the errors would have had to have been added regardless of whether the means were added or subtracted. In any case, the approach used in the SPU is glaringly incorrect. The website below explains how to add and subtract both simple average errors and confidence intervals. http://www.rit.edu/cos/uphysics/uncertainties/Uncertaintiespart2.html.

The Panel's response says, "The reviewers note that the length of record for the gauge at Duck is not consistent with the time period used to establish a global SLR of 1.7 mm/yr and conclude that therefore the computed local effect at Duck is in error." Actually, this comment holds for all the NC gauges with the lack of consistency being greater the shorter the record. The SPU approach results in spurious "local effects" for all gauges with the spurious effects being about equally large at Oregon Inlet and Duck. We noted in our review that it was not valid to use a global sea level rate of 1.7 mm/yr over the periods of NC gauge measurements because this rate was determined for 1900 to 2009, whereas global rates during actual times of NC gauge measurements were all greater, and sometimes much greater. We showed for all the NC gauges and for the Norfolk and Charleston gauges that if a simple approach is used to estimate realistic global sea level rates, when these rates are added to vertical motion rates, the results match measured data within confidence intervals for every gauge - that is, there are no residuals for any of the gauges. The SPU only obtains residuals that it calls "local effects" because 1.7 mm/yr is lower than the actual global sea level rise rates during the periods of tide gauge measurements. No one would claim that the global rise in sea level was 1.7 mm/yr from 1977 (Oregon Inlet gauge) or 1978 (Duck gauge) to 2013, when satellite altimeters (and tide gauges within confidence intervals) say the rise from late 1992 to 2013 was 3.2 mm/yr. We do not know yet if the increase in global sea level rise from the early 1990s to today is an enduring increase or a multidecadal variation. However, there is no doubt from measurements that it occurred and the global sea level rate from 1977 or 1978 to 2013 was a good deal greater than 1.7 mm/yr. The SPU did not justify using the incorrect global rise of 1.7 mm/yr during gauge measurements, but just "assumed" it was true and as a result obtained spurious local effects. If realistic values for global rates during periods of gauge measurements are used, these residuals all disappear (within confidence intervals of measurements). The Panel's response provided no rebuttal of our demonstration that the global sea level rate it used over the periods of NC gauge measurements was incorrect and led to its spurious "local effects".

We also showed in our comments that even if there had been local effects, the SPU's own references, which it uses to justify projecting the effects forward, do not support projecting varying and non-enduring phenomena forward. We noted that Smeed et al (2014) say that evidence suggests that the decrease in the AMOC, "… represents decadal variability of the AMOC system rather than a response to climate change." We noted that Knopp (2013) says, "Consistent with the hypothesis that the regional 'hot spot' represents variability rather than the start of a trend, none of these indexes currently exceeds its range of historical variability. As the changes in these indices reflect the driving factors underlying the 'hot spot', the phenomenon may not prove to be enduring." Eber (2013) says, "The results suggest that global SLR is accelerating in recent years but that this acceleration is a combination of long-term trends and multidecadal variations." IPCC (2013) projections include acceleration and are the best source for determining the long-term global trend that Eber noted. "Multidecadal variations" that Eber noted north of Cape Hatteras are oscillatory, and even if they were significant today in NC, they would have different values in 30 years, and could even have phases that reduce sea level rise somewhat. We also provided a classic case of why a multidecadal variation on the Pacific Coast of the US, which has resulted in an actual fall in sea level over more than 20 years, cannot be projected forward at present values. As we noted in our review, "Varying and non-enduring phenomenon cannot be assumed constant and projected into the future." The Panel provides no rebuttal of our criticism and no justification for carrying forward a varying and non-enduring effect, even if it were shown to exist.

In its response, the Panel justifies using a 1.7 mm/yr rate and assuming the resulting local effects persist unchanged for 30 years because it says they are "clearly stated" assumptions. However, the Panel cannot justify assumptions that are not supported by evidence by merely saying the assumptions are clearly stated. Incorrect assumptions lead to incorrect outcomes regardless of how clearly the incorrect assumptions are stated.

The Panel did not even comment on our question as to whether the Duck pier might be sinking relative to land.

We had numerous comments on the last four pages of our review of the SPU, and none of these comments were addressed by the Panel. It only said it would “consider” the comments. Considering comments and addressing them are not the same.

An adequate response would have sent the latest version of the draft report and provided real responses to our comments. The Panel would have addressed our comments by rebutting our criticisms and justifying its assumptions or agreeing with us and changing its approach. Instead it basically ignored the comments, providing no rebuttals and keeping assumptions that it does not justify.

We recommend that the Panel adequately address our comments even with the pressing time constraints. It can easily remove the approach in the SPU that it has not been able to justify, making the SPU simple, understandable, and defensible. We would happy to review another version of the SPU to determine if it is publishable.

Science Panel response to January 17th comments from Robert Dean and James Houston
March 18, 2015

1) *Calculation of confidence intervals.*

The reviewers were correct in pointing out that the propagation of error in the estimates should be added in quadrature. Therefore, the 30 year change in sea level for RCP 2.6 and RCP 8.5 is 5.3 (3.1 to 7.6) inches and 6.3 (3.8 to 8.8) inches, respectively. This has also been incorporated into the projections including VLM (see No. 2).

2) *Estimation of local effects and use of 1.7 ± 0.2 mm/yr for global sea level rise.*

The panel appreciates the detailed review comments related to global and local sea level rates and their computation. The Panel met on March 13, 2015 and has agreed to adopt the approach of combining the IPCC projections with VLM estimates from Zervas. The revised projections presented in the table below have also been combined considering quadrature error propagation as discussed above.

RCP 2.6 + VLM				
	Mean	**Low**	**High**	**95% CI**
Duck	7.1	4.8	9.4	2.3
OI	6.3	3.9	8.7	2.4
Beaufort	6.5	4.2	8.7	2.3
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Note that the VLM and IPCC confidence intervals were added in quadrature.

3) *Since the Duck pier pilings are concrete, is it known whether the pier itself is sinking, so that it is not representative of land subsidence in the area?*

As part of NOAA's maintenance program, they routinely (once or twice a year) run a new level from the land-based benchmarks to the gauge. These data show that the pier has not settled.

4) *Using three sentences to dismiss the possibility of deceleration may not satisfy critics.*

We have changed the structure and revised these sections to separate Potential Decrease in Sea Level Rise (now section 5.2) from Potential Increase in Sea Level Rise (now section 5.3). We have revised Section 5.2 based on the comments as follows:

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) *We suggest a brief introductory paragraph in the Executive Summary and an expanded discussion of GIA in the body of the report.*

A brief note on GIA has been added to the body of the report. However, we have not modified the Executive Summary to include comments on GIA because we are not emphasizing this factor as a result in itself but rather as a contributor to the results.

Section 3.1 Vertical Land Motion (VLM)

<u>This phenomenon also causes some ocean basins to be subsiding as mantle material moves from under the oceans into previously glaciated regions on land.</u>

In addition a reference to satellite data has been added to **Section 8 Recommendations for Updating the Report**:

<u>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. This will also provide the opportunity to examine coincident time frames with varying data sources (i.e., satellite altimetry and tide gauges).</u>

7) *There should be a description of terms and acronyms including Relative Sea Rise (RSL), etc.*

After the Table of Contents a section describing Terms and Acronyms has been added.

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Figure 5 and references to it have been removed and conclusion has been added that:

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.

Panel feels this discussion is important to bring forward and an area of research that should be followed closely.

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The paragraph has been rephrased as:

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 about 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.

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Robert Dean and James Houston Final Review
March 20, 2015

The Science Panel's reply to comments that Professor Bob Dean and I made was thorough and quite responsive.

I highly commend Science Panel members for the many hours they spent and expertise they contributed in developing the Science Panel Update (SPU). Their task was difficult, but they successfully adhered to a tight schedule to produce the SPU on time and in accordance with NC General Assembly Session Law 2012-202. The State of North Carolina is indebted to them for their voluntary service and the fine product they produced. Special recognition must be given to Professor Margery Overton for her leadership as Chair of the SPU. The State also is very much indebted to Mr Frank Gorham, Chairman, Coastal Resource Commission, who set up a process that stayed on schedule and faithfully followed a peer review process.

Projecting future sea level rise is a difficult task, given that there are many uncertainties in everything from local ground motions to local oceanographic processes to global sea level change. The SPU presents two basic approaches to project sea level change over the next 30 years in North Carolina. First, it takes empirical data of relative sea level rise rates (that include ground motions) at five NC gauges and projects the rates into the future. Second, it takes the 2013 projections of global sea level rise made by the Intergovernmental Panel on Climate Change (IPCC) and adds local ground motion determined by Zervas (2014). The first approach provides an estimate of relative sea level rise at the NC gauges if the rise in the future is the same as in the past. The second approach provides an estimate of relative sea level rise if climate projections made by the IPCC occur. These two approaches cover the likely range of sea level rise over the next 30 years.

I believe the SPU is a good contribution to the scientific literature and agree with SPU recommendations for further research and a five-year update. I recommend the highlights of the SPU be submitted to a peer-reviewed journal for publication. Many states and local communities would be interested in the approach.

I discussed the SPU with Professor Bob Dean up to three days before his death, including the conversation Professor Overton and I had about the planned SPU response to our comments. He would have agreed with all of my comments above.

James R. Houston
Director Emeritus
Engineer Research and Development Center
Corps of Engineers

PUBLIC COMMENTS

CRC Meeting
April 29-30, 2015
Dare County Government Complex
Manteo, NC

Public Comment on Sea-Level Rise Report 2015 Update

Heather Jarman, Regulatory Affairs Director with BASE, commented that BASE has provided feedback throughout the process and believes this report is a much better, thorough report that encompasses not only a scientific approach, but plain common sense that is applicable in today's development world. We will continue to be supportive of the process that this Board put forth.

Jim Early, retired engineer from Kitty Hawk, stated this is very well written report and I would like to add my appreciation for the excellent effort. I only take exception with one parameter used in the report and that is the current rate of sea level rise, not the future projections, just the current rate. The value used in the report was taken from the IPCC report and the value is higher than can be justified. The IPCC value is much higher than the measures by NOAA.

Dave Burton stated this report is much better than the 2010 report and pointed out the differences in the two. Mr. Burton was concerned that this report relied too heavily on sources from one end of the scientific opinion spectrum and questioned its credibility.

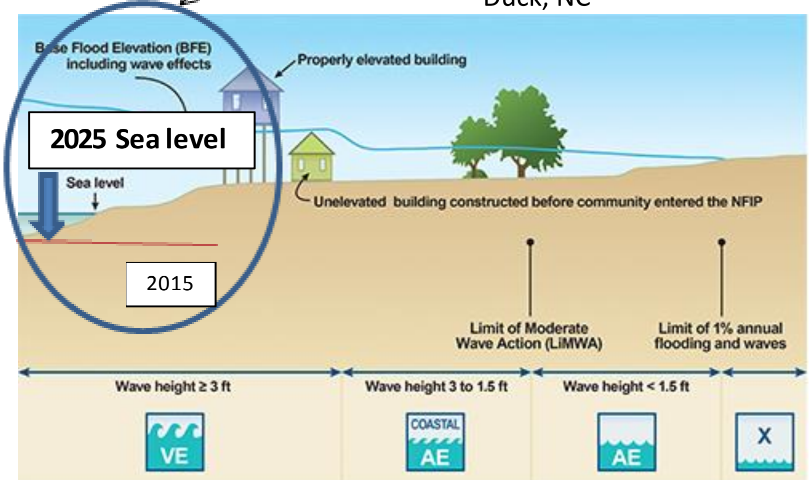
Mattie Lawson, retired engineer from Kill Devil Hills, requested that the CRC not come up with a one-size fits all regulation for the entire state of NC, but please allow the localities to manage this problem.

Wally Overman, Vice-Chairman Dare County Board of Commissioners, agreed that a 30-year plan or assessment of sea level rise was a better option than 100-years. Mr. Overman expressed his support for the position of Chairman Gorham that any decisions regarding regulations should be made at the local level.

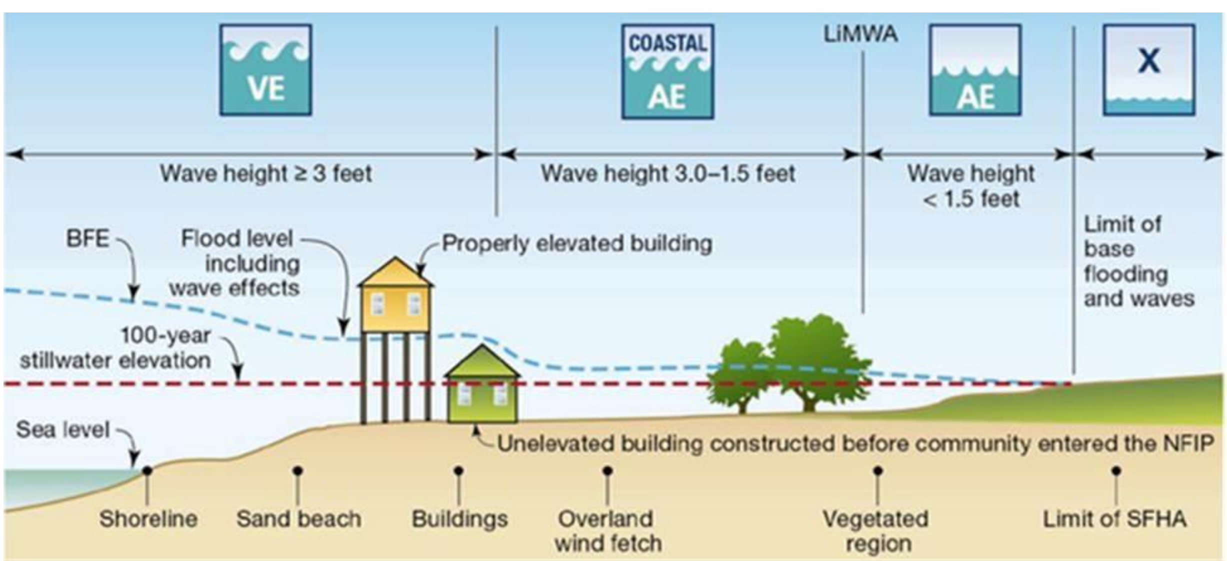
Neil L. Perry, NCDOT Rail Division (via email on 4/26/2015)

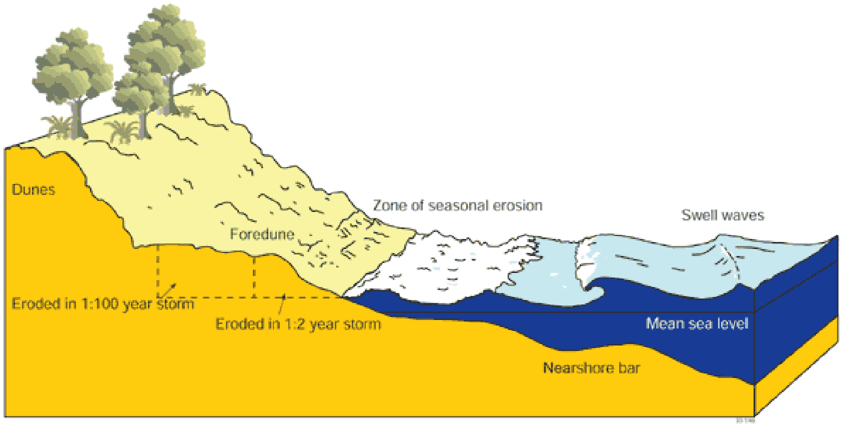
I've read through the updated report and wanted to provide a general comment.
You are **<u>NOT</u>** telling your story in a manner that the general public and general assembly will understand. The most important information that you are trying to get across needs to be disseminated pictorially. See below.
FYI, I'm a former student of Dr. Overton's at NC State. BSCE 1995. I grew up in Virginia Beach and along the northern Outer Banks (Kill Devil Hills, NC). I'm very familiar with this issue and surrounding politics.

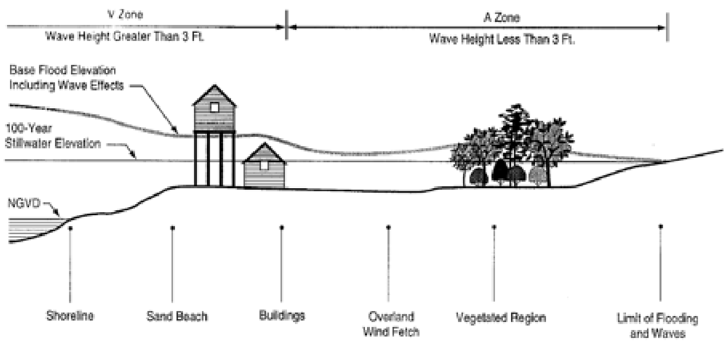
Duck, NC

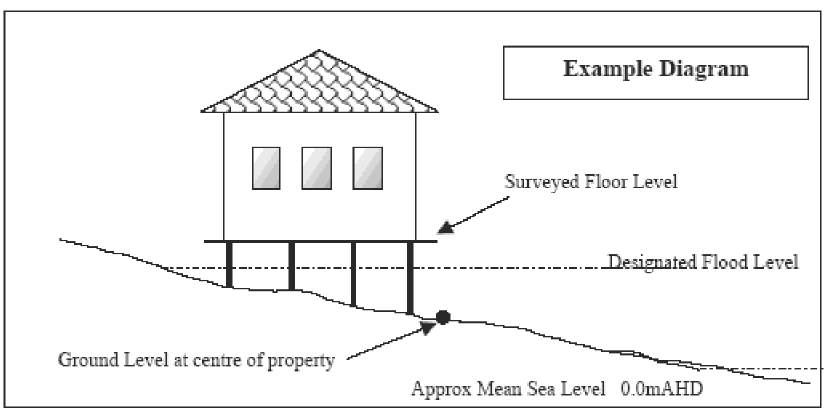


Or use one of the diagrams below or create your own. Point is you HAVE to tell this story pictorially or much of your work will be misunderstood.









Neil L. Perry, PE, PTOE, PTP, LEED BD+C
Rail Planning Manager
NCDOT Rail Division
Planning & Development Branch
1553 Mail Service Center
Raleigh, NC 27699-1553
Direct: 919-707-4711
Main Office: 919-707-4700

Michael OBrian (via email on 4/8/2015)

NC Sea Level Rise Report Is Biased High

Hi,

The sea level rise report released at the end of March is biased high. There is no scenario for steady or declining global sea temperatures which may be likely if we experience a grand minimum in solar activity over the next 30 years. There are scientists predicting a global temperature drop of 1 to 1.5 degrees Celsius over the forecast horizon of the NC Sea Level Rise Study. Currently solar cycle 24 is showing significantly reduced sun spot activity with cycle 25 forecast at grand minimum levels.

By using the UN's climate study as the only likely outcomes for global sea temperatures, the study appears political rather than scientific. It is hard to find a more political organization than the UN.

The Commission should revise its study to include at least one scenario of falling ocean temperatures.

Best regards,

Mike

Mike Hayes (via email on 4/10/2015)

greetings

Subsidence Subsidence

The Atlantic Ocean is expanding from the Mid Atlantic Ridge. The shore lines are being moved away from the MARidge. The shorelines have been eroding the whole time. There are no natural phenomena to add materials to the ever moving shorelines other that river carried materials to replace what is eroded away by normal ocean activity. The ocean has not been rising. The shorelines are eroding. Additionally Ocean level rises at the same rate on every inch of shoreline equally. This has been true for the past 18K years. Every body of water on the globe with depths over 420 feet has an escarpment at 420 feet deep that is a remnant of the end of the last Ice Age which ended 18K years ago. That's every ocean has an old historic beach displayed by a level plateau area at the depth of 420 feet. Yes, a beach, now 420 feet deep in the ocean.

So, ocean rises at different levels at different locations on The NC shoreline. NOT and NEVER. I think the sky is falling. Let's get that fixed first.

Show me where the Ocean is rising anywhere!

Mike Hayes.....NC Outer Banks resident and former Virginia Beach resident of the Pungo Ridge, an older outer banks dune ridge, ranging from the Chesapeake Bay to the Atlantic Ocean in southern NC that is 125K old when the ocean level was 20 feet higher that it is right now. Show me how stupid you are by proving me wrong without using CO2. If you are interested I can show you that less CO2 leaves North America into the Atlantic than comes off the Pacific into North America. Read the previous sentence carefully! Geeze the CO2 disappeares

Self-appointed amateur marine geologist.....Mike Hayes

Mike Hayes (via email on 4/11/2015)

greetings from the Outer Banks, and please enjoy, and good luck

How can I respond in any other way than idiotic, when your science is so idiotic. I tried otherwise but just couldn't get it done. Why are you people getting paid to do this? Are you not glad I had nothing else to do this morning April 11, 2015. I will be referencing my representative to reference this from you! Enjoy the humor.

****

How about calling it what it is: Subsidence by linear erosion. It is impossible for the ocean to NOT rise equally on every inch of shoreline. It is also impossible for the ocean to NOT drop equally on every inch of shoreline. Remember, there is a substantial tide that causes the ocean to rise and fall unequally on every inch of shoreline. Be careful when you measure. Don't create another hockey stick scam. Call it what it is, and stop with the snake oil campaign. Borrow a government laser measuring device (satellite) that is used to measure a submerged submarine wake on the ocean surface when the sub is running in stealth mode 1000 feet deep, and then measure ocean level rise and you will find out that the ocean level might be falling right now! This satellite system is accurate beyond 1/100 of an inch. It might be all the submarines that cause the next epic of ocean rise? No that wont work because the subs are not actually adding water to the ocean.

What might be fun is to take you scientists to the Netherlands. How in this world did the Dutch gather vast amounts of land from the North Sea that in some cases is 22 feet below seal level? What is that all about? Plus, those ingenious people are sequestering the CO2 from their Shell Refinery and pumping this CO2 into the greenhouses in their massive greenhouse industry that grows vegetables for the markets in Europe. You know that CO2 fertilizer, grows great vegetables.

****

The Scientist's Mantra: "Lie so we can get funded"

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"Sea-Level Rise Study Update"

"The Coastal Resources Commission's Science Panel is working to update its 2010 report on sea-level rise in North Carolina, as required by Session Law 2012-202. The CRC's charge to the panel is 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 directed the panel to limit the scope of the study to a 30-year rolling time table, to be updated every five years.

The panel’s initial draft report was completed in December 2014, and forwarded to a technical peer review group for comment.

The draft report and all comments were submitted to the CRC and released for public comment on Mar. 31:”

****

Subsidence Subsidence

The Atlantic Ocean is expanding from the Mid Atlantic Ridge. The shore lines are being moved away from the MARidge. The shorelines have been eroding the whole time. There are no natural phenomena to add materials to the ever moving shorelines other that river carried materials to replace what is eroded away by normal ocean activity. The ocean has not been rising. The shorelines are eroding. Additionally Ocean level rises at the same rate on every inch of shoreline equally. This has been true for the past 18K years. Every body of water on the globe with depths over 420 feet has an escarpment at 420 feet which is a remnant of the end of the last Ice Age which ended 18K years ago. That’s every ocean has an old historic beach displayed by a level plateau area at the depth of 420 feet. Yes, a beach, now 420 feet deep in the ocean.

****

So ocean rise is at different levels at different levels at different locations on The NC shoreline. NOT. I think the sky is falling. Let’s get that fixed first.

Show me where the Ocean is rising!

****

Mike Hayes.....NC Outer Banks resident and former Virginia Beach resident of the Pungo Ridge, an older outer banks dune ridge, ranging from the Chesapeake Bay to the Atlantic Ocean in southern NC that is 125K years old when the ocean level was 20 feet higher that it is now. Show me how stupid you are by proving me wrong without using CO_2. If you are interested I can show you that less CO_2 leaves North America into the Atlantic than comes on to North America off the Pacific Ocean. Read the previous sentence carefully! Wow, that’s bad for your conspiracy theory!!!!!

Self-appointed amateur, marine geologist, climatologist, skeptic, and conspiracy theorist .....Mike Hayes

George Mears (via email on 4/13/2015)

My undergraduate (U of Wisconsin) was in geology and my Masters is in Environmental Engineering Old Dominion University). I've also been a project manager for several coastal engineering projects over the past decade.

I am very skeptical of the agenda driven IPCC reports--and especially the Executive Summary section of each report which has been proven many times over to distort or actually refute the claims and actual conclusions of the actual authors of sections of the full report. The use of a global average SLR metrics is a farce to start with because local conditions dictate coastal conditions which are far more driven by coastal dynamics, urban stormwater hydrology, and coastal sediment consolidation and compression over time which has little to do with SLR.

At the risk of coming off as an alarmist loon, I have personally come to the conclusion that the political left wants to create a Climate Caliphate and to declare climate jihad against anyone smart enough to understand that none of their climate models have proven predictive, not one of their apocalyptic predictions has been proven true, and—given that the average global temperature hasn't risen over the past 18 years while carbon dioxide in the atmosphere has increased by
8 percent, CO2 clearly isn't driving global temperatures! Even with constant NOAA and NASA cherry picking of data points and after hundreds of weather station temperature data "adjustments" in North America and around the world, they still haven't been able to force a trend that can be statistically defended or justified. And they don't have a substitute herring to blame so they play whack-a-mole with global warming, ocean acidification, SLR, biodiversity and species extinction--almost all with cherry picked data, annecdotal evidence, improper statistices (Mann-made Hockey Stick) all with little to no government QA, taking unpaid volunteers years to study and refute.
And most for increased budgets, political influence, and academic one-upsmanship.

Before becoming an engineer I had over 5,800 flight hours that included several years of flying scientific research missions with John Hopkins, Scripps and Woods Hole, Naval Oceanographic Office scientists studying extreme north and south latitude ice reconnaissance, deep ocean eddy current data collection, and worldwide vector magnetic survey all over the globe. I also helped train NOAA aircrews to take over the hurrican penetration missions from the Navy during the late 1970s.

These are becoming desperate times for desperate minions committed to overthrowing capitalist economies and redistributing wealth using any garbage scientific rationale they can come up with for our media to run with without questioning!

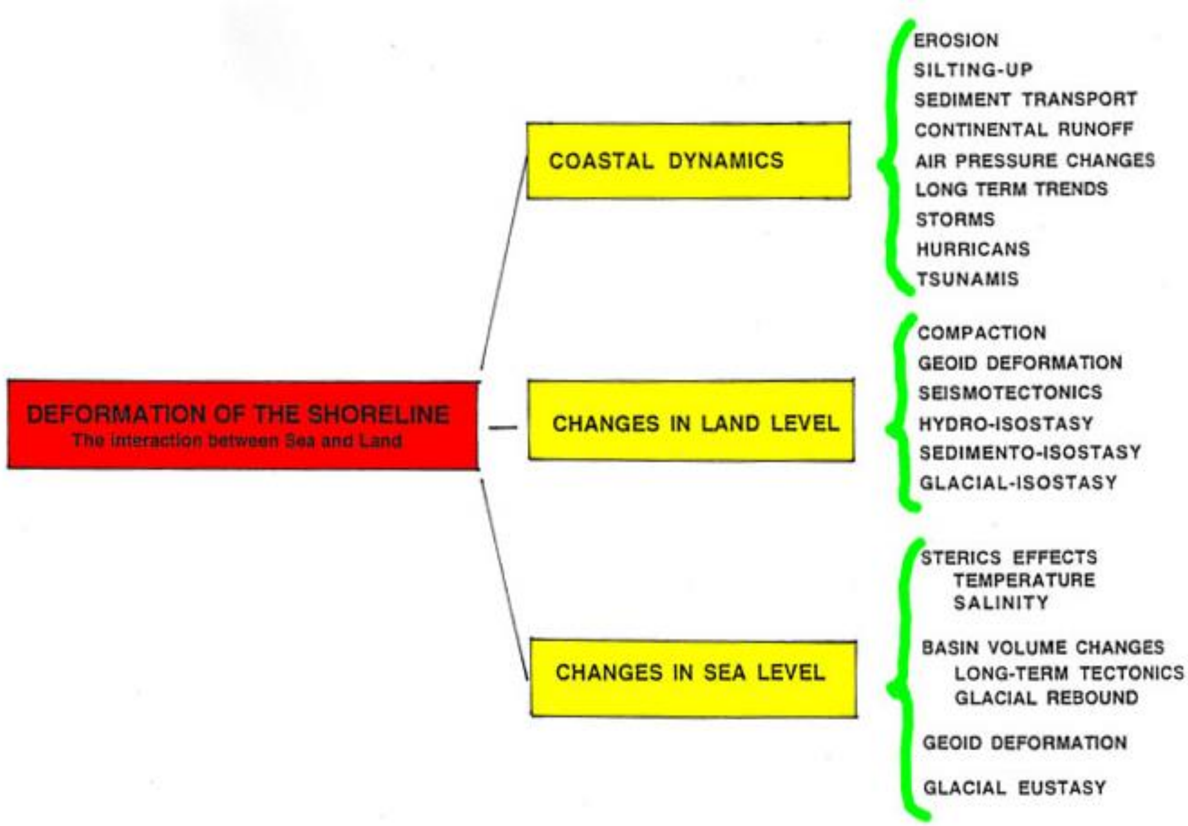
Thank you,

George H. Mears ME, MBA, PMP
Hydrologist/Environmental Engineer
4304 Ainslie Court South
Suffook, VA 23434

(Attachment)

The entire Sea Level Rise mantra is misunderstood by politicians and most in the public, and I dare say, most scientists. Please note the figure below that depicts where Sea Level Rise plays in the overall process of what the environmental left and the media loves to blame on SLR but is much more related to Coastal

Dynamics, urban stormwater hydrology, and coastal sediment consolidation and compression over time. As shown, SLR is limited to steric impacts, eustatic changes in sea level, glacial isostacy-eustacy, and basin geoid deformation and resulting volume change—most of which are literally drowned out by dominant coastal and hydrologic factors that have little relationship to SLR.



Professor Nils-Axel Mörner of Stockholm University was the former President of the INQUA Commission on Neotectonics (1981-1989) and President of the INQUA Commission on Sea Level Changes and Coastal Evolution (1999-2003). In 2000, he launched an international research project on sea level in the Maldives. In 2008, at an international meeting on sea level in Portugal, Professor Mörner was awarded the Golden Chondrite of Merit from the University of the Algarve "for his irreverence and his contribution to our understanding of sea-level change". He has argued for years that global sea levels are not rising significantly or dangerously. In a recent paper (the 547th in his 42-year career) he continued his arguments and a fellow researcher summarized his main points for those outside the oceanographic community below:

- At most, global average sea level is rising at a rate equivalent to 2-3 inches per century. It is probably not rising at all.
- Sea level is measured both by tide gauges and, since 1992, by satellite altimetry. One of the keepers of the satellite record told Professor Mörner that the record had been interfered with to show sea level rising, because the raw data from the satellites showed no increase in global sea level at all.
- The raw data from the TOPEX/POSEIDON sea-level satellites, which operated from 1993-2000, shows a slight uptrend in sea level. However, after exclusion of the distorting effects of the Great El Niño Southern Oscillation of 1997/1998, a naturally-occurring event, the sea-level trend is zero.
- The GRACE gravitational-anomaly satellites are able to measure ocean mass, from which sea-level change can be directly calculated. The GRACE data show that sea level fell slightly from 2002-2007.

- These two distinct satellite systems, using very different measurement methods, produced raw data reaching identical conclusions: sea level is barely rising, if at all.
- Sea level is not rising at all in the Maldives, the Laccadives, Tuvalu, India, Bangladesh, French Guyana, Venice, Cuxhaven, Korsør, Saint Paul Island, Qatar, etc.
- In the Maldives, a group of Australian environmental scientists uprooted a 50-year-old tree by the shoreline, aiming to conceal the fact that its location indicated that sea level had not been rising. This is a further indication of political tampering with scientific evidence about sea level.
- Modeling is not a suitable method of determining global sea-level changes, since a proper evaluation depends upon detailed research in multiple locations with widely-differing characteristics. The true facts are to be found in nature itself.
- Since sea level is not rising, the chief ground of concern at the potential effects of anthropogenic "global warming" – that millions of shore-dwellers the world over may be displaced as the oceans expand – is baseless.
- We are facing a very grave, unethical "sea-level-gate".

How much of the current SLR argument is hype to justify more government regulations and to advance the radical environmentalist agenda? As a hydrogeologist and an environmental engineer, I suspect, most of it. Is flooding increasing? Absolutely! But is this related to sea level rise, or climate change? Unlikely and only at the margins and if there was any cost effective way to alter that in any measurable way, we still wouldn't notice any difference in the nuisance flooding because SLR isn't a major factor in it. The primary cause involves that have been well understood by urban hydrologists for decades. As areas become more urbanized-- more developed—areas increasingly loose surface stormwater retention sites as building activity continues. This turns fields and lowlands into impermeable rooftops and pavement and fewer places to contain stormwater following rains. The result is a vastly reduced Time of Concentration—the time it takes for a raindrop to fall on the outer edge of a watershed and travel to the lowest spot where flooding starts. At this point, cue crickets and glazing over of eyes of media, politicians, and climate zealots since this means thinking—which certainly doesn't support their activist agendas.

Most people recognize the impact of a large business or a parking lot when it comes to increased runoff. Unfortunately, the state of municipal planning and environmental oversight is such that if the developers can divert any increase in runoff away from their building site, many believe the problem has "gone away" when all they have managed to do is push the problem into other low areas within the same watershed. But even singular construction sites can increase the flooding problem as long as local inspectors consider it OK to allow increased runoff to leave the property where the increase is generated. Every time we build larger houses, provide parking for an extra vehicle, or level and pave what was undisturbed land before, we potentially increase storm runoff unless we insist upon Best Management Practices (BMPs)—engineering solutions to capture, use, or retain the increased runoff to prevent it from leaving the property. So, am I arguing for ceasing development as do many of the radical environmentalists? No. But I would argue that they who develop, build, or alter land be responsible for the consequences of their own activity in the external environment. Regulators should hold developers, builders, and even individual property owners to a standard that does not make it permissible to allow increased runoff to exit that property. Allow prudent development but require developers –and even individual property owners--capture and deal with any increase in site runoff due to improvements to the property that they are making.

Too few builders or even municipal planning and building officials seem to understand the impact of developing or expanding impermeable surfaces at the single lot level—business or residential. Federal regulations naturally focus on large areas of developmental impact but this shouldn't mean that the municipalities shouldn't be concerned with individual building sites when dealing with neighborhoods. There is a legal concept that when you do something to your property that impacts mine, you should be held accountable. But that requires me to sue you over something neither of us know much about. I'd suggest that the municipalities exist to protect the liberty and property rights of its citizens. So the municipality is in the best position to insist that each building permit is issued with a land disturbance permit that insists requires the land owner, builder, or developer to be responsible for dealing with any increased runoff generated by building or site modification activities.

More often than not, the best building lots in a community are chosen first and developed early on in the history of the neighborhood. As area populations grow, the best lots disappear and individuals start buying and trying to develop less desirable building lots—and in so doing, making only the improvements that municipality or community building inspectors mandate. These lost are likely to be smaller, lower topographically, and subject to more frequent flooding, overgrown and costlier to develop, or near areas of heavy traffic, business, or industrial activity. So as properties that were formerly low areas that captured and contained stormwater are filled in and converted to building lots, the increase in runoff is often disproportionate to the sizes of the infill lots being developed. The low lands disappear and are replaced with fill, rooftops, and pavement. Areas that used to capture stormwater now shed it into the neighborhoods surrounding them. And this is by far the greatest single contributor to increased area flooding in both urban and suburban areas. Ranking well below development comes local subsidence since most of the Atlantic Coastal Plain consists of 10,000 to 15,000 vertical feet of consolidating sediment. This is a geological reality and as sediment compacts, land sinks. And as municipalities, businesses, and residential homeowners use groundwater pumps to supply their needs, subsidence only increases. So the real problem is reduced Time of Concentration as rain runoff that used to stay within an area, no longer does. Sea level rise and climate change is just a convenient red herring that advances the agenda of the bigger government environmentalists. But if you really want to reduce local flooding, start paying attention to the increase in runoff from properties following construction by insisting on pre-and post-development hydrographs generated by a neutral arbiter. I've suggested for years that where local or regional colleges with hydrology departments and students who need to learn are available, this could be a win-win, with the work funded by the developers but executed by folks who aren't paid for the result the developer is hoping to find. This will only work with the cooperation of reputable professors who are available and willing to supervise their students closely to maintain standards.

Jim Early (via email on 4/28/2015)

Frank Gorham, Chair NCDENR CRC April 29, 2015
Margery Overton, Chair NCDENR CRC Science Panel

The Science Panel report on sea level rise (SLR) is clearly written and is a major improvement over the previous (2010) document. I wish to comment on only one problem, the value used for the current global sea level rise rate.

In the preliminary Panel meetings the Panel seemed committed to using the Church & White (2011) paper for recent past and current global sea level rise data and to using the IPCC document for future sea level acceleration projections. In the later drafts the Panel chose to also use the IPCC document as the source for the current global sea level rise rate.

The single **most important** number in this entire report is the value assumed for the current SLR rate. It is much more important than the small accelerations projected by the two IPCC cases. The Panel inserts the IPCC value of 4.0mm/y into its calculations with no mention or discussion. The Panel only presents and discusses the time integral of the sea level rise rates which hides the actual rates used. The panel takes this value without question or comment from the IPCC report.

This sea level rise rate is higher than global tide gauge values from NOAA or the questionable satellite values as can be seen in figure 1. It is also higher than tidal gauge data from the CW paper. More importantly, this value is incompatible with the tidal gauge data from Wilmington where the land is known to have a low subsidence rate or even may be rising (figure 2).

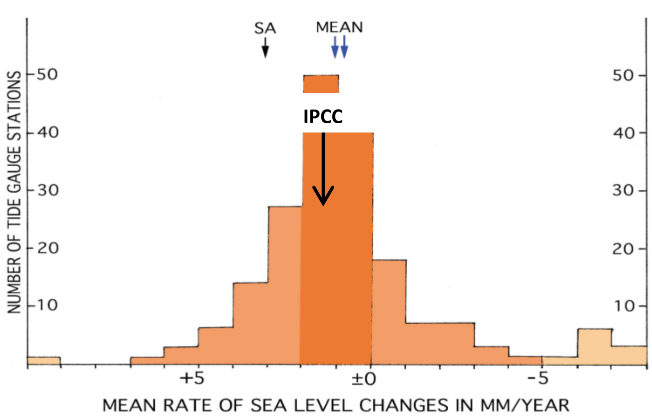


Figure 1. SLR rate distribution of 204 world wild tide gauges used by NOAA
[*Morner,N. 2013,Energy & Environment, 24,509-536.*]

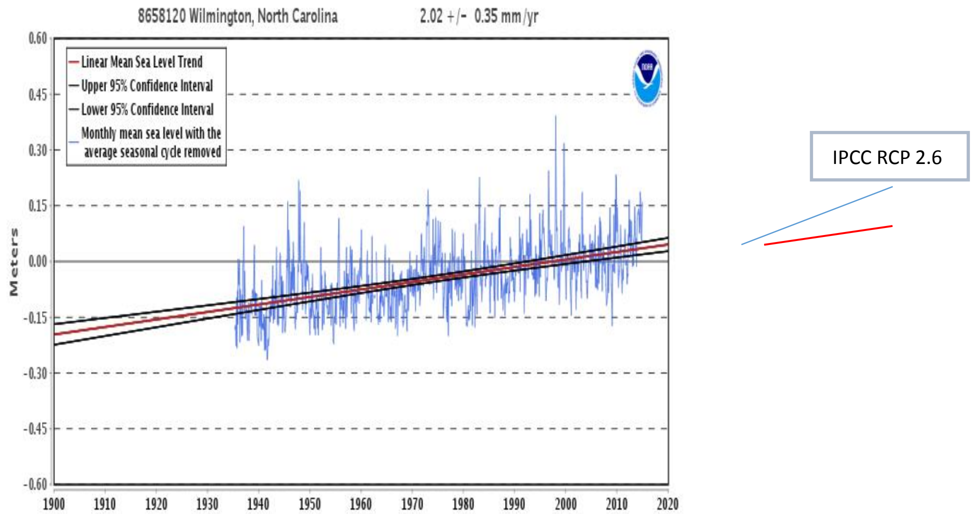


Figure 2. Wilmington tide gauge (NOAA)

As I have stated at previous meetings, you cannot simply ignore any discussion of the current SLR rate which you use. This report will be of little value and no credibility without such a discussion. The best approach would be to simply use the NC tide gauge data as the best measure of the current local sea level rise rates. The IPCC document could then be used to estimate the future increases in the sea level rise rate. This was the procedure that the Panel initially discussed. It would base the estimates of current rates on real local scientific data. Using the value from the IPCC document for a current local measurable rate is simply an appeal to authority rather than science.

James Early
Kitty Hawk, NC
Retired engineer from DOE Lawrence Livermore National Laboratory
(Doctorate in engineering from Stanford University)

Dave Burton (via email on 4/2+/2015)

Comments to the CRC April 29, 2015.

By Dave Burton
www.sealevel.info
www.NC-20.com
http://www.sealevel.info/burtonvita.html

This is one of those glass half-empty or half-full situations. This draft report is much, much better than the 2010 Report. That Report showed no actual tide gauge graphs; this one does. That Report ignored the differences between local rates of sea-level change in different parts of the State; this one analyzes them. That Report made an erroneous central claim that SLR has accelerated in response to global warming; this one does not make that error. That Report relied heavily on a discredited paper by Stefan Rahmstorf; this one does not.

However, I still have concerns.

One is that this draft report does not acknowledge any of the errors in the previous report, not even the mistaken claim that SLR accelerated due to global warming. I think we have a responsibility to do our best to undo the confusion which was caused by that error.

Another concern is the Report's exclusive reliance on sources from one end of the scientific opinion spectrum, primarily global sea level rise predictions from the most recent U.N. Intergovernmental Panel on Climate Change's 5th Assessment Report (AR5).

I was an Expert Reviewer of that IPCC Report, and I'm here to tell you that it's not a firm foundation. Their so-called expert review process was a sham. Their accelerated SLR scenarios are not credible. Even their low emission scenario projects over twice the current global rate of sea-level rise, 5.3" vs 2.2" for 30 years. That's ridiculous.

The next 30 years will probably see only about 70 additional ppmv CO_2, which, because of its logarithmically decreasing effect, will have much less effect than the last 100 ppmv – and that hasn't caused any acceleration in SLR at all. It is absurd for the IPCC to predict that global SLR will double in response to a small forcing, when it didn't increase at all in response to a much larger forcing.

This draft report praises the IPCC and notes the 50,000 comments they received on their Report. But those comments were often ignored, and that praise is misplaced.

To balance the IPCC, I recommended that our Science Panel use the relevant sections of the reports from the Nongovernmental International Panel on Climate Change (NIPCC) and the U.S. Senate's Environment and Public Works Committee's Republican staff reports on climate change, but they did not.

The most important fact that everyone needs to understand about sea-level rise is that it has not accelerated at all in response to human greenhouse gas emissions.

The vast majority of human GHG emissions have been since the 1940s. Since then, we've driven up CO_2

from about 300 ppm to 400 ppm – yet the rate of sea-level rise hasn't increased at all.

This fact is a huge problem for the models that the IPCC relies on. Dr. Steven Koonin was undersecretary for science in the Energy Department during President Obama's first term. After he left that position, he finally felt at liberty to tell the inconvenient truth. He said, *"Even though the human influence on climate was much smaller in the past, the models do not account for the fact that the rate of global sea-level rise 70 years ago was as large as what we observe today."*

And yet, the IPCC still relies on those models. They just can't accept the empirical fact that anthropogenic CO_2 has very little effect on sea-level rise. They still base their sea-level projections on hypothetical extreme acceleration scenarios, which they claim will be caused by CO_2 emissions.

This Report is much better than the last one, but the Science Panel erred by basing so much of their work on the flawed projections of the UN IPCC's 5th Assessment Report, and by not examining more credible sources, like the Nongovernmental International Panel on Climate Change.

# # #

Clyde Hunt, Jr (via email on 6/4/2015)

If I read the results of the recent meeting in Manteo correctly, concerning decisions on how the state should or should not respond to the estimated future sea level rise, please accept my appreciation for your overall involvement **and** the apparent decision to allow more local autonomy on this. And, for your rejection of the estimated/guess of 39” and 55” sea level rise.

We (the Hunt Family) have had four ocean-front nice rental houses at Ocean Isle since the mid ‘60’s. I have been directly involved with several projects beneficial to not only the Ocean Isle property owners but ultimately every citizen of North Carolina. I’ve never hesitated to explain this to my more inland friends and associates here in Greensboro and elsewhere…ie…North Carolina coastal tourism is a huge revenue generator, supporting thousands of local businesses, tens of thousands of jobs, and accounting for millions of tax dollars for NC. Why do tourists from not only NC but dozens of other states and some foreign countries come to our coast? For the **beaches**! For the developed beaches. If we do not retain our developed beaches, no one will come. But obviously, any responsible person recognizes we must **responsibly** develop and maintain our magnificent beaches.

It appears most recognized the 39” (and 55”) sea level rise estimates are apparently way out of line, just as the hope of **no** sea level rise is equally untenable, unrealistic. I guess the bottom line is….(a) We cannot move everything and everybody 50 miles inland based on a projected, estimated, guess that 39” is absolute….(b) So, let’s locally keep a keen eye on what the rise is (or is not) each year or so, and based on several criteria…eg…past history, present 5, 10, 15 year trends, other coastal area trends, etc., make appropriate decisions. Duck has very different “challenges” than our Brunswick county beaches, and therefore very different solutions would apply.

Importantly, let’s not put our heads in the sand, totally ignoring the possibility of sea level rise, **and** let’s not over-react to scare tactics of those with a total anti-development/abandon the coast agenda.

Hope you fellows continue to give this most important topic the attention and consideration it deserves. And that your decisions are based on the very best scientific analysis, and not on emotion. A great deal of North Carolina’s future depends on it.

Jim Early, John Droz and Stan Young (via email from Jim Early on 6/16/2015)

Frank Gorham, Chair NCDENR CRC June 16, 2015

Comments on 2015 NC Sea Level Rise Assessment Report

The Science Panel report on sea level rise (SLR) is clearly written and is an improvement over the previous (2010) document. It does a particularly good job on explaining the differences in SLR within North Carolina.

In this note we wish to comment on only one problem, the value used for the current sea level rise rate. This parameter does not depend on complicated projections of future behavior; rather it depends only on past and current physical measurements of sea level. It is also the most important single parameter in the report.

The Panel chose an admirable goal of only using publicly documented data and literature in this report. There is little literature written specifically on the SLR along the coast of North Carolina, but the detailed tidal gauge data from the five stations along the NC coast are available on the NOAA website [1]. This data can be used directly to determine the recent SLR rate at each location, and the long term average values for each are given on the NOAA site.

An alternative approach, the one chosen by the Panel, is to use the extensive literature on the world wide average SLR rates. Specifically the Panel used the value from the last IPCC report [2]. Currently the tide gauges for the measurement of SLR have an uneven distribution around the world's oceans, and older tide gauges had a much more limited coverage. This data must be manipulated to account for the limited distribution in space and time to calculate the world average rate. This calculation introduces many sources of possible errors.

The resulting world average rate must then be adjusted to account for local conditions at any specific site which introduces more opportunities for errors. The need for this last step can be illustrated by the fact that US tide gauge data shows that the average SLR rate on the US East coast is over three times the value for the US West Coast (excluding Alaska)[3]. The Panel uses the local NC tide gauge measurements to estimate the correction needed for the world sea level rate. This introduces the circular reasoning of using local sea level rise rates measured by tide gauges to correct the world sea level rise rate with the objective of finding the local sea level rise rate.

We believe the CRC should directly use the data from the local tide gauges to determine the current local SLR rate. This procedure introduces much less opportunity for error. We will discuss the two approaches and show that the procedure of going through the world wide average value gives results that are clearly incorrect for the North Carolina sites.

First the procedures used by the panel are discussed. The referenced IPCC result is then shown to have been questioned in the literature. Finally, the Panel's projections of SLR are compared to NC tide gauge data and shown to be clearly inconsistent.

The use of IPCC reports to project future acceleration of SLR rates is not discussed in this comment. However the Appendix lists a number of references provided by John Droz which discuss the subject.

Science Panel procedure and the IPCC SLR rate

The Science Panel chose the Fifth IPCC report [2] as its primary source of documentation on the projected SLR due to future warming from current and potential future increases in greenhouse gases. The IPCC document reports the calculated impact of a range of future emission scenarios in order to capture a range of potential sea level rises. The Panel referenced the IPCC summary, Table A11.7.7, shown below.

Table AII.7.7 | Global mean sea level rise (m) with respect to 1986–2005 at 1 January on the years indicated. Values shown as median and *likely* range; see Section 13.5.1.

Year	SRES A1B	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2007	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]	0.03 [0.02 to 0.04]
2010	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]	0.04 [0.03 to 0.05]
2020	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.10]	0.08 [0.06 to 0.11]
2030	0.12 [0.09 to 0.16]	0.13 [0.09 to 0.16]	0.13 [0.09 to 0.16]	0.12 [0.09 to 0.16]	0.13 [0.10 to 0.17]
2040	0.17 [0.13 to 0.22]	0.17 [0.13 to 0.22]	0.17 [0.13 to 0.22]	0.17 [0.12 to 0.21]	0.19 [0.14 to 0.24]
2050	0.23 [0.17 to 0.30]	0.22 [0.16 to 0.28]	0.23 [0.17 to 0.29]	0.22 [0.16 to 0.28]	0.25 [0.19 to 0.32]
2060	0.30 [0.21 to 0.38]	0.26 [0.18 to 0.35]	0.28 [0.21 to 0.37]	0.27 [0.19 to 0.35]	0.33 [0.24 to 0.42]
2070	0.37 [0.26 to 0.48]	0.31 [0.21 to 0.41]	0.35 [0.25 to 0.45]	0.33 [0.24 to 0.43]	0.42 [0.31 to 0.54]
2080	0.44 [0.31 to 0.58]	0.35 [0.24 to 0.48]	0.41 [0.28 to 0.54]	0.40 [0.28 to 0.53]	0.51 [0.37 to 0.67]
2090	0.52 [0.36 to 0.69]	0.40 [0.26 to 0.54]	0.47 [0.32 to 0.62]	0.47 [0.33 to 0.63]	0.62 [0.45 to 0.81]
2100	0.60 [0.42 to 0.80]	0.44 [0.28 to 0.61]	0.53 [0.36 to 0.71]	0.55 [0.38 to 0.73]	0.74 [0.53 to 0.98]

This table only gives the sea levels at future dates in meters (which the Panel converted to inches). The associated SLR rates are not apparent from this table. The Panel just incorporates the SLR values for the years 2015 to 2045 in their report without ever discussing the underlying SLR rates. It can be seen that the change in SLR by 2050 between the different cases is not significant, only 0.03m (1 inch). Of much greater importance, Table A11.7.7 assumes the initial global average SLR rate in 2010 is 4.0mm/y.

If the Panel had used the figures from the section of the IPCC report where this table originated (Section 13.5.1), then this hidden assumption would have been apparent. This can be seen in the frames below on the right where the black lines represent the total value of the SLR rates. It can be seen that in both cases the rates are assumed to start at 4.0mm/y.

Dave Burton and Jim Early both tried to point out the importance of this hidden assumption to the Panel. Whether from the press of time, inertia, miscommunication or some other reason, the Panel never addressed the problem.

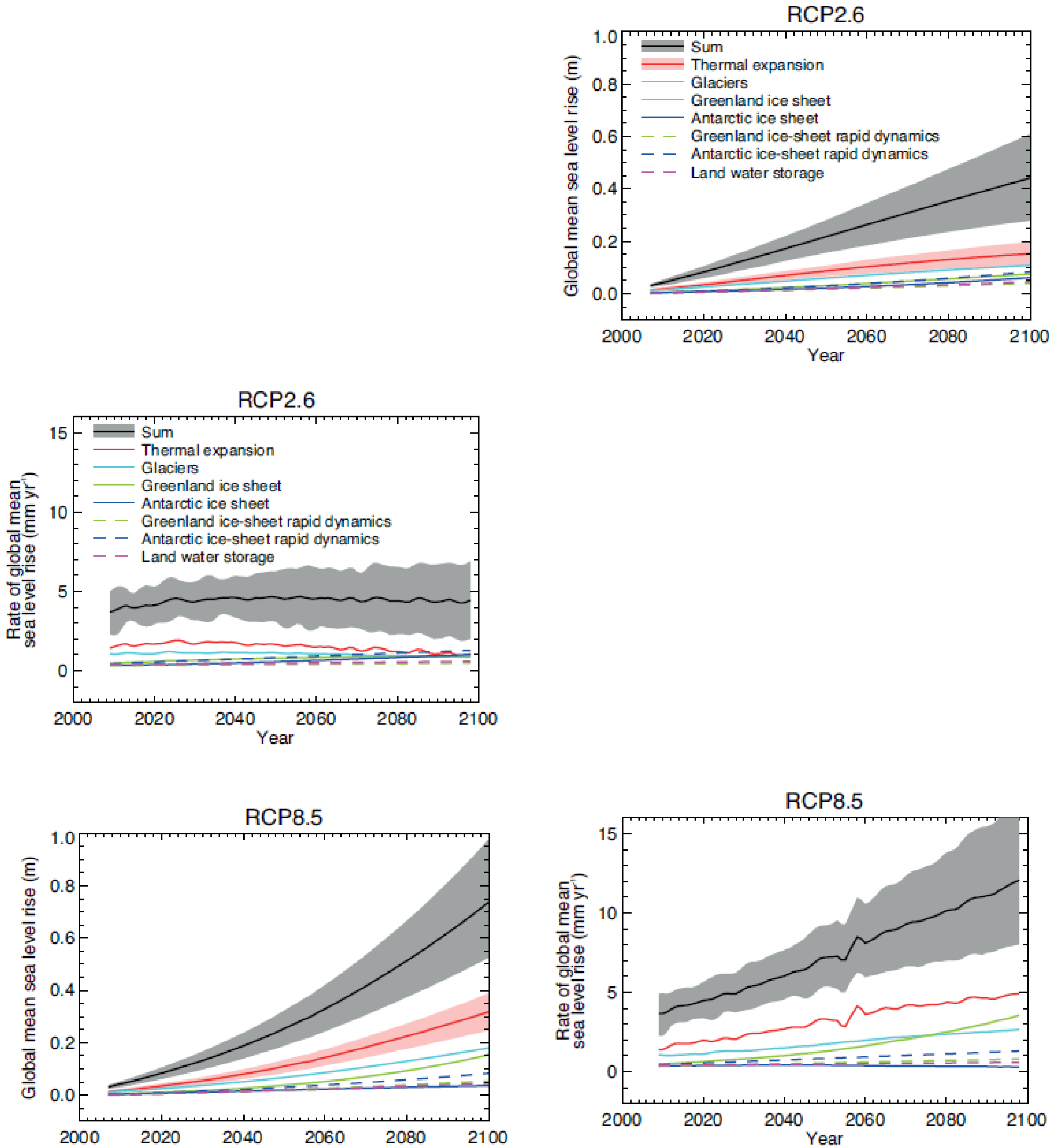


Figure 13.11 | Projections from process-based models of (a) global mean sea level (GMSL) rise relative to 1986–2005 and (b) the rate of GMSL rise and its contributions as a function of time for the four RCP scenarios and scenario SRES A1B. The lines show the median projections. For GMSL rise and the thermal expansion contribution, the *likely* range is shown as a shaded band. The contributions from ice sheets include the contributions from ice-sheet rapid dynamical change, which are also shown separately. The time series for GMSL rise plotted in (a) are tabulated in Annex II (Table AII.7.7), and the time series of GMSL rise and all of its contributions are available in the Supplementary Material. The rates in (b) are calculated as linear trends in overlapping 5-year periods. Only the collapse of the marine-based sectors of the Antarctic ice sheet, if initiated, could cause GMSL to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a metre of sea level rise.

Critique of IPCC current SLR rate

The IPCC report does not provide a detailed explanation of the source of the 4.0mm/y SLR rate. It references the work of Church and White [4] which gives a value of 2.8mm/y based on tide gauges and

3.2mm/y based on satellites. The world-wide average of tide gauge data requires complicated statistics to offset the uneven tide gauge distribution in space and time. The satellite data also requires adjustments for instrument calibrations. Both procedures are thus vulnerable to systematic errors.

Morner [5] shows the statistical distribution of tide gauge data (Figure 1) for SLR rates from a world-wide NOAA database of 204 tide gauges. The wings of the distribution represent locations where the land is either subsiding or rising. Clearly the average or median rate is between 1 to 2 mm/y.

The satellite (sa) value of 3.2mm/y and the IPCC value of 4.0mm/y are outside of any reasonable reading of the data. A review of the British data base of 1000 world-wide tide gauges by Beenstock et.al.[6] indicates an average of 0.4-1.1mm/y. They note that the spatial distribution of the older tide gauge distribution was much narrower with most of those tide gauges located in harbors served by European commerce (ie, Northeastern US, the Baltic, the European Atlantic, and the Mediterranean). Much of this group is located in areas with known land subsidence which strongly biased the older data. The author suggests that the efforts to weigh the world wide average has not adequately accounted for the distribution bias, and this problem has led to the strange discrepancy between data from current tide gauges and the "adjusted" values of the IPCC and satellites. A recent analysis of US coastal gauges [3] points to this same conclusion.

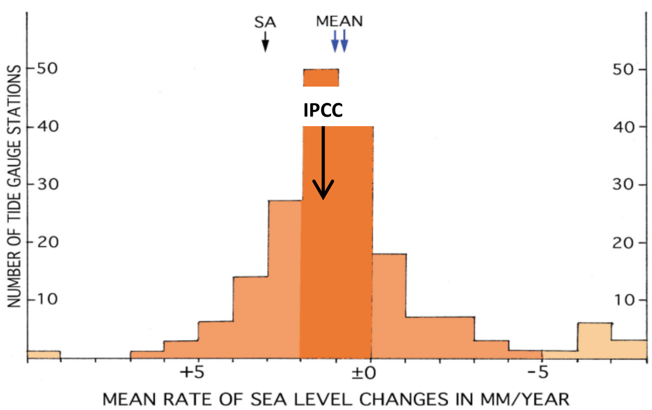
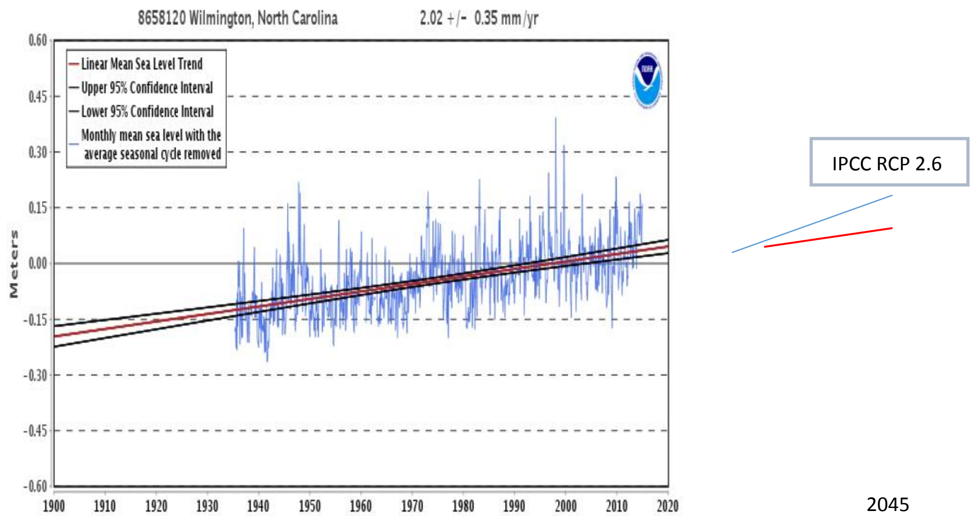


Figure 1. SLR rate distribution of 204 world wild tide gauges used by NOAA
[*Morner,N. 2013,Energy & Environment, 24,509-536*.]

Comparison of IPCC SLR rate and NC tide gauge data

In the IPCC case RCP2.6 the SLR rate is relatively constant, rising to only 4.7mm/y by 2045. This means they are projecting very little change from the current SLR rate within the next 30 years for that scenario. This case can be compared with a simple linear extrapolation of the NC tide gauge.

Figure 2 shows the NOAA tide gauge data with a linear extrapolation for thirty years shown by the red line. By comparison the blue line shows the IPCC RCP 2.6 case with the Panel values for local adjustments added. The IPCC case requires a change in the rate of SLR which is not supported by the data nor discussed in the report.



Wilmington tide gauge (NOAA)

Figure 2. Comparison of thirty year SLR for IPCC case RCP2.6 versus simple linear projections

Recommended Procedure

We would recommend that the CRC use the linear projection of the local NC tide gauges at each location as the best measure of the current local SLR rates. It can be seen from the plots of tide gauge data that the local rates fluctuate over short time scales, but that there is no evidence of any change in the local rates over the time scale of the measurements. The advantage of this procedure is the direct relation to published experimental data. No complex or questionable manipulation of data sets for remote locations would need to be justified. Both simplicity and clarity would recommend this procedure.

To account for future increase in the SLR rates, the IPCC report could be used as a documented estimate. Simply take the thirty year changes in SLR rates estimated in the two IPCC cases, and add these changes to the current rate obtained from the tide gauges. Since case RCP2.6 shows almost no change in SLR rate, we would drop that case and use the linear extrapolation as the low SLR estimate. Case RCP8.5 could then be used as the basis for the increase in SLR rate for the conservative or high SLR case. Table ES1 in the assessment would become:

Table ES1. Two relative sea level rise (RSLR) scenarios by 2045 using published NC tide gauges (NOAA 2014a) and IPCC scenario projection RCP 8.5 (Church et al. 2013). The linear projection of the tide gauge data representing the lowest scenario and the sea level rise acceleration from RCP 8.5 added to the tide gauge projection representing the highest warming scenario.

Station	Tide Gauge Projections RSLR in 30 years (inches)		Tide Gauge + IPCC RCP 8.5 Projections RSLR in 30 years (inches)	
	Mean	Range	Mean	Range
Duck	5.4	4.4-6.4	6.7	5.7-7.9
Oregon Inlet	4.3	2.7-5.9	5.6	4.0-7.3
Beaufort	3.2	2.8-3.6	4.5	2.4-5.2
Wilmington	2.4	2.0-2.8	3.7	3.3-4.4
Southport	2.4	1.9-2.8	3.7	3.3-4.4

References:

1. NOAA Mean Sea Level Trends, http://tidesandcurrents.noaa.gov/sltrends/sltrends_states.htm?gid=1237
2. IPCC Fifth Assessment Report (AR5), Climate Change 2013-The Physical Science Basis,Chapter 13 http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter13_FINAL.pdf
3. Parker, A. and C. Ollier, *Discussion of a Modelling Study of Coastal Inundation Induced by Storm Surge, Sea-level Rise, and Subsidence in the Gulf of Mexico: The US Average Tide Gauge is not Accelerating Consistently with the Worldwide Average,* Physical Science International Journal 7(1): XX-XX, 2015, Article no.PSIJ.2015.057, ISSN: 2348-0130
4. 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.
5. Morner,N. 2013,Energy & Environment, 24,509-536.
6. Beenstock, Michael, Daniel Felsenstein, Eyal Frank, and Yaniv Reingewertz. "Tide gauge location and measurement of global sea level rise." *Environmental and Ecological Statistics* (2014): 1-28.

James Early, Kitty Hawk, NC; retired engineer from DOE Lawrence Livermore National Laboratory, .
Doctorate in engineering from Stanford University
S. Stanley Young, Doctorate in Statistics and Genetics from NC State University
Fellow of the American Statistical Association and the AAAS
John Droz, jr. Morehead City, NC Physicist

Appendix

The intention of this Commentary is to achieve two objectives:

a) a timely response to the NC 2015 SLR Report that is technically significant & accurate, *as well as*

b) a response to the NC SLR Report that is understandable by the public, and our NC legislators.

To simultaneously achieve both goals, is a substantial challenge. The *Appendix* was setup to separate out some of the more technical parts of this complex subject — which the casual reader can just peruse, and still hopefully get the point. [BTW: here is a good layman's overview of SLR measurements.]

The key issue with this Report is the authors' adulation with the IPCC (Intergovernmental Panel on Climate Change). Yes, on the surface the IPCC seems like a credible, objective source — *but is it really?*

Let's start with this **insightful synopsis** that's a good overview of IPCC issues. Here's another. As mentioned in those analyses, there is a significant and fundamental problem with the IPCC that needs to be clearly understood:

> Many people believe that the IPCC objectively and scientifically looked at the whole climate situation — and then concluded that human factors were dominant. Subsequent to that presumed scientific assessment, the IPCC focused on the human related climate change elements.

However, that is **not the case**. Read what their charter said:

> "The role of the IPCC is to assess on a comprehensive, objective, open and trans-parent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk **of human-induced climate change**, its potential impacts and options for adaptation and mitigation. The IPCC does not carry out research, nor does it monitor climate related data **or other relevant parameters**."

I've put the key parts in red. What this says is that the IPCC, by *statute*, is forced to **ONLY** consider human related climate changes. No other climate related changes — *no matter how important* — are seriously analyzed.
Science is a **Process** that involves a *comprehensive*, *objective*, *transparent* and *empirical* analysis of a technical issue.

Understanding the IPCC's directive makes it clear why their reports focus on human related climate change: *not that it's necessarily so important, but rather that this is what their charter had mandated them to do*. So, no matter how many scientists work with the IPCC, or how much "peer-review" there is, or how polished their methodology seems, the IPCC's charter **is fundamentally contrary to how real Science works!**

On January 2nd, 2015, a request was sent to several SLR experts — asking that they review the Version 4 draft of the CRC advisory Panel SLR Report. Below is a brief summary of some of the more applicable studies received to date, in response:

1 - There was a well-known Australian Report ("South Coast Regional Sea Level Rise Policy and Planning Framework": summary here) that basically regurgitated the IPCC conclusions. That is of interest, as this is essentially the same position taken by the NC CRC's technical advisory Panel. There were two detailed critiques of the Australian Report, and arguments against the IPCC very much apply to the NC situation:

- **a -** NIPCC Commentary (authored by 11 scientists). There is **considerable** information here about the veracity of the IPCC and satellite SLR data.
- **b -** Dr. John Happs Commentary (sent by the author)

2 - US Congressional testimony (2/26/14) by Dr. Patrick Michaels and Dr. Paul Knappenberger. They have a section in that worthwhile document that deals with SLR, and the IPCC's models. Their point appears to be: if the IPCC can't get the temperatures right, how can they accurately forecast SLR?

3 - US Congressional testimony (2/26/14) by Dr. Randy Randol. He pointedly objects to the IPCC scenarios — noting that none of them have been calibrated. He has a particularly worthwhile section ("VI") on SLR.

4 - US Congressional testimony (5/29/14) by Dr. Daniel Botkin. His very reasoned discussion is about the accuracy of IPCC models, which is a key matter here.
5 - State of the Climate Debate (9/16/14) by Dr. Judith Curry. She likewise discusses the IPCC process and the accuracy of its assumptions.

6 - Understanding The IPCC AR5 Climate Assessment (10/13) by Dr. Richard Lindzen. He writes that "the IPCC report ... is a political document, and as George Orwell noted, 'is designed to make lies sound truthful.'"

7 - The IPCC AR5 Report: Facts -vs- Fictions (10/13) by Dr. Don Easterbrook, concludes that: "the IPCC report must be considered the grossest misrepresentation of data ever published." See also this critique.

8 - Sea Level Changes in the 19, 20th and 21st Centuries (10/14) by Dr. Nils-Axel Mörner. He cites considerable empirical records, concluding that: "This data set is in deep conflict with the high rates proposed by the IPCC."

9 - German Review: Sea Level Rise Way Below Projections – No Hard Basis For Claims Of Accelerating Rise (1/23/14) by Dr. Sebastian Lüning. This very detailed analysis concludes that the IPCC projections are "unscientific."

10-IPCC AR5: Unprecedented Uncertainty (10/13) by Dr. Euan Mearns. He concludes that "The IPCC has become confused… The consensus is broken."

11-A strong critique (7/16/14) by Larry Hamlin concludes: "IPCC AR5 claims of increasing rates of sea level rise from 1971 to 2010 are unsupported." That, in turn, undermines the veracity of their proposed scenarios.

12-Multi-scale dynamical analysis (MSDA) of sea level records versus PDO, AMO, and NAO indexes (5/14) by Dr. Nicola Scafetta. He concludes that SLR predictions (like IPCC's) are inaccurate as their basic methodology is flawed.

13-Ethics and Climate Change Policy (12/15/14) by Dr. Peter Lee. Although a bit more general, he analyzes the IPCC and its methodology. There is a subsequent discussion of this insightful paper on Dr. Curry's site.

14-Regional Climate Downscaling: What's the Point? (1/31/12) by Dr. Roger Pielke. This well-researched paper discusses the differences and limitations between short term weather predictions, and long term climate predictions.

15-Twentieth-Century Global-Mean Sea Level Rise (6/13) by Gregory, et al. "Semi-empirical methods for projecting GMSLR depend on the existence of a relationship between global climate change and the rate of GMSLR, but the implication of the authors' closure of the budget is that such a relationship is weak or absent during the twentieth century."

16-Secular and Current Sea Level Rise (2014) by Dr. Klaus-Eckart Puls is mostly about how satellite readings have diverged from tidal gauges. However, he strongly criticizes the IPCC saying: "IPCC forecasts do not have much to do with objective science any more."

17-Evidence for Long-term Memory in Sea Level (8/5/14) by Dangendorf, et al observes that "natural variations could be playing a large role in regional and global sea level rise than previously thought."

18-Stop Climate Fear Mongering (12/23/14) by Dr. William Gray. His conclusion about the IPCC scenarios: "The science behind these CO_2 induced warming projections is very badly flawed and needs to be exposed."

19-Video Link to Sea-Level Rise Reality by Dr. Tom Wysmuller. He wrote me: "the NC SLR report treats the Glacial Isostatic Adjustment rather poorly (as does the University of Colorado and the IPCC)." [Ref page 7 of the Report.]

20-Statistical analysis of global surface air temperature and sea level using cointegration methods (2012) by Dr. Torben Schmith, et. al. They conclude that "the number of years of data needed to build statistical models that have the relationship expected from physics, exceeds what is currently available by a factor of almost ten."

Robert Kopp (on behalf of Kopp, Ben Horton, Andrew Kemp, and Claudia Tebaldi, via email on 6/23/2015)

Dear Mr. Miller,

On behalf of myself and my collaborators Ben Horton, Andrew Kemp and Claudia Tebaldi, I'm writing to comment upon the March 31, 2015, draft of "North Carolina Sea-Level Rise Assessment Report: 2015 Update to the 2010 Report and 2012 Addendum." Please find attached a PDF with detailed comments, along with a preprint copy of a background report currently in press at Climatic Change. We hope these comments are helpful, and we would be happy to be of further assistance as you revise the draft.

Sincerely,

Bob Kopp
--
Robert E. Kopp, Ph.D.
Associate Professor, Department of Earth & Planetary Sciences
Associate Director, Rutgers Energy Institute
Rutgers University

June 23, 2015

Mr. Tancred Miller
Division of Coastal Management
North Carolina Department of Environment and Natural Resources 1601
Mail Service Center, Raleigh, NC 27699-1601
tancred.miller@ncdenr.gov

Comments re: March 31, 2015, Draft of "North Carolina Sea-Level Rise Assessment Report: 2015 Update to the 2010 Report and 2012 Addendum"

Dear Mr. Miller,

As researchers working on the risks posed by sea-level rise and climate change to coastal communities, infrastructures, and ecosystems, we appreciate the opportunity to comment upon the March 31, 2015, draft of the 2015 update to the 2010 North Carolina Sea-Level Rise Assessment Report and 2012 Addendum.

As background, we attach our paper "Past and future sea-level rise along the coast of North Carolina, USA," which is currently in press at *Climatic Change* (Kopp et al., 2015)[1]. A version of this paper is publicly available from arXiv at http://arxiv.org/abs/1410.8369.

The current draft of "North Carolina Sea-Level Rise Assessment Report: 2015 Update to the 2010 Report and 2012 Addendum" makes a fundamental error in interpreting the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

Nowhere does the IPCC estimate sea-level change beyond what it calls the 'likely' range (67% probability range; i.e., the 17th–83rd percentiles). The current report mistakenly describes these as "*5-95% uncertainty ranges*" (p. 18) and then uses these ranges as the basis for constructing its uncertainty estimates for regional sea-level rise. (Note that these mistakenly construed 90% confidence intervals subsequently turn into 95% confidence intervals on page 19.)

Consistent with the IPCC estimates upon which they are based, the ranges of the current projections should be viewed as bracketing the central 67% of the probability distribution. As such, there is a 17% probability that sea-level rise will exceed the 'high' projections.

The current draft includes "no quantification of oceanographic effects … in the sea level projections."

This is not a tenable strategy, given the observed history of dynamic sea level off of North Carolina over the last three decades. It is also not a tenable strategy when trying to quantify uncertainty in projections of future sea-level change. Kopp et al. (2014)[2] and Kopp et al. (2015) estimate that oceanographic factors are responsible for about 80% of the variance in sea-level rise projections for Wilmington in the 2040s.

As discussed in the background paper, ocean dynamics (likely associated with either a long-term shift or multidecadal variability in the Gulf Stream) caused a sea-level deceleration off parts of North Carolina

[1] R. E. Kopp, B. P. Horton, A. C. Kemp and C. Tebaldi (2015). Past and future sea-level rise along the coast of North Carolina, United States. *Climatic Change*, arXiv:1410.8369, doi:10.1007/s10584-015-1451-x.
[2] R. E. Kopp, R. M. Horton, C. M. Little, J. X. Mitrovica, M. Oppenheimer, D. J. Rasmussen, B. H. Strauss, and C. Tebaldi (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide gauge sites. *Earth's Future* 2: 287–306, doi:10.1002/2014EF000239.

over the last ~30 years. Relative sea-level rise in Wilmington from 1980-2010 was 0.7 ± 0.9 mm/y, compared to a 20th century average of 2.1 ± 0.5 mm/y. When projecting future sea-level rise for Wilmington (and other locations in North Carolina), one of two assumptions must be made. (1) The sea-level rise that was suppressed over 1980-2010 will not be recovered. This is the implicit assumption made in the report by using IPCC projections for 2015 as a baseline. (2) Alternatively, the suppressed sea-level rise represents natural variability that will be recovered, in which case projected sea-level rise should be measured from an earlier baseline.

Bound up in this issue is the report's use of 2015 as a baseline. Sea-level trends generally do not refer to year-to-year variability, which can be quite significant. At Wilmington for example, the difference between annual mean sea level and 20-year average sea level has a standard deviation of ~8 cm (~3 inches). Therefore, in an average 20-year interval, one year will experience an annual average sea level 5 inches above the 20-year mean, and another will experience an annual average sea level 5 inches below the 20-year mean. For this reason, it is commonplace to use a multi-decadal average as the baseline for sea-level projections. The IPCC uses 1986-2005 as its baseline; Kopp et al. (2014) take 19-year running averages of dynamic sea level, so their baseline is effectively 1991-2009.

In light of these concerns, the purported precision of the draft report should be viewed skeptically.

The practical need for localized sea-level rise estimates that cover more of the range of possible futures led Kopp et al. (2014) to develop a framework for generating self-consistent, probabilistic projections of localized sea-level rise.

Below, we present percentiles of the Kopp et al. (2014, 2015) sea-level rise projections for Wilmington and Duck from 2015 (i.e., the 2006-2024 average) to 2045 (the 2036-2054 average) under two different assumptions. The first set of assumptions (labeled 'a') follow the practices used in the current draft report, where 2015 is used as a baseline and the suppressed sea-level rise caused by ocean dynamic changes during the last ~30 years is not be recovered. In the second set of assumptions (labeled 'b') we assume that the suppressed sea-level rise is recovered over the next ~30 years. This difference in interpretation results in a ~2-4 inch difference between projections.

We highlight the 17th-83rd percentile projections, as these should be most comparable to the mistakenly construed '95% confidence intervals' in the draft report. For Wilmington, under RCP 8.5 and assumption a, we find a 67% probability interval of 5.9-10.2 inches, which compares to 4.3-9.3 inches in the draft report. For Duck under RCP 8.5 and assumption a, we find a 67% probability interval of 7.9-12.6 inches, which compares to 5.5-10.6 inches in the draft report. These differences of less than 2.5 inches arise both from the inclusion of ocean dynamic effects and from modestly higher global projections that arise in the self-consistent probabilistic framework employed by Kopp et al. (2014). As noted previously, a different assumption about the nature of dynamic sea-level variability over the last ~30 years (assumption b) would amplify these projections by 2-4 inches. Neither assumption is necessarily correct; rather, these should be taken as guides to one source of uncertainty that arise in projecting sea level, and should be judged appropriately in risk analysis.

More generally, we note that the 97.5th percentile (the upper bound of the central 95% probability interval), is ~2.3-3.5 inches higher at Wilmington than the 83rd percentile. Similarly, the 2.5th percentile (the lower bound of the central 95% probability interval) is ~2.0-3.2 inches lower at Wilmington than the 17th percentile. This indicates the extent to which the high and low estimates in the draft report must be extended if the goal is to offer a 95% probability interval. We also note that a 95% probability interval may not be the only relevant probability window for sea-level rise projections. The 1% average annual probability flood level, for example, is often used to define the flood plain, which suggests the 99th

percentile projection merits some attention. Under RCP 8.5, this reaches 14-19 inches at Wilmington and 17-22 inches at Duck.

By construction of the Kopp et al. (2014) framework, the estimates of the 99.9th percentile under RCP 8.5 align with other estimates of the maximum physically possible sea-level rise and may also be of interest. Over 2015-2045, this maximum possible level is 24 inches at Wilmington and 26 inches at Duck.

Based on the concerns described above, we urge that the draft report be revised to (1) give appropriate attention to the role of ocean dynamics, (2) correctly describe the probability intervals it is presenting, and (3) span a broader range of probability intervals than the 67% interval used, so as to better inform risk analysis.

Thank you for your consideration of these suggestions. We would be happy to be of further assistance as you revise the draft.

Sincerely, Robert

Kopp
Associate Professor, Department of Earth & Planetary Sciences
Associate Director, Rutgers Energy Institute Rutgers
University

Benjamin P. Horton
Professor, Department of Marine & Coastal Sciences Rutgers
University

Andrew C. Kemp
Assistant Professor, Department of Earth & Ocean Sciences
Tufts University

Claudia Tebaldi
Project Scientist III, Climate and Global Dynamics Laboratory National
Center for Atmospheric Research

Affiliations are provided for identification purposes only. The opinions expressed herein are solely those of the authors, and not necessarily of our respective institutions.

Sea-Level Projections for Wilmington, NC and Duck, NC

after Kopp et al. (2014, 2015)

Wilmington (inches of sea-level rise, 2015-2045)

	Percentile										
	1%	**2.5%**	**5%**	**16.7%**	**50%**	**83.3%**	**95%**	**97.5%**	**99%**	**99.5%**	**99.9%**
RCP 8.5a	3.1	3.9	4.7	5.9	7.9	10.2	11.8	12.6	13.8	15.4	20.1
RCP 8.5b	3.5	4.7	5.9	7.9	11.0	14.2	16.5	17.7	19.3	20.1	24.4
RCP 2.6a	2.4	3.1	3.5	5.1	7.1	9.1	10.6	11.4	12.6	13.8	18.5
RCP 2.6b	3.1	4.3	5.1	7.1	9.8	12.6	15.0	16.1	17.7	18.9	22.8

Duck (inches of sea-level rise, 2015-2045)

	Percentile										
	1%	**2.5%**	**5%**	**16.7%**	**50%**	**83.3%**	**95%**	**97.5%**	**99%**	**99.5%**	**99.9%**
RCP 8.5a	4.7	5.5	6.3	7.9	10.2	12.6	14.2	15.4	16.5	17.7	22.8
RCP 8.5b	3.9	5.5	6.7	9.1	12.6	15.7	18.5	20.1	21.7	22.8	26.4
RCP 2.6a	3.9	4.7	5.1	6.7	9.1	11.0	13.0	13.8	15.4	16.5	20.9
RCP 2.6b	3.5	4.7	5.9	7.9	11.4	14.6	17.3	18.5	20.1	21.7	24.8

RCP 8.5: High emissions pathway, consistent with continued fossil-fuel intensive economic growth
RCP 2.6: Low emissions pathway, consistent with a rapid transition away from fossil fuels **Assumption a:** Sea-level rise suppressed by ocean dynamics over last two decades is not recovered **Assumption b:** Sea-level rise suppressed by ocean dynamics over last two decades is recovered

Pre-print
Published as: *Climatic Change*, doi:10.1007/s10584-015-1451-x

Past and future sea-level rise along the coast of North Carolina, USA

Robert E. Kopp, Benjamin P. Horton, Andrew C. Kemp and Claudia Tebaldi

Received: 31 October 2014. Accepted: 8 June 2015.
The final publication is available at http://dx.doi.org/10.1007/s10584-015-1451-x

Abstract We evaluate relative sea level (RSL) trajectories for North Carolina, USA, in the context of tide-gauge measurements and geological sea-level reconstructions spanning the last ~11,000 years. RSL rise was fastest (~7 mm/yr) during the early Holocene and slowed over time with the end of the deglaciation. During the pre-Industrial Common Era (i.e., 0–1800 CE), RSL rise (~0.7 to 1.1 mm/yr) was driven primarily by glacio-isostatic adjustment, though dampened by tectonic uplift along the Cape Fear Arch. Ocean/atmosphere dynamics caused centennial variability of up to ~0.6 mm/yr around the long-term rate. It is extremely likely (probability $P = 0.95$) that 20th century RSL rise at Sand Point, NC, (2.8 ± 0.5 mm/yr) was faster than during any other century in at least 2,900 years. Projections based on a fusion of process models, statistical models, expert elicitation, and expert assessment indicate that RSL at Wilmington, NC, is very likely ($P = 0.90$) to rise by 42–132 cm between 2000 and 2100 under the high-emissions RCP 8.5 pathway. Under all emission pathways, 21st century RSL rise is very likely ($P > 0.90$) to be faster than during the 20th century. Due to RSL rise, under RCP 8.5, the current '1-in-100 year' flood is expected at Wilmington in ~30 of the 50 years between 2050-2100.

1 Introduction

Sea-level rise threatens coastal populations, economic activity, static infrastructure, and ecosystems by increasing the frequency and magnitude of flooding in low-lying areas. For example, Wilmington, North Carolina (NC), USA, experienced nuisance flooding ~2.5 days/yr on average between 1938 and 1970, compared to 28 days/yr between 1991 and 2013 (Ezer and Atkinson, 2014). However, the likely magnitude of 21st century sea-level rise – both globally and regionally – is uncertain. Global mean sea-level (GMSL) trends are driven primarily by ocean heat uptake and land ice mass loss. Other processes, such as ocean dynamics, the static-equilibrium 'fingerprint' effects of land ice loss on the height of Earth's geoid and surface, tectonics, and glacio-isostatic adjustment (GIA), are spatially variable and cause sea-level rise to vary in rate and magnitude between regions (Milne et al, 2009; Stammer et al, 2013). Sound risk management necessitates that decision-makers tasked with creating resilient coastal ecosystems, communities, and economies are informed

R. E. Kopp
Department of Earth & Planetary Sciences, Rutgers Energy Institute, and Institute of Earth, Ocean, & Atmospheric Sciences, Rutgers University, New Brunswick, NJ, USA. E-mail: robert.kopp@rutgers.edu

B. P. Horton
Sea Level Research, Department of Marine & Coastal Sciences and Institute of Earth, Ocean, & Atmospheric Sciences, Rutgers University, New Brunswick, NJ, USA and Earth Observatory of Singapore and Asian School of the Environment, Nanyang Technological University, Singapore

A. C. Kemp
Department of Earth & Ocean Sciences, Tufts University, Medford, MA, USA

C. Tebaldi
National Center for Atmospheric Research, Boulder, CO, USA

by reliable projections of the risks of regional relative sea-level (RSL) change (not just GMSL change) on policy-relevant (decadal) timescales (Poulter et al, 2009).

The North Carolina Coastal Resources Commission (CRC)'s Science Panel on Coastal Hazards (2010) recommended the use of 1 m of projected sea-level rise between 2000 and 2100 for statewide policy and planning purposes in North Carolina. Since the CRC's 2010 assessment, several advances have been made in the study of global and regional sea-level change. These include new reconstructions of sea level in the U.S. generally and North Carolina in particular during the Holocene (the last ~11.7 thousand years) (Engelhart and Horton, 2012; van de Plassche et al, 2014) and the Common Era (the last two millennia) (Kemp et al, 2011, 2013, 2014), estimates of 20th century GMSL change (Church and White, 2011; Ray and Douglas, 2011; Hay et al, 2015), localized projections of future sea-level change (Kopp et al, 2014), and state-level assessments of the cost of sea-level rise (Houser et al, 2015).

Political opposition led to North Carolina House Bill 819/Session Law 2012-202, which blocked the use of the 1 m projection for regulatory purposes and charged the Science Panel on Coastal Hazards to deliver an updated assessment in 2015 that considered *"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"* (North Carolina General Assembly, 2012). Here, we assess the likelihood of these trajectories with respect to past and future sea-level changes in North Carolina.

2 Mechanisms for global, regional, and local relative sea-level changes

Relative sea level (RSL) is the difference in elevation between the solid Earth surface and the sea surface at a specific location and point in time. Commonly, it is time-averaged to minimize the influence of tides and is compared to the present as the reference period (Shennan et al, 2012). RSL averaged over all ocean basins yields an estimate of GMSL.

GMSL rise is driven primarily by (1) increases in ocean mass due to melting of land-based glaciers (e.g., Marzeion et al, 2012) and ice sheets (e.g., Shepherd et al, 2012) and (2) expansion of ocean water as it warms (e.g., Gregory, 2010). Changes in land water storage due to dam construction and groundwater withdrawal also contributed to 20th century GMSL change (e.g., Konikow, 2011). RSL differs from GMSL because of (1) factors causing vertical land motion, such as tectonics, sediment compaction, and groundwater withdrawal; (2) factors affecting both the height of the solid Earth and the height of Earth's geoid, such as long-term GIA and the more immediate 'sea-level fingerprint' static-equilibrium response of the geoid and the solid Earth to redistribution of mass between land-based ice and the ocean; and (3) oceanographic and atmospheric factors affecting sea-surface height relative to the geoid, such as changes in ocean-atmospheric dynamics and the distribution of heat and salinity within the ocean (e.g., Kopp et al, 2014, 2015)

Along the U.S. Atlantic coast, the principal mechanism for regional departures from GMSL during the Holocene is GIA, which is the ongoing, multi-millennial response of Earth's shape and geoid to large-scale changes in surface mass load (e.g., Clark et al, 1978) (Figure 1e). Growth and thickening of the Laurentide ice sheet during the last glaciation caused subsidence of land beneath the ice mass (Clark et al, 2009). A compensating outward flow in the mantle created a peripheral bulge around the ice margin in the U.S. mid-Atlantic region. In addition to uplifting the solid Earth in the U.S. mid-Atlantic region, these flows also increased the regional height of the geoid and reduced the global volume of the ocean basin. These latter two factors led to a rising sea-surface height in the U.S. mid-Atlantic region and thus a total RSL fall less than the regional uplift (Farrell and Clark, 1976). As the Laurentide ice sheet shrunk, mantle flow back toward the center of the diminishing ice sheet caused subsidence and progressive inward migration of the peripheral forebulge. One commonly used physical model of GIA (ICE-5G-VM2-90) yields contributions to 20th century sea-level rise of ~1.3 mm/yr at New York City and ~0.5 mm/yr at Wilmington, NC (Peltier, 2004), but exact values depend upon assumptions regarding ice-sheet history and mantle viscosity.

Along much of the U.S. Atlantic coast, the tectonic contribution to RSL change is assumed to be negligible over timescales of centuries to millennia (e.g., Rowley et al, 2013), but parts of the North Carolina coastal plain are underlain by the Cape Fear Arch (Sheridan, 1976) (Figure 1b). Geologic and geomorphic data suggest that uplift of the crest of the Cape Fear Arch began during the Pliocene (Wheeler, 2006) and is ongoing (Brown, 1978). Late Holocene rates of uplift (RSL fall) have been estimated at ~0.2 ± 0.2 mm/yr (e.g., Marple and Talwani, 2004; van de Plassche et al, 2014).

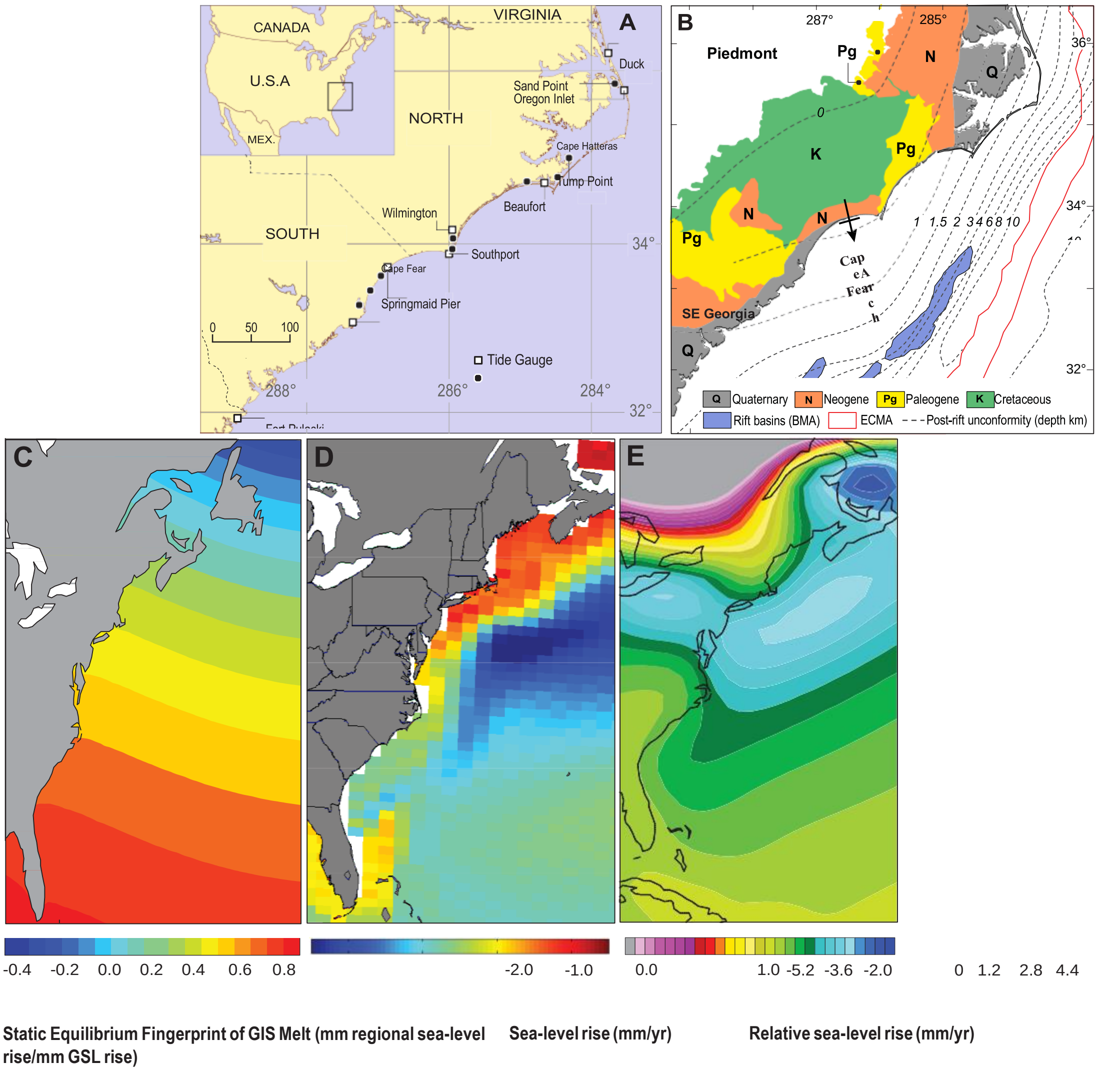


Fig. 1 (A) Location map. (B) Map of regional shallow subsurface geology, post-rift unconformity, and large-scale structural geology (Dillon and P., 1988; Gohn, 1988; Grow and Sheridan, 1988; North Carolina Geological Survey, 2004). (C) Static-equilibrium fingerprint of RSL change from uniform melting of the Greenland Ice Sheet (Mitrovica et al, 2011), in units of mm RSL rise per mm GMSL rise. (D) Ocean dynamic contribution to RSL over 2006-2100 in the Community Earth System Model RCP 8.5 experiment from the Coupled Model Intercomparison Project Phase 5 (Taylor et al, 2012). (E) GIA contribution to RSL under the ICE-6G VM5b model (Engelhart et al, 2011)

The static-equilibrium 'fingerprint' contribution to RSL changes arises from the immediate response of Earth's geoid, rotation, and elastic lithosphere to redistribution of mass between land ice and the ocean (Clark and Lingle, 1977; Mitrovica et al, 2011). As the mass of an ice sheet or glacier shrinks, sea-level rise is greater in areas geographically distal to the land ice than in areas close to it, primarily because the gravitational attraction between the ice mass and the ocean is reduced. Greenland Ice Sheet (GrIS) mass loss, for instance, generates a meridional sea-level gradient along the U.S. Atlantic coast (Figure 1c), where Maine experiences ~30% of the global mean response, compared to ~60% in North Carolina and ~80% in south Florida. Melting of the West Antarctic Ice Sheet (WAIS), by contrast, causes a nearly uniform rise along the U.S. Atlantic coast (including North Carolina), which is about 20% higher than the global average due primarily to the effect of WAIS mass loss on Earth's rotation (Mitrovica et al, 2009). Though the magnitude of sea-level fingerprints proximal to a changing ice mass is sensitive to the internal distribution of that mass, this sensitivity diminishes with distance. For example, at the distance of North Carolina, assumptions about the distribution of mass lost from GrIS have only an ~10% effect on the fingerprint (i.e., a RSL effect equal to ~6% of the global mean) (Mitrovica et al, 2011).

Oceanographic effects change sea-surface height relative to the geoid (e.g., Kopp et al, 2010). They in- clude both global mean thermal expansion and regional changes in ocean-atmospheric dynamics and in the distribution of heat and salinity within the ocean. For example, changes in the Gulf Stream affect sea level in the western North Atlantic Ocean (e.g., Kienert and Rahmstorf, 2012; Ezer et al, 2013). As observed by satellite altimetry, the dynamic sea-surface height off of New Jersey averages ~60 cm lower than the height off of Bermuda. By contrast, off the North Carolina coast, the dynamic sea-surface height averages ~30 cm lower than off Bermuda, and this difference diminishes much more quickly off shore than it does north of Cape Hatteras, where the Gulf Stream separates from the U.S. Atlantic coast and turns toward northern Europe (Yin and Goddard, 2013). Ocean modeling shows that a slower Gulf Stream, which can be caused by a weaker Atlantic Meridional Overturning Circulation or by shifting winds, would reduce these sea-level gradients, increasing sea level along the U.S. Atlantic coast north of Cape Hatteras (Figure 1d). A northward shift in the position of the Gulf Stream, which could result from a migration of the Intertropical Convergence Zone (ITCZ), would similarly raise mid-Atlantic sea levels. In contrast, sea-surface height in coastal regions south of Cape Hatteras is less influenced by changes in the Gulf Stream (Yin and Goddard, 2013).

Locally in North Carolina, RSL also changes in response to sediment compaction (Brain et al, 2015), groundwater withdrawal (Lautier, 2006), and tidal-range shifts. North Carolina is partly located within the Albemarle Embayment (Figure 1b), a Cenozoic depositional basin (Foyle and Oertel, 1997) stretching from the Norfolk Arch at the North Carolina/Virginia border to southern Pamlico Sound at the Cape Lookout High. The embayment is composed of ~1.5 km thick post-rift sedimentary rocks and Quaternary unconsolidated sediments (e.g., Gohn, 1988), currently undergoing compaction (e.g., van de Plassche et al, 2014).

The influence of local factors on regional RSL reconstructions is minimized by using proxy and instru- mental data from multiple sites. For example, Kemp et al (2011) concluded that local factors were not the primary driving mechanisms for RSL change in North Carolina over the last millennium, because the trends reconstructed at two sites located >100 km apart in different water bodies closely agree.

3 Methods

3.1 Historical reconstruction

Tide gauges provide historic measurements of RSL for specific locations (Figure 1a). In North Carolina, there are two long-term tide-gauge records: Southport (covering 1933-1954, 1976-1988, and 2006-2007) and Wilmington (covering 1935 to present). Both have limitations: Southport has temporal gaps in the record, while the Wilmington record was influenced by deepening of the navigational channels, which increased the tidal range (Zervas, 2004). There are also shorter records from Duck (1978 to present), Oregon Inlet (1977 and 1994 to present), and Beaufort (1953-1961, 1966-1967, and 1973 to present), which we also include in our analysis.

Geological reconstructions provide proxy records of pre-20th century RSL. Our database of Holocene RSL reconstructions from North Carolina includes 107 discrete sea-level constraints from individual core samples collected at a suite of sites (Horton et al, 2009; Engelhart and Horton, 2012; van de Plassche et al, 2014). It also includes two continuous Common Era RSL reconstructions, from Tump Point (spanning the last ~1000 years) and Sand Point (spanning the last ~2000 years), produced using ordered samples from cores of salt-marsh sediment (Kemp et al, 2011) (Figure 1a). Salt marshes from the U.S. Atlantic Coast provide higher-resolution reconstructions than other sea-level proxies (in North Carolina, < 0.1 m vertically and ± 1 to ± 71 y geochronologically). The combination of an extensive set of Holocene sea-level index points, multiple, high-resolution Common Era reconstructions, and tide-gauge measurements makes North Carolina well suited to evaluating past sea-level changes.

We fit the proxy and tide-gauge observations to a spatio-temporal Gaussian process (GP) statistical model of the Holocene RSL history of the U.S. Atlantic Coast. The model is similar to that of Kopp (2013), though with a longer temporal range and with geochronological uncertainty accommodated through the noisy-input GP method of McHutchon and Rasmussen (2011). To provide regional context, the fitted data also include records from outside of North Carolina, in particular salt-marsh reconstructions from New Jersey (Kemp et al, 2013) and Florida (Kemp et al, 2014) and all U.S. Atlantic Coast tide-gauge records in the Permanent Service for Mean Sea Level (2014) database with >60 years of data. To aid comparison with the proxy reconstructions, tide-gauge measurements were incorporated into the analysis as decadal averages. The GP model represents sea level as the sum of spatially-correlated low-frequency (millennial), medium-frequency (centennial) and high-frequency (decadal) processes. Details are provided in the Supporting Information. All estimated rates of past RSL change in this paper are based on application of the GP model to the combined data set and are quoted with 2σ uncertainties.

3.2 Future projections

Several data sources are available to inform sea-level projections, including process models of ocean and land ice behavior (e.g., Taylor et al, 2012; Marzeion et al, 2012), statistical models of local sea-level processes (Kopp et al, 2014), expert elicitation on ice-sheet responses (Bamber and Aspinall, 2013) and expert assessment of the overall sea-level response (Church et al, 2013; Horton et al, 2014). Kopp et al (2014) synthesized these different sources to generate self-consistent, probabilistic projections of local sea-level changes around the world under different future emission trajectories.

Combined with historical records of storm tides, RSL projections provide insight into the changes in expected flood frequencies over the 21st century. We summarize the RSL projections of Kopp et al (2014) for North Carolina and apply the method of Tebaldi et al (2012) and Kopp et al (2014) to calculate their implications for flood-return periods.

Note that the projections of Kopp et al (2014) are not identical to those of the expert assessment of the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (Church et al, 2013). The most significant difference arises from the use of a self-consistent framework for estimating a complete probability distribution of RSL change, not just the likely (67% probability) GMSL projections of the IPCC. Kopp et al (2014) and the IPCC estimate similar but not identical likely 21st century GMSL rise (under RCP 8.5, 62–100 cm vs. 53–97 cm, respectively; under RCP 2.6, 37–65 cm vs. 28–60 cm).

4 Holocene sea-level change in North Carolina

RSL rose rapidly during the early and mid-Holocene, increasing in central North Carolina from -30.1 ± 1.8 m at 9000 BCE to -4.1 ± 0.7 m at 2000 BCE (Fig. 2a). The rate of RSL rise decreased over time, as a result of declining input from shrinking land ice reservoirs and slowing GIA (Peltier, 2004; Milne and Mitrovica, 2008), from a millennially-averaged rate of 6.8 ± 1.2 mm/yr at 8000 BCE to 0.8 ± 1.0 mm/yr at 2500 BCE.

A declining GIA rate with increasing distance from the center of the Laurentide ice sheet (Engelhart et al, 2009), along with a contribution from tectonic uplift along the Cape Fear Arch (van de Plassche et al, 2014), caused spatial variability in the rate of Common Era RSL rise along the U.S. Atlantic coast and within North Carolina (Fig. 3a). At Sand Point in northern North Carolina, RSL rose from -2.38 ± 0.06 m at 0 CE to -0.37 ± 0.05 m by 1800 CE, an average rate of 1.11 ± 0.03 mm/yr. In the Wilmington area, the estimated average rate of RSL rise from 0 to 1800 CE was 0.8 ± 0.2 mm/yr (Fig. 3a-b; Table S-1).

Century-average rates of RSL change varied around these long-term means. For example, between 1000 and 1800 CE at Sand Point, century-average rates of RSL change ranged from a high of 1.7 ± 0.5 mm/yr (in the 12th century) to a low of 0.9 ± 0.5 mm/yr (in the 16th century) (Figure 2b). Synchronous sea-level changes occurred in southern NC over the same period of time (Kemp et al, 2011). However, the sign of the North Carolina RSL rate changes contrasts with that reconstructed at sites further north in New Jersey (Kopp, 2013) (Figure 2c). This contrast suggests a role for changes in ocean and atmosphere circulation, such as a shift in the position or strength of the Gulf Stream, in explaining these variations. A strengthening of the Gulf Stream (the opposite of the pattern depicted in Figure 1d) would be consistent with the observations. The absence of similarly timed variations in Florida (Kemp et al, 2014) excludes a significant contribution from the static-equilibrium fingerprint of GrIS mass changes (Figure 1c).

5 Twentieth-century sea-level changes in North Carolina

The most prominent feature in the North Carolina Common Era sea-level record is the acceleration of the rate of rise between the 19th and 20th centuries (Figure 2b-c). At Sand Point, the average rate of RSL rise over the 19th century (1.0 ± 0.5 mm/yr) was within the range of previous Common Era variability and close

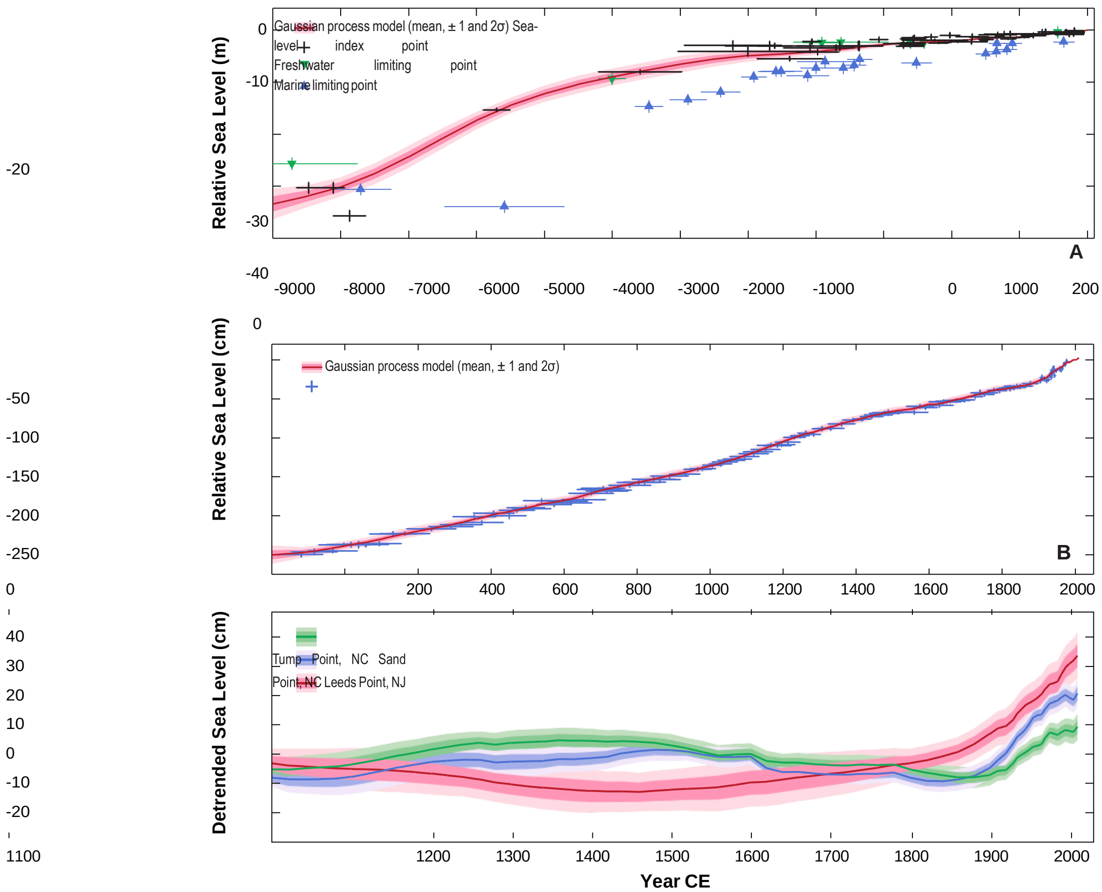


Fig. 2 (a) Holocene RSL in North Carolina, showing a representative GP estimate for central North Carolina (*red*), as well all index points (*crosses*), marine limiting points (*blue upward triangles*), and freshwater limiting points (*green downward triangles*) from North Carolina. Index/limiting points shown with 2σ error bars. (b) RSL over the Common Era at Sand Point, North Carolina. (c) RSL detrended with respect to the 1000-1800 CE average rate for North Carolina (NC) and New Jersey (NJ). GP estimates are shown with 1σ (*dark shading*) and 2σ (*light shading*) errors.

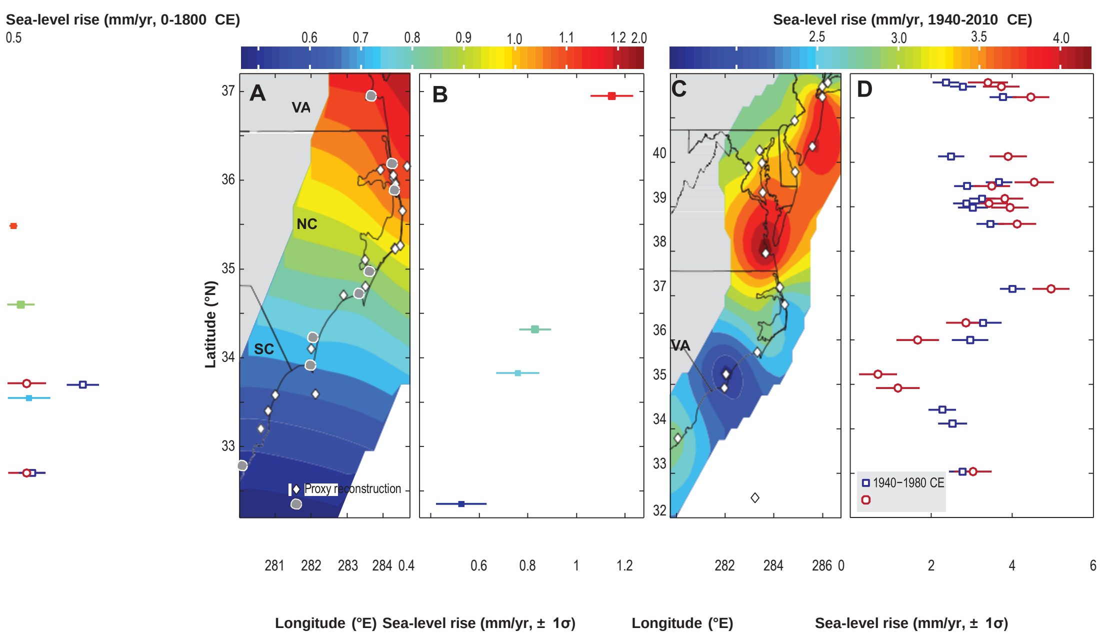


Fig. 3 (a) Pre-Industrial Common Era rate of RSL rise (0-1800 CE; mm/yr). Diamonds: proxy sites; grey circles: selected tide gauges and continuous proxy records (as in Tables S-1 and S-2). Uncolored areas have 1σ uncertainty >0.15 mm/yr. (b) shows estimates at indicated tide-gauge and continuous proxy record sites (1σ errors). (c) 1940-2010 rate of RSL rise. Diamonds: tide-gauge locations with >60 years of data. Uncolored areas have 1σ uncertainty >0.5 mm/yr. (d) 1940-1980 (blue squares) and 1980-2010 (red circles) rates of RSL rise at tide-gauge sites.

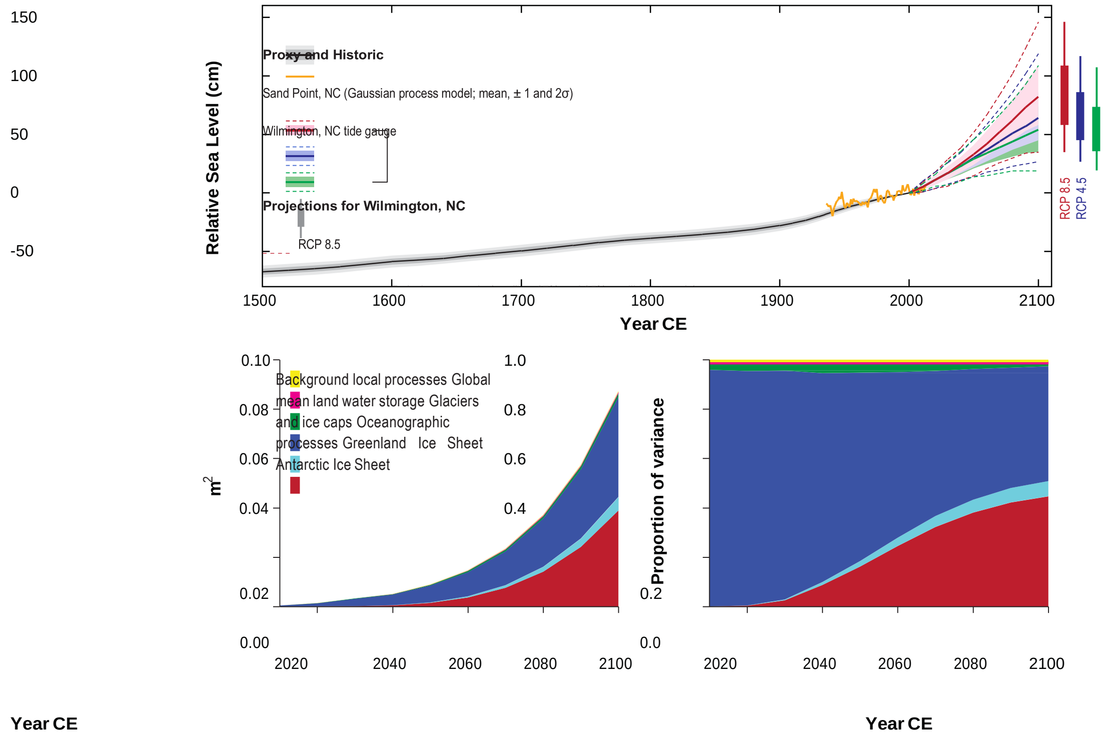


Fig. 4 (a) GP estimate of sea-level at Sand Point (*black*), annual Wilmington tide-gauge data (*orange*), and Kopp et al (2014) projections for RCP 8.5 (*red*), 4.5 (*blue*), and 2.6 (*green*). Shading/dashed lines = 67%/95% credible intervals. Bars and whiskers represent 67% and 95% credible intervals of 2100 CE projections. All heights relative to 2000 CE. (b-c) Sources of uncertainty in RCP 8.5 20-year-average sea-level rise projection at Wilmington, shown in units of (b) variance and (c) fractional variance as in Kopp et al (2014).

to the long-term average. By contrast, it is extremely likely ($P = 0.95$) that the 2.7 ± 0.5 mm/yr experienced in the 20th century was not exceeded in any century since at least the 10th century BCE (which had a rate of 1.2 ± 1.6 mm/yr). Average 20th century RSL rates range from 2.1 ± 0.5 mm/yr at Wilmington to 3.5 ± 0.3 mm/yr at Tump Point (Table S-1).

Spatial patterns of sea-level variability are detectable at higher temporal frequencies in the tide-gauge record (Kopp, 2013; Yin and Goddard, 2013) (Figure 3c-d; Table S-2). From 1940 to 1980 CE, sea-level rise in both North Carolina and the U.S. mid-Atlantic region exceeded the global mean. At Wilmington and Duck, the average rates were 2.3 ± 0.7 mm/yr and 3.3 ± 0.9 mm/yr, respectively, compared to 2.8 ± 0.6 mm/yr at New York City and a GMSL rise of 0.8 ± 0.8 mm/yr (Hay et al, 2015). This pattern changed over the interval from 1980 to 2010 CE, when the rate of GMSL rise increased to 2.5 ± 0.5 mm/yr while rates of RSL rise south of Cape Hatteras remained stationary or decreased (1.7 ± 1.0 mm/yr at Beaufort, 0.7 ± 0.9 mm/yr at Wilmington, and 1.2 ± 1.1 mm/yr at Southport). In contrast, sites north of Cape Hatteras experienced a significant increase in rate; at New York City, for example, RSL rose at 3.7 ± 0.9 mm/yr.

Several recent papers identified this regional phenomenon in the northeastern U.S. as a “hot spot” of sea-level acceleration (Sallenger et al, 2012; Boon, 2012; Ezer and Corlett, 2012; Kopp, 2013). Less attention has been paid to its counterpart in the southeastern U.S., which might be regarded as a “hot spot” of deceleration, especially when considered in the context of the GMSL acceleration occurring over the same interval. The pattern of a sea-level increase north of Cape Hatteras and sea-level decrease south of Cape Hatteras is consistent with a northward migration of the Gulf Stream (Yin and Goddard, 2013; Rahmstorf et al, 2015). It is also consistent with the dominant spatial pattern of change seen in the North Carolina and New Jersey proxy reconstructions from the 16th through the 19th century (Figure 2c). Dredging has, however, contaminated some North Carolina tide gauges, rendering a simple assessment of the ocean dynamic contribution during the 20th century challenging.

Table 1 Projected sea-level rise in North Carolina under RCP 8.5 and RCP 2.6

cm	RCP 8.5					RCP 2.6			
	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5
DUCK, NC									
2030	23	16–29	12–33	6–39	43	22	17–28	12–32	7–38
2050	41	31–51	24–59	15–72	83	37	28–46	22–53	13–66
2100	100	73–129	54–154	29–214	304	70	50–93	36–113	17–181
2150	160	124–206	103–255	76–425	627	99	71–136	56–184	39–357
2200	225	166–304	134–394	99–715	1055	131	80–196	58–287	33–607
WILMINGTON, NC									
2030	17	12–23	8–27	3–33	36	17	12–21	9–25	4–30
2050	33	24–42	18–48	10–61	75	29	21–36	16–42	9–55
2100	82	58–109	42–132	20–194	281	54	36–74	24–94	8–162
2150	135	101–180	81–230	57–395	596	77	48–113	34–161	16–334
2200	194	136–273	105–364	74–678	1016	101	50–166	27–257	3–575

Values represent two-decade averages and are in cm above 1990–2010 ('2000') mean sea level. Columns correspond to different projection probabilities. For example, the "5-95" columns correspond to the 5th to 95th percentile; in IPCC terms, the 'very likely' range.
The RCP 8.5 99.9th percentile corresponds to the maximum level physically possible.

6 Future sea-level projections for North Carolina

The integrated assessment and climate modeling communities developed Representative Concentration Pathways (RCPs) to describe future emissions of greenhouse gases consistent with varied socio-economic and policy scenarios (Van Vuuren et al, 2011). These pathways provide boundary conditions for projecting future climate and sea-level changes. RCP 8.5 is consistent with high-end business-as-usual emissions. RCP 4.5 is consistent with moderate reductions in greenhouse gas emissions, while RCP 2.6 requires strong emissions reductions. These three RCPs respectively yield likely ($P = 0.67$) global mean temperature increases in 2081-2100 CE of 3.2–5.4°C, 1.7–3.2°C, and 0.9–2.3°C above 1850-1900 CE levels (Collins et al, 2013).

A bottom-up assessment of the factors contributing to sea-level change (Kopp et al, 2014) indicates that, regardless of the pathway of future emissions, it is virtually certain ($P > 0.998$) that both Wilmington and Duck will experience a RSL rise over the 21st century and very likely ($P > 0.90$) that the rate of that rise will exceed the rate observed during the 20th century. Below, we summarize the bottom-up projections of Kopp et al (2014) for Wilmington and Duck, NC, which bracket the latitudinal extent and degree of spatial variability across the state (Tables 1, S-3, S-4, S-5).

Under the high-emissions RCP 8.5 pathway, RSL at Wilmington will very likely ($P = 0.90$) rise by 8–27 cm (median of 17 cm) between 2000 and 2030 CE and by 18–48 cm (median of 33 cm) between 2000 and 2050 CE (Figure 4a). Projected RSL rise varies modestly across the state, with a very likely rise of 12–33 cm (median 23 cm) between 2000 and 2030 CE and of 24–59 cm (median of 41 cm) between 2000 and 2050 CE at Duck. Because sea level responds slowly to climate forcing, projected RSL rise before 2050 CE can be reduced only weakly (~3-6 cm) through greenhouse gas mitigation.

It is important to consider these numbers in the context of the background variability in annual-mean and decadal-mean RSL. Relative to 20-year-mean RSL, annual-mean RSL as measured by the Wilmington tide gauge has a standard deviation of ~8 cm, so the median projection for 2030 CE is only slightly above twice the standard deviation. It would therefore not be surprising to see an isolated year with RSL as high as that projected for 2030 CE even in the absence of a long-term trend. However, consecutive years of that height would be unexpected, as decadal-mean RSL has a standard deviation of ~1 cm. Given the magnitude of decadal variability, however, differences in projections of <~4 cm should not be viewed as significant.

Reductions in greenhouse gases over the course of the 21st century can significantly affect sea-level rise after 2050 CE. Under the high-emissions RCP 8.5 pathway, RSL at Wilmington is very likely to rise by 42–132 cm (median of 82 cm) between 2000 and 2100 CE, while under the low-emissions RCP 2.6 pathway, it is very likely to rise by 24–94 cm (median of 54 cm). The maximum physically possible 21st century sea-level rise is significantly higher (~280 cm), although the estimated probability of such an outcome is extremely low ($P \approx 0.001$) (Kopp et al, 2014). Projected RSL rise varies modestly across the state, with a very likely rise of 54–154 cm (median of 100 cm) under RCP 8.5 and 36–113 cm (median of 70 cm) under RCP 2.6 at Duck, a difference from Wilmington of ~12–22 cm.

Uncertainty in projected RSL rise in North Carolina stems from two main sources: the (1) oceanographic and (2) Antarctic ice sheet responses to climate change. The former source dominates the uncertainty through most of the century, with the Antarctic response coming to play a roughly equal role by the end of the century (Figure 4b-c). At Wilmington, under RCP 8.5, ocean dynamics is likely ($P = 0.67$) to contribute -9 to +17 cm (median 5 cm) to 21st century sea-level rise. The dynamic contribution increases to the north, with -9 to +25 cm (median 8 cm) likely at Duck. These contributions are less than those in the northeastern United States; for example, at New York, ocean dynamics are likely to contribute -6 to +35 cm (median 14 cm).

The GrIS contribution to uncertainty in North Carolina RSL change is smaller than the Antarctic contri- bution because of two factors. First, GrIS makes a smaller overall contribution to GMSL uncertainty, because GrIS mass change is dominated by surface mass balance, while the behavior of WAIS is dominated by more complex and uncertain ocean/ice sheet dynamics. Second, the GrIS contribution to North Carolina RSL change and to its uncertainty is diminished by the static-equilibrium fingerprint effect to about 60% of its global mean value.

7 Implications of sea-level rise for flood risk and economic damages

Based on historical storm tides, the '1-in-10 year' flood (i.e., the flood level with a probability of 10% in any given year) at the Wilmington tide gauge is 0.60 m above current mean higher high water (MHHW). In the absence of sea-level rise, one would expect three such floods over a 30-year period. Assuming no increase in the height of storm-driven flooding relative to mean sea level and accounting for the probability distribution of projected sea-level rise as in Kopp et al (2014), seven similar magnitude floods are expected between 2000 and 2030 (regardless of RCP). Between 2000 and 2050, the expected number of years experiencing a flood at 0.60 m above current MHHW increases from 5 to 21. After 2050, regardless of RCP, almost every year is expected to see at least one flood at 0.60 m above current MHHW. Similarly, the expected number of 0.93 m '1-in-100 year' floods will increase with projected sea-level rise. The '1-in-100 year' flood is expected about 1.6–1.8 times between 2000 and 2050 (rather than the 0.5 times expected in the absence of sea-level rise). During the second half of the century, '1-in-100 year' flooding is expected in 29 of 50 years under RCP 8.5 and 17 of 50 years under RCP 2.6.

Houser et al (2015) characterized the costs of projected sea-level rise and changes in flood frequency using the Risk Management Solutions North Atlantic Hurricane Model, which models wind and coastal flood damage to property and interrupted businesses caused by a database of tens of thousands of synthetic storm events. Under all RCPs, projected RSL rise in North Carolina would likely ($P = 0.67$) place >$4 billion of current property below MHHW by 2050 and >$17 billion by 2100. Statewide (assuming fixed distribution and value of property), average annual insurable losses from coastal storms will very likely ($P = 0.90$) increase by 4-17% between 2011 and 2030 and by 16-75% between 2011 and 2050 (regardless of RCP). By 2100, they are very likely to increase by 50-160% under RCP 8.5 and 20-150% under RCP 2.6 (Houser et al, 2015). Projected increases in the intensity of tropical cyclones under RCP 8.5 (Emanuel, 2013) may amplify the increase in losses by ~1.5x by 2050 and ~2.1x by 2100. These cost estimates assume a fixed distribution and valuation of property; intensification of development along the coastline will increase exposure and therefore cost, while protective measures will decrease exposure and cost.

8 Concluding remarks

North Carolina Session Law 2012-202/House Bill 819 requires assessment of future sea-level change trajectories that include "sea-level fall, no movement in sea level, deceleration of sea-level rise, and acceleration of sea-level rise." Geological and historical records indicate that, over the last 11,000 years, North Carolina experienced periods of RSL deceleration and acceleration, but no periods of RSL stasis or fall.

- Millennially-averaged RSL rise in central North Carolina decelerated from 8000 BCE (6.8 ± 1.2 mm/yr) until 2500 BCE (0.8 ± 1.0 mm/yr).

- From 0 to 1800 CE, average RSL rise rates within North Carolina varied from 1.11 ± 0.03 mm/yr in northern North Carolina to 0.8 ± 0.2 mm/yr in southern North Carolina (in the vicinity of the Cape

Fear Arch, and farther away from the peripheral bulge). Century-average rates of sea-level change varied around these long-term means. Comparison of records along the U.S. Atlantic coast indicate that pre-Industrial Common Era sea-level accelerations and decelerations had a spatial pattern consistent with variability in the strength and/or position of the Gulf Stream.

– It is extremely likely ($P = 0.95$) that the accelerated rate of 20th century RSL rise at Sand Point, NC, (2.7 ± 0.5 mm/yr) had not been reached in any century since at least the 10th century BCE.

– Between 1940-1980 and 1980-2010, sea level in North Carolina decelerated relative to the global mean and possibly in absolute terms (at Wilmington, from 2.3 ± 0.5 mm/yr to 0.7 ± 0.9 mm/yr; at Southport, from 2.5 ± 0.7 mm/yr to 1.2 ± 1.1 mm/yr), while sea-level rise accelerated north of Cape Hatteras. The spatial pattern and the magnitude of change are consistent with Gulf Stream variability.

– It is virtually certain ($P = 0.99$) that RSL rise at Wilmington between 2000 and 2050 will exceed 2.2 mm/yr, nearly three times the 0-1800 CE average rate. It is extremely likely ($P = 0.95$) that it will exceed 3.2 mm/yr, in excess of the 20th century average of 2.2 ± 0.6 mm/yr. Under the high-emissions RCP 8.5 pathway, RSL is very likely to rise by 42–132 cm, and under the low-emissions RCP 2.6 pathway RSL is very likely to rise by 24–94 cm between 2000 and 2100.

– Storm flooding in North Carolina will be increasingly exacerbated by sea-level rise. After 2050, the current ‘1-in-10 year’ flood is expected to occur in Wilmington almost every year and the ‘1-in-100 year’ flood is expected to occur in about 17–29 years. Assuming the current distribution of property and economic activity, average annual insurable losses statewide would very likely increase by 50-160% under RCP 8.5 and 20-150% under RCP 2.6.

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Supporting Information: Spatio-temporal statistical model

The spatio-temporal sea-level field $f(\mathbf{x}, t)$ is modeled as a sum of Gaussian processes (Rasmussen and Williams, 2006) with different characteristic spatial and temporal scales.

$$f(\mathbf{x}, t) = l(\mathbf{x}, t) + m(\mathbf{x}, t) + h(\mathbf{x}, t) \quad \text{(S-1)}$$

Each field has a prior mean of zero and spatially and temporally separable prior covariances given by

$$k_l(\mathbf{x_1}, t_1, \mathbf{x_2}, t_2) = \sigma_l^2 \cdot C_{3/2}(|t_2 - t_1|, \tau_l) \cdot C_{5/2}(r(\mathbf{x_1}, \mathbf{x_2}), \gamma_l) \quad \text{(S-2)}$$

$$k_m(\mathbf{x_1}, t_1, \mathbf{x_2}, t_2) = \sigma_m^2 \cdot C_{3/2}(|t_2 - t_1|, \tau_m) \cdot C_{1/2}(r(\mathbf{x_1}, \mathbf{x_2}), \gamma_m) \quad \text{(S-3)}$$

$$k_h(\mathbf{x_1}, t_1, \mathbf{x_2}, t_2) = \sigma_h^2 \cdot C_{3/2}(|t_2 - t_1|, \tau_h) \cdot C_{1/2}(r(\mathbf{x_1}, \mathbf{x_2}), \gamma_m) \quad \text{(S-4)}$$

(S-5)

where $C_\nu(r, \lambda)$ is a Matérn covariance function with scale λ and smoothness parameter ν. Here σ_i^2 are the amplitudes of the prior variances, τ_i are characteristic time scales, γ_i are characteristic length scales, and $r(\mathbf{x_1}, \mathbf{x_2})$ is the angular distance between $\mathbf{x_1}$ and $\mathbf{x_2}$.
The observations $y(\mathbf{x}, t^i)$ are modeled as

$$y(\mathbf{x}, t^i) = f(\mathbf{x}, t + \epsilon_t) + w(\mathbf{x}, t^i) + \epsilon_y + y_0(\mathbf{x}), \quad \text{(S-6)}$$

where t^i is the true age of the observation, t the mean observed age, w a process that captures sea-level variability at a sub-decadal level (which we treat here as noise), ϵ_t and ϵ_y are errors in the age and sea-level observations, and y_0 is a site-specific datum offset. For tide gauges, ϵ_t is zero and ϵ_y is estimated during a smoothing process (see below) in which annual data are assumed to have uncorrelated, normally distributed noise with standard deviation 3 mm. For proxy data, ϵ_t and ϵ_y are treated as independent and normally distributed, with a standard deviation specified for each observation based on the original publication. The sub-decadal and datum offset processes are modeled as Gaussian processes with mean zero and prior covariances given by

$$k_w(\mathbf{x_1}, t_1, \mathbf{x_2}, t_2) = \sigma_w^2 \delta(t_1, t_2)\delta(\mathbf{x_1}, \mathbf{x_2}) \quad \text{(S-7)}$$

$$k_0(\mathbf{x_1}, \mathbf{x_2}) = \sigma_0^2 \delta(\mathbf{x_1}, \mathbf{x_2}), \quad \text{(S-8)}$$

where $\delta(\mathbf{x_1}, \mathbf{x_2})$ is the Kronecker delta function. Geochronological uncertainties are incorporated using the noisy-input Gaussian process method of McHutchon and Rasmussen (2011):

$$y(\mathbf{x}, t^i) \approx f(\mathbf{x}, t^i) + \epsilon_t f'(\mathbf{x}, t^i) + w(\mathbf{x}, t) + \epsilon_y + y_0(\mathbf{x}). \quad \text{(S-9)}$$

The low-frequency process $l(\mathbf{x}, t)$ (physically corresponding to GIA, tectonics, long-term sediment compaction, and long-term GMSL change), medium-frequency process $m(\mathbf{x}, t)$, and high-frequency process $h(\mathbf{x}, t)$ all have Matérn temporal covariance functions with smoothness parameter $\nu = 1.5$, implying a functional form in which the first derivative is everywhere defined. The low-frequency process is assumed to vary smoothly over space ($\nu = 2.5$), while the medium- and high-frequency process are allowed to vary more roughly ($\nu = 0.5$). The length scale γ_m is required to be equal for the medium- and high-frequency processes, as both are expected to reflect similar oceanographic processes operating on different timescales.
The hyperparameters $\mathbf{\Theta} = \{\sigma_l, \sigma_m, \sigma_h, \sigma_w, \sigma_0, \tau_l, \tau_m, \tau_w, \gamma_l, \gamma_m\}$ are set through a three-step optimization process. First, the hyperparameters of a simplified model, in which a linear term replaces the low-frequency process, are globally optimized through simulated annealing to maximize the marginal likelihood $L(\mathbf{\Theta}|\mathbf{y_1})$, where $\mathbf{y_1}$ is the set of post-1000 BCE observations. Second, the hyperparameters of $m(\mathbf{x}, t)$, $h(\mathbf{x}, t)$ and $w(\mathbf{x}, t)$ are fixed. The remaining hyperparameters of the full model – the amplitude, scales, and spatial roughness of the low-frequency process, as well as the datum offset – are globally optimized so as to maximize the marginal

likelihood $L(\mathbf{\Theta}|\mathbf{y_2})$, where $\mathbf{y_2}$ is the complete data set . Finally, all the hyperparameters are locally optimized to maximize the marginal likelihood $L(\mathbf{\Theta}|\mathbf{y_2})$. This multi-step process improves performance relative to
globally optimizing all hyperparameters simultaneously and is guided by the recognition that the long-term, low-resolution data provide the greatest insight into the lowest-frequency processes while the salt-marsh and tide-gauge data provide the greatest insight into the medium-frequency and high-frequency processes. The optimized time scales of the high-, medium- and low-frequency processes are respectively τ_l = 14.5 kyr, τ_m = 296 years and τ_h = 6.3 years; other hyperparameters are shown in Table S-6.

Annual mean tide-gauge data are decadally averaged prior to incorporation into the analysis. To accommodate data gaps estimate the covariance of the decadal averages, we fit each annual record $y_j(t)$ separately with the model

$$y_j(t) = a_j(t - t_0) + d_j(t) + y_{0,j}, \tag{S-10}$$

where a_j is a slope, t_0 a reference time period, and $d_j(t)$ a Gaussian process with prior mean zero and a prior Matérn covariance. Hyperparameters are optimized on a site-by-site basis to maximize their marginal likelihood. Decadal averages, including their covariances, are then taken from the interpolated process $y_j(t)$.

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Table S-1 Common Era sea-level rates (mm/yr)

Site	Lat	Long	0-1800		1000-1500		1500-1800		1800-1900		1900-2000	
GMSL											**1.3**	**± 0.2**
New York, NY	40.7	-74.0	1.69	± 0.18	1.5	± 0.5	1.9	± 0.7	2.1	± 0.7	2.9	± 0.3
Leeds Point, NJ	39.5	-74.4	1.52	± 0.09	1.2	± 0.2	1.7	± 0.4	2.4	± 0.8	3.8	± 0.5
Cape May, NJ	39.1	-74.8	1.46	± 0.10	1.2	± 0.2	1.5	± 0.3	2.2	± 0.6	3.7	± 0.5
Sewell's Point, VA	37.0	-76.3	1.15	± 0.18	1.2	± 0.5	0.9	± 0.6	1.6	± 0.9	4.2	± 0.5
Duck, NC	36.2	-75.8	1.13	± 0.08	1.4	± 0.3	1.0	± 0.4	1.2	± 0.6	3.1	± 0.6
Sand Point, NC	35.9	-75.7	1.11	± 0.03	1.4	± 0.1	1.0	± 0.2	1.0	± 0.5	2.7	± 0.5
Oregon Inlet, NC	35.8	-75.6	1.11	± 0.07	1.4	± 0.2	1.0	± 0.3	1.1	± 0.6	2.6	± 0.5
Tump Point, NC	35.0	-76.4	0.87	± 0.11	1.2	± 0.2	0.7	± 0.2	1.4	± 0.4	3.5	± 0.3
Beaufort, NC	34.7	-76.7	0.83	± 0.13	1.2	± 0.3	0.7	± 0.4	1.2	± 0.7	2.9	± 0.5
Wilmington, NC	34.2	-78.0	0.76	± 0.18	1.0	± 0.5	0.7	± 0.6	0.9	± 1.0	2.1	± 0.5
Southport, NC	33.9	-78.0	0.70	± 0.18	0.9	± 0.5	0.6	± 0.6	0.9	± 1.0	2.3	± 0.6
Charleston, SC Fort	32.8	-79.9	0.53	± 0.21	0.6	± 0.6	0.4	± 0.7	1.1	± 1.1	2.9	± 0.5
Pulaski, GA	32.0	-80.9	0.47	± 0.19	0.5	± 0.5	0.3	± 0.7	1.0	± 1.1	2.7	± 0.5
Nassau, FL	30.6	-81.7	0.41	± 0.05	0.5	± 0.2	0.4	± 0.3	0.7	± 0.8	1.9	± 0.4

Errors are $\pm 2\sigma$. GMSL from Hay et al (2015).

Table S-2 Industrial era sea-level rates (mm/yr)

Site	Lat	Long	1860-1900	1900-1940	1940-1980	1980-2010
GMSL			**1.2 ± 1.1**		**0.8 ± 0.8**	**2.5 ± 0.5**

New York, NY	40.7	-74.0	2.5	± 0.7	2.7	± 0.7	2.8	± 0.6	3.7	± 0.9
Atlantic City, NJ	39.4	-74.4	3.0	± 1.1	3.7	± 0.9	3.7	± 0.7	4.6	± 1.0
Cape May, NJ	39.1	-74.8	2.8	± 1.0	3.4	± 0.9	3.4	± 0.8	4.4	± 1.1
Sewell's Point, VA	37.0	-76.3	2.3	± 1.3	3.9	± 1.1	4.0	± 0.6	5.0	± 0.9
Duck, NC	36.2	-75.8	1.7	± 1.1	3.2	± 1.0	3.3	± 0.9	2.9	± 1.0
Sand Point, NC	35.9	-75.7	1.4	± 1.0	3.0	± 0.9	3.0	± 0.8	2.0	± 1.1
Oregon Inlet, NC	35.8	-75.6	1.5	± 1.0	3.0	± 0.9	3.0	± 0.9	1.7	± 1.1
Tump Point, NC	35.0	-76.4	2.0	± 0.9	4.0	± 0.8	3.7	± 0.7	2.0	± 1.1
Beaufort, NC	34.7	-76.7	1.7	± 1.1	3.5	± 1.0	3.1	± 0.8	1.7	± 1.0
Wilmington, NC	34.2	-78.0	1.3	± 1.3	2.5	± 1.2	2.3	± 0.7	0.7	± 0.9
Southport, NC	33.9	-78.0	1.4	± 1.4	2.5	± 1.2	2.5	± 0.7	1.2	± 1.1
Charleston, SC Fort	32.8	-79.9	1.7	± 1.5	2.8	± 1.1	3.0	± 0.7	2.9	± 0.9
Pulaski, GA	32.0	-80.9	1.5	± 1.4	2.4	± 1.2	2.8	± 0.7	3.0	± 0.9
Fernandina Beach, FL	30.7	-81.5	1.2	± 1.3	1.5	± 0.7	1.9	± 0.7	2.3	± 0.9

Errors are $\pm 2\sigma$. GMSL from Hay et al (2015).

Table S-3 Projected sea-level rise in North Carolina by decade under RCPs 8.5 and 2.6

cm	RCP 8.5					RCP 2.6			
	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5
DUCK, NC									
2010	7	5–9	4–10	1–12	13	7	5–9	3–11	1–13
2020	14	11–18	8–21	4–25	27	15	11–18	9–21	5–24
2030	23	16–29	12–33	6–39	43	22	17–28	12–32	7–38
2040	31	24–39	18–45	11–53	60	30	22–37	17–43	10–51
2050	41	31–51	24–59	15–72	83	37	28–46	22–53	13–66
2060	52	40–65	32–74	20–93	120	44	33–57	25–66	13–85
2070	64	49–80	39–92	24–118	158	51	38–65	28–77	15–103
2080	76	57–95	45–111	27–146	201	57	43–74	32–87	17–125
2090	88	66–112	51–132	30–179	250	63	46–83	34–100	18–151
2100	100	73–129	54–154	29–214	304	70	50–93	36–113	17–181
2150	160	124–206	103–255	76–425	627	99	71–136	56–184	39–357
2200	225	166–304	134–394	99–715	1055	131	80–196	58–287	33–607
WILMINGTON, NC									
2010	5	3–7	2–8	0–10	11	5	4–7	2–8	1–10
2020	11	8–15	5–17	1–21	22	11	8–14	6–16	4–18
2030	17	12–23	8–27	3–33	36	17	12–21	9–25	4–30
2040	25	18–31	13–36	6–44	51	23	17–29	12–34	6–42
2050	33	24–42	18–48	10–61	75	29	21–36	16–42	9–55
2060	42	31–53	24–62	13–80	107	34	25–44	18–52	9–70
2070	52	39–66	29–78	17–103	142	39	28–51	20–61	9–88
2080	62	46–79	35–94	19–130	183	44	31–58	23–71	10–111
2090	73	53–94	40–113	21–162	229	49	34–66	24–82	10–135
2100	82	58–109	42–132	20–194	281	54	36–74	24–94	8–162
2150	135	101–180	81–230	57–395	596	77	48–113	34–161	16–334
2200	194	136–273	105–364	74–678	1016	101	50–166	27–257	3–575

Values represent two-decade averages and are in cm above 1990–2010 ('2000') mean sea level. Columns correspond to different projection probabilities. For example, the "5-95" columns correspond to the 5th to 95th percentile; in IPCC terms, the 'very likely' range.
The RCP 8.5 99.9th percentile corresponds to the maximum level physically possible.

Table S-4 Projected sea-level rise in North Carolina by decade under RCP 4.5

cm	RCP 4.5			
50		17–83	5–95	0.5–99.5
DUCK, NC				
2010	7	5–9	3–11	1–13
2020	14	11–18	8–21	4–25
2030	22	17–27	13–31	8–36
2040	30	24–37	19–42	13–50
2050	39	30–47	23–54	15–67
2060	47	36–59	28–68	17–86
2070	56	42–71	32–82	18–108
2080	64	48–82	37–96	21–130
2090	72	54–93	41–110	23–158
2100	81	60–105	45–126	25–188
2150	121	84–164	60–209	30–374
2200	160	101–232	67–315	24–618
WILMINGTON, NC				
2010	5	3–7	1–9	-1–11
2020	11	7–14	5–17	1–20
2030	17	12–21	9–24	5–29
2040	23	17–29	13–33	8–40
2050	30	22–37	17–43	10–55
2060	37	27–47	20–55	11–72
2070	44	32–56	24–66	12–91
2080	51	37–66	27–78	14–114
2090	57	41–75	30–91	16–140

2100	64	45–86	33–105	16–170
2150	96	62–137	40–182	14–344
2200	128	71–199	39–282	0–581

Values in cm above 1990–2010 mean sea level.
Columns correspond to different probability ranges.

Table S-5 Projected contributions to sea-level rise at Wilmington, NC, in 2100 CE

cm	RCP 8.5					RCP 2.6			
	50	17–83	5–95	0.5–99.5	99.9	50	17–83	5–95	0.5–99.5
Oc	41	23–61	10–74	-10–93	100	21	8–34	-1–44	-15–57
GrIS	9	5–16	3–25	2–44	60	4	2–7	2–11	1–20
AIS	4	-8–18	-12–38	-15–109	180	7	-4–20	-8–40	-11–111
GIC	16	12–19	10–21	6–25	25	10	8–13	6–15	3–18
LWS	5	3–7	2–8	0–11	10	5	3–7	2–8	0–11
Bkgd	5	3–6	2–8	0–10	10	5	3–6	2–8	0–10
Sum	82	58–109	42–132	20–194	280	54	36–74	24–94	8–162

Oc: Oceanographic. GrIS: Greenland ice sheet. AIS: Antarctic ice sheet.
GIC: Glaciers and ice caps. LWS: Land water storage. Bkgd: Background.
All values are cm above 1990–2010 CE baseline. Columns correspond to probability ranges.

Table S-6 Optimized hyperparameters

Low frequency			
amplitude	σ_l	19.1	m
time scale	τ_l	14.5	kyr
length scale	γ_l	25.0	degrees
Medium frequency			
amplitude	σ_m	119	mm
time scale	τ_m	296	yr
length scale	γ_m	3.0	degrees
High frequency			
amplitude	σ_h	13.7	mm
time scale	τ_h	6.3	y
length scale	γ_m	3.0	degrees
White noise	σ_w	4.2	mm
Datum offset	σ_0	45	mm

Bob Emory (via email on 11/19/2015)

Please accept these comments on the 2015 SLR Update. While I have used my work e-mail to send these comments, they are strictly my own, not those of my employer.

Thank you.

Bob

Bob Emory
17 Batts Hill Road
New Bern, NC 28562

November, 19, 2015

To:
Chairman Frank Gorham
Tancred Miller
Dr. Braxton Davis
Dr. Margery Overton

Subject: Comments Regarding the 2015 Update to the 2010 Sea Level Rise Report

Dear Sirs and Madam,

Please accept my comments on the 2015 Update to the 2010 Sea Level Rise Report.

I found the Update to be straightforward, science-based and free of conjecture or opinion. The Update allowed the Science Panel to utilize more up to date data and their reliance on the IPCC Fifth Assessment is appropriate given that it is the most robust study of SLR available.

Among the significant improvements incorporated in the Update are the explanation of the different conditions and dynamics associated with different regions of our coast and the differential levels of SLR predicted for those regions. The explanation of Vertical Land Motion and Ocean Dynamics was also helpful.

The use of ranges of predicted SLR based on a range of emissions scenarios was helpful. The use of ranges and the inclusion of various futures that are not totally predictable acknowledge that there is uncertainty regarding future conditions and the rates of SLR that will result. The acknowledgement of uncertainty was included in the 2010 Report but is made more obvious in the 2015 Update.

Regarding criticism of the 2010 Report and the 2012 Addendum, many of those criticisms were a result of the questions posed by the CRC to the Panel. The Panel faithfully responded to the

CRC's questions and produced a very valuable Report that would have been subject to less criticism had the CRC's questions been better thought out. I appreciate the Panel's willingness to persevere in spite of criticism, some of which was simply outlandish.

So, what to do now.

If I read the Update correctly, the data do not suggest that a decrease in the rate of SLR is likely, and just using existing rates of SLR over the next 30 years we can expect SLR of approximately 6" in the North and 2" inches in the South. Another clear message from the Update is that whatever rate of SLR you assume, we can expect an increased frequency of coastal flooding. The CRC should proactively communicate that coastal flooding, particularly in the northern coastal region, is becoming more frequent. And as SLR increases, the number of people exposed to flooding will increase. Such communication need not come across as alarmist but coastal residents and towns that are likely to experience more frequent flooding should be made aware of this likelihood and advice on responses should be provided. In many cases the response may be as simple as elevating new construction a foot or two more than is typical. Existing development presents greater challenges but there are remedies available. I am not suggesting regulation; just education on hazard mitigation based on the Update and the voluminous other sources of information that are available.

The CRC's decision to focus on the next thirty years instead of looking toward 2100 does make the Update seem more relevant for residents and policy makers. However, the longer-term outlook should not be ignored, particularly for projects with a lifespan greater than thirty years such as highways, water and sewage treatment plants, bridges and large structures which are difficult to elevate or move, including some houses. Looking beyond thirty years, at least in the northern region of the coast where a simple extension of current SLR for sixty years could easily be a foot or more, SLR should be considered when planning long-lived development. The CRC has the ability, and I would argue obligation, to keep this information in front of coastal citizens and other branches of government. And again there is the opportunity to provide this information in a way that does not open the CRC to accusation of alarmism, although there will continue to be individuals and groups that will criticize you, no matter what you do. Your obligation is to be forthright with costal property owners and local governments.

Thank you for this opportunity to provide comments and thank you to the CRC, DCM and the Science Panel for everything you do to make the North Carolina coastal region such a wonderful place.

Sincerely,

Robert R. Emory, Jr.

Bob Emory

E. Matheson (via email on 12/10/2015)

Late in the game, but my sound front land has gained height from the natural process. Decaying plant matter accumulates at a surprising rate in certain locations. CO 2 plus solar plus soil creates plant matter that adds to top soil that adds to height above sea level. Complicated measurement in total but not in particular. Seems driven by solar more than other factors. The question is significance. That's your department.

E Matheson BSME BS Bio Science
7008 Sound Drive
Emerald Isle NC

Larry Baldwin (via email on 12/21/2016)

1. To: Tancred Miller, NCDCM

Please add the attached reference to the public comments regarding the proposed NC Sea Level Rise Report (NCSLRR).

Much of the current NCSLRR draft relies upon projections by the UN-IPCC. The attached report is creditable and critical of much of the philosophy, scientific methods, and data used within the UN-IPCC document. In science all theories must be considered until proven false, or until a scientific theory can be repeated and proven positive through a rigorous scientific method process.

Thank you for accepting this reference and public comment.

Larry F. Baldwin, CPSS / NCLSS
(910) 471-0504 LBaldwin@ec.rr.com

Reference: https://www.heartland.org/sites/default/files/12-04-15_why_scientists_disagree.pdf

2. To: Tancred Miller, NCDCM

One more creditable reference to be submitted as part of the public comment period for the draft NC Sea Level Rise Report. This is recent data and testimony to the U.S. Senate regarding global warming, which is considered as a paramount factor for accelerated sea level rise to occur.

Thank you for accepting this public comment and reference.

Larry F. Baldwin, CPSS / NCLSS
(910) 471-0504 LBaldwin@ec.rr.com

Reference: https://curryja.files.wordpress.com/2015/12/christyjr.pdf

3. Tancred,

Thank-you for acknowledgment and receipt of these additional recently produced references.

I sent these references to NCDCM as informational sources on their own merit, and as a private citizen. Please do not put any additional emphasis or value on this information as my current position.
Just trying to provide both sides of the issue and science.

Hope the holiday break was enjoyable for you and your family, and I too look forward to 2016.

Larry F. Baldwin, CPSS / NCLSS
(910) 471-0504 LBaldwin@ec.rr.com

Clyde Hunt, Jr. (via email on 12/28/2015)

As an Ocean Isle Beach ocean-front property owner since 1965, anything relative to coastal NC is of great interest to me and my family. Fourth generation Hunts are now enjoying the pleasures of our wonderful beach. We have worked closely with Ocean Isle Beach and Brunswick County officials, our elected officials in Raleigh and Washington as well as the several environment agencies over these years, for the responsible development, preservation and maintenance of Ocean Isle Beach.

Fortunately, Ocean Isle Beach has had a succession of elected and appointed officials with the best interests of our beach as their prime concern and responsibility…ie…the less our federal, state and county “officials” are involved in the policy-making processes for Ocean Isle, and the more truly **local** control exists, the better the outcome for local residents and businesses and our many revenue producing visitors each year.

I was very pleased to hear that apparently……1. More thoroughly investigated and compiled information on “projected”/ estimated possible sea level rise information will be made available, and……2. Our **local** authorities will be given much more leeway in decisions on how to interpret and respond to this information.

Federal, state and county departments, keep the good information coming, and please leave it to the locals (who will be affected most) to make the necessary decisions on how to respond; a much more democratic (and I feel confident, **effective**) approach.

END OF RECORD