North Carolina Sea-Level Rise Assessment Report

March 2010

Prepared by the N.C. Coastal Resources Commission's Science Panel on Coastal Hazards

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Cover Image: Location of active tide gauges in N.C. (represented by red dots). Base map shows relative coastal elevation from LiDAR data (lighter greens represent lower elevations).

Disclaimer: This report was prepared by the N.C. Coastal Resources Commission's Science Panel on Coastal Hazards, 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.

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Introduction

The N.C. Coastal Resources Commission's (CRC) Science Panel on Coastal Hazards was invited by Division of Coastal Management (DCM) staff to provide input into DCM's sea-level rise (SLR) initiatives. The Science Panel offered to prepare a report, based on a review of the published literature, of the known state of SLR for North Carolina. The CRC and DCM asked the Science Panel to provide the best available information on the following questions:

1. An explanation of how SLR is measured: globally, and at the state and regional scales
2. Relative SLR ranges for different sections of the North Carolina coast, as appropriate to account for regional differences
3. Relative SLR ranges for North Carolina expressed in time slices for the years 2025, 2050, 2075, and 2100
4. Relative SLR rate curves for North Carolina through 2100
5. A discussion of the confidence level or margin of error for the reported ranges and rate curves
6. Recommendations as to what needs to be done for improved SLR monitoring in the State of North Carolina
7. Recommendations as to how frequently the State of North Carolina should update its projected SLR ranges and rates

The Science Panel has prepared this report in response to the CRC's request, and has included a recommendation regarding how much SLR the CRC should be planning for by 2100. This report was researched and prepared by the Science Panel and six additional individuals who were selected because of their relevant expertise.

This report synthesizes the best available science on SLR as it relates specifically to North Carolina. The study of sea level change is inherently more accurate in revealing historic changes than in making predictions of the future. There is abundant research on historic sea level changes for North Carolina, but to date this data has not been synthesized into a form that can be used to inform policy and planning.

The intent of this report is to provide North Carolina's planners and policy makers with a scientific assessment of the amount of SLR likely to occur in this century. The report does not attempt to predict a specific future rate or amount of rise because that level of accuracy is not considered to be attainable at this time. Rather, the report constrains the likely range of rise and recommends an amount of rise that should be adopted for policy development and planning purposes.

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Measuring sea-level rise: globally and regionally

Sea level is the average height of the sea with respect to a conceptual reference surface called the geoid. The geoid is an equipotential surface, a surface where the gravitational attraction is equal at all points, and is well defined. Determining the average height of the sea involves isolating the long-term SLR associated with global warming from a variety of regular water level fluctuations including those driven by waves, tides, currents, storm surge, atmospheric pressure differences, and ocean surface topography resulting from large-scale ocean circulation. Such an assessment is possible given our understanding of the mechanics of these fluctuations.

There are two types of sea level change over the long-term, local or relative sea level (RSL), and global mean or eustatic sea level (MSL). Changes in RSL result from factors that are causing the local land or sea floor to move up and down. This can be mountain building resulting from tectonic plate collisions, glaciation, sediment compaction in large deltas, or anything that adds to or subtracts from the weight of Earth's crust. MSL is simply a measure of the increase in the volume of water in the oceans, expressed as a change in the height of the oceans. Currently, MSL is rising at a rate of approximately 2mm per year (0.08 inches/yr) if averaged over the last hundred years, and around 3mm per year (0.12 inches/yr) over the last fifteen years. The rate of MSL rise has increased in response to global warming.

SLR can be directly measured in a straightforward way. The longest record of direct measurement of sea level comes from tide gauges. A tide gauge is a device built to measure water level variations due to tides and weather, and to eliminate effects due to waves. A tide gauge can be as simple as a long ruler nailed to a post on a dock. More sophisticated instruments, like those used by NOAA, are usually placed in a stilling well, or pipe, that protects a float connected to a recording device from waves. As tides rise and fall, the float's motion is recorded. Tide gauges were not built with the intention of measuring changes in sea level, but they have proven very useful for doing so. When looking at a tide gauge record, the data is representative only of RSL (as discussed above), so areas that are experiencing tectonic or sediment compaction change will bias any attempt to determine the global, MSL signal. However, it is RSL that is more relevant for coastal management.

A drawback to tide gauges in North Carolina, in addition to their small number, is that most of them don't extend back in time more than 50 years, making it difficult to resolve changes in the rate of rise over the decades. The RSL rise record for northern North Carolina was recently extended back in time to AD 1500 using organisms, which are sensitive to the level of the sea and preserved in thick peat deposits, as a proxy for sea level (Kemp et al., 2009). This record resolves an increase in the rate of SLR from 0.8 mm per year to 3.8 mm per year that occurred AD 1879-1915, which corresponds well with nearby tide gauges.

Sea level can also be measured from space. The TOPEX/Poseidon satellite, launched in 1992, measured sea level and was also used to map the ocean floor. As TOPEX/Poseidon orbited Earth, an altimeter bounced radar signals off the ocean's surface. The altimeter recorded the time it took for the radar signal to return to the satellite and that gave a precise measurement of the distance between the satellite and the sea surface. Measurement from orbit is the only way to assess sea level independently of land-level changes. TOPEX/Poseidon served as the primary means for monitoring the oceans until it was supplanted by the more accurate sea level monitoring satellite Jason-1, launched in 2001.

The global average rate of SLR measured via satellite altimetry for the period 1993-2003 was 3.1 mm per year (0.12 inches/yr) according to the Intergovernmental Panel on Climate Change (IPCC). Interestingly, the MSL rise signal is not uniform in the global ocean. Variability in ocean temperatures, ocean currents, and events such as El Nino can locally mask the global signal. For example, sea level in the Atlantic and the eastern Indian oceans was rising from 1993-2003, while sea level in the eastern Pacific was falling during that period. The 2007 IPCC report estimates that for the period 1961-2003, approximately 60 percent of the SLR was due to an addition of freshwater to the oceans from melting glaciers, while 40 percent was due to thermal expansion. For the period 1993-2003, the ratio reversed, with thermal expansion accounting for 60 percent of the rise.

Relative sea-level rise along the North Carolina coast

The IPCC Fourth Assessment Report (IPCC, 2007) contains forecasts for global average SLR ranging from 0.18 meters to 0.59 meters (7 to 23 inches) by the year 2100 AD. The report acknowledges that SLR will be variable depending on location, but does not provide specific regional predictions (Gehrels and Long, 2008). IPCC estimates are conservative because contributions to SLR from melting Greenland and Antarctic ice sheets are uncertain and this uncertainty was not included when calculating estimates (Velicogna and Wahr, 2006; Bamber et al., 2009). Several studies that use semi-empirical relationships between sea level and climate have predicted up to 1.4 meters (55 inches) of sea-level rise by AD 2100 when ice sheet contributions are included (e.g., Rahmstorf, 2007; Pfeffer et al., 2008). In summary, there is consensus that the rate of SLR will increase during the 21st century and beyond (IPCC, 2007; CCSP, 2008, 2009).

Several factors influence sea-level change at the local to regional scale including global sea-level change, local vertical land movements (subsidence or uplift), changes in tidal range, changes in coastal currents, changes in water temperature, and gravitational effects. SLR caused by the melting of an ice sheet will not be evenly distributed across the globe (Mitrovica and Milne, 2002). The term "relative sea level" is used when referring to the cumulative effects of these factors at a particular location. RSL change will, for most coastal locations, be different from globally predicted MSL changes. It is for this reason that management plans should consider rates of RSL rise specifically pertinent to North Carolina rather than rates from other regions or global averages.

Four studies provide data on rates of RSL rise in North Carolina. Each covers a different time period, but the studies that cover shorter time intervals are nested within those that cover longer time intervals (12,000 year ago to present, 2,000 years ago to present, 400 years ago to present, and ca. 70 years ago to present. The first three studies utilize geological data whereas the study covering the shortest time interval utilizes instrumental data.

Study 1: Horton et al. (2009) developed a sea-level database for North Carolina from new, published and unpublished geological data that cover the past 12,000 years. During this period, long-term average rates of SLR varied from approximately 5 mm per year (19 inches/century) until approximately 3,500 y BP (y BP = years before present, where "present" is AD 1950), to about 1 mm per year (4 inches/century) from 3,500 y BP until today.

Study 2: Kemp (2009 thesis) presented continuous, high resolution constructions of SLR in North Carolina for the past 2,000 years using geological data from Sand Point (Roanoke Island) and Tump Point (Cedar Island). The rate of RSL rise was close to 1mm per year (4 inches/century) for most of this period. The rate almost doubled to 1.7mm per year (6.7 inches/century) for about 350 years during the Medieval Warm Period (AD 1000 to 1350), and then returned to 1.0 mm/yr for the next few centuries. The rate then increased in the 20^{th} century to about 3.2 mm per year (12.6 inches/century).

Study 3: Kemp et al. (2009) concentrated on the RSL records at Sand Point and Tump Point since AD 1500. They noted that the 20^{th} century rate of RSL rise of 3.0 to 3.3 mm per year (13 inches/century) is in agreement with local tide gauges (Fig. 1) and instrumental records from the north-west Atlantic (Woodworth et al., 2008).

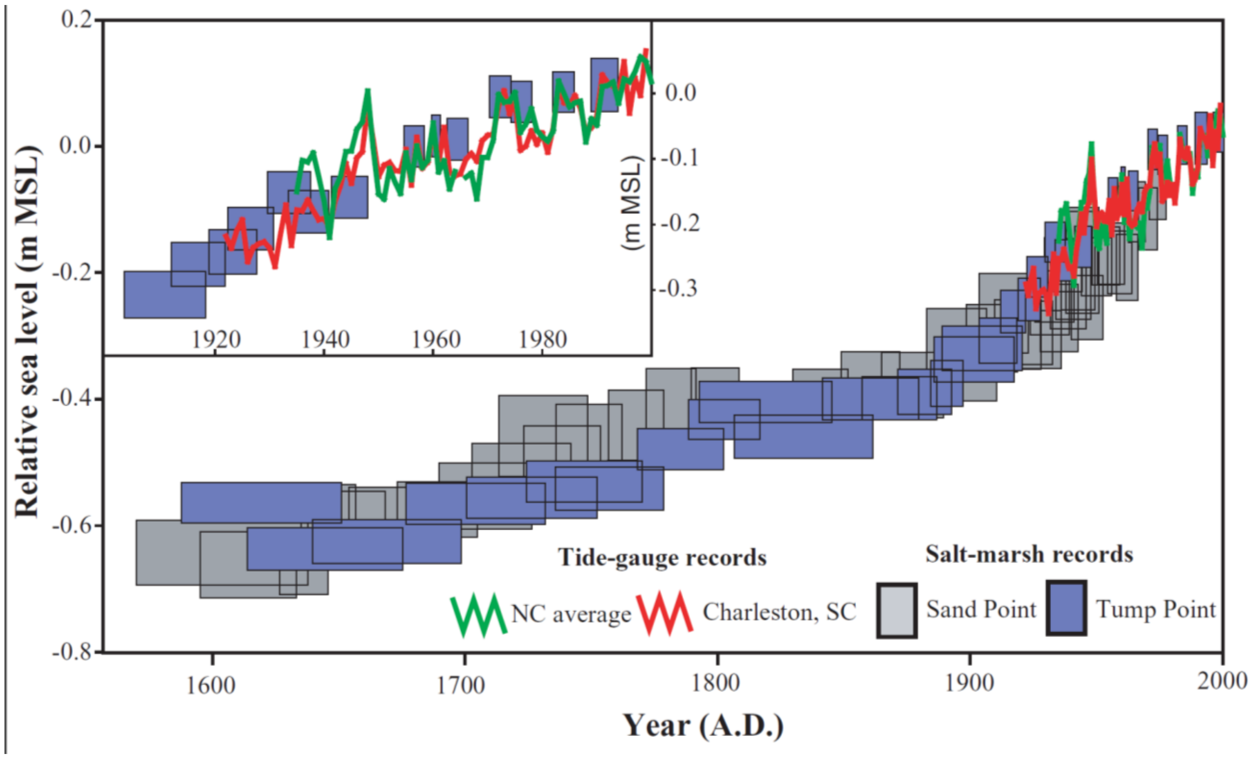

Figure 1. Reconstructions of RSL at Sand Point (grey boxes) and Tump Point (blue boxes) for the period since AD 1500. An average tide-gauge record from North Carolina (green) and the record from Charleston, South Carolina (red) are also shown. Inset: 20th century RSL reconstructed at Tump Point is compared to tide-gauge records (from Kemp et al., 2009).

Study 4: Zervas (2004) documented the MSL trends for eight water level stations in North Carolina (Table 1). The intervals of time represented by the data vary from station to station and dredging has resulted in variation in the trends of different tidal datums. These factors led Kemp et al. (2009, Study 3) to average North Carolina tide gauge records. The highest rates (up to 16.8 inches/century) are in the northern portion of the state.

Table 1. MSL trends for N.C. water-level stations in mm/year (adapted from Zervas, 2004).

Station Number	Station Name	Mean Sea-Level Trend mm/yr	Mean Sea-Level Trend inches/century	Period of Data
8651370	Duck	4.27 ± 0.74	16.8 ± 2.9	1978-2002
8652587	Oregon Inlet Marina	2.55 ± 1.21	10.1 ± 4.8	1977-1980, 1994-2002
8654400	Cape Hatteras	3.46 ± 0.75	13.6 ± 3	1978-2002
8656483	Beaufort	3.20 ± 0.54	12.6 ± 2.2	1973-2002
8656590	Atlantic Beach	2.48 ± 1.99	9.7 ± 7.8	1977-1983, 1998-2000
8658120	Wilmington	2.12 ± 0.23	8.4 ± 0.8	1935-2002
8659084	Southport	2.04 ± 0.25	8 ± 1	1933-1954, 1976-1988
8659182	Yaupon Beach	2.92 + 0.77	11.5 ± 3	1977-1978, 1996-1997

The cumulative data from these four investigations indicate that RSL change varies as a function of latitude along the NC coast, with higher rates of rise in the north, and lesser rates of rise in the south. This is a function of the local geology as well as differential crustal subsidence and uplift.

The geological data (Studies 1-3) provide the basis for understanding the potential for future changes in the rate of rise. It is clear that the SLR rates have varied in the past (the rate of rise appears to have doubled at c. AD 1900) and will likely change again in the future (Fig. 2). The Science Panel has chosen to use the tide gauge data for projections because the tide gauge data represent a more direct indicator of sea level. The fact that the tide gauge data are in agreement with the geological data adds credence to the geological methods used.

Relative sea-level rise projections for North Carolina through 2100

The IPCC reports rely on emissions scenarios as the basis for projecting future SLR ranges. This approach has been widely adopted as seen in the literature and in the planning efforts conducted in several other states and countries. There are pros and cons associated with scenario-based planning, but the growing consensus at this time appears to be that scenario-based planning is the preferred method.

Over the course of 90 years (to 2100 A.D.), the differences in RSL rise are not substantial enough to warrant detailed determinations of RSL curves for all areas, as these local differences are likely to be overwhelmed by the global effects of accelerating ice melting and thermal expansion. Therefore, in order to most easily accommodate these differing rates of rise, it is the recommendation of the Science Panel that a single set of sea-level curves be adopted for planning purposes. The sea-level curves should utilize maximum modern relative sea level rise rates and best estimates from the scientific literature in order to provide a planning buffer into the next century. For the purposes of this report, the Science Panel feels most confident in the data retrieved from the Duck gauge, given its installation, continuous length of service and lack of influence by maritime navigation projects.

A set of sea-level curves is presented in Figure 2, which present scenarios of differing rates of SLR acceleration. The curves are projected to 90 years in the future (2100 AD) and the initial rate of rise is set at 4.27 mm per year (Zervas, 2004). A rise of 0.4 meter (15 inches) is considered a minimum, since this is the amount of rise that will occur given a linear projection with zero acceleration. Various models and observations indicate that accelerated rates of SLR in the future are likely (IPCC, 2007; Rahmstorf, 2007; Pfeffer et al., 2008). In fact, various investigations indicate a two- to four-fold increase in rates of rise over the last century (Church and White, 2006; Rahmstorf, 2007; Kemp et al., 2009).

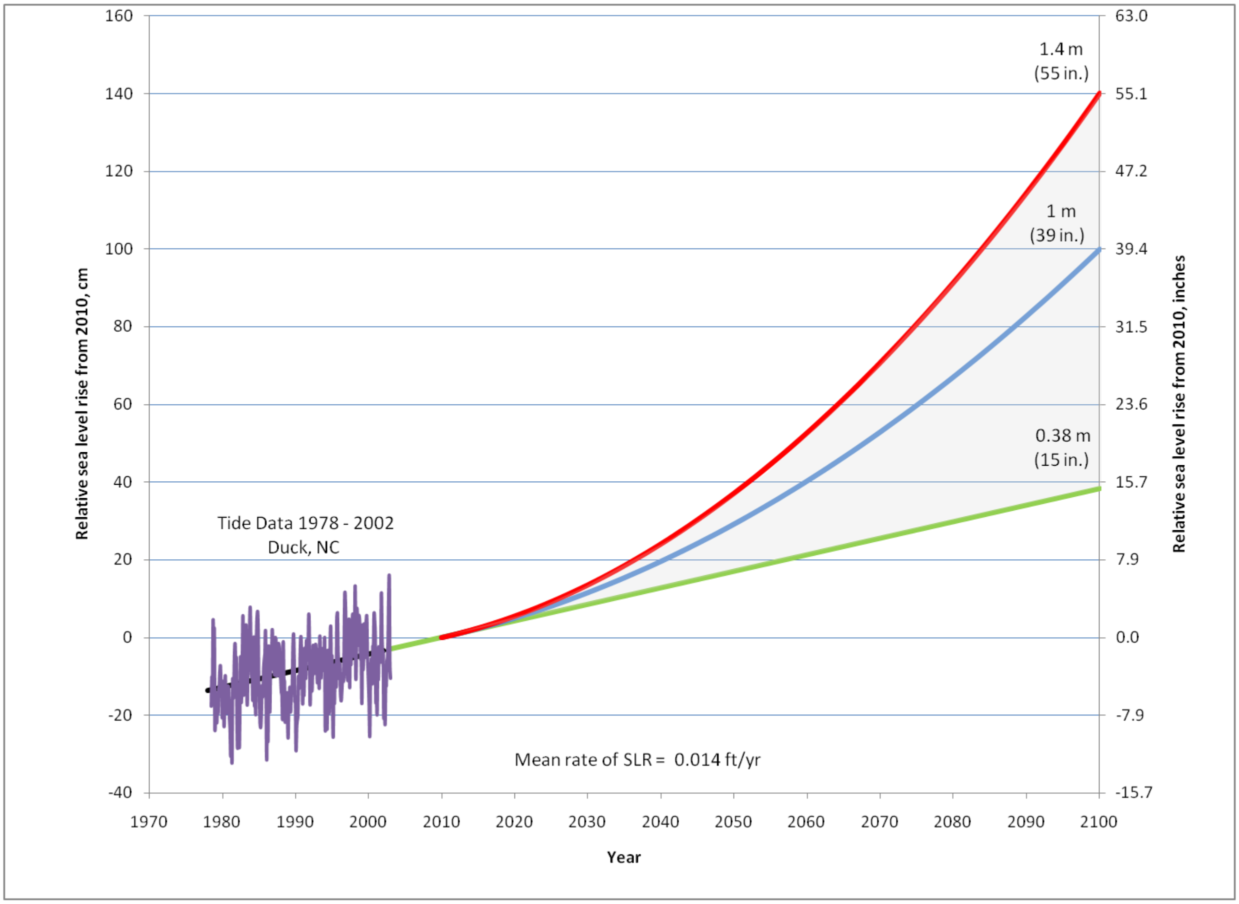

Figure 2. This chart illustrates the magnitude of SLR resulting from differing rates of acceleration. The most likely scenario for 2100 AD is a rise of 0.4 meter to 1.4 meters (15 inches to 55 inches) above present.

Rahmstorf (2007) proposed that there is a roughly proportional relationship between global mean near-surface air temperature and global MSL. Rahmstorf's "method" for projecting future SLR has been adopted by several states and municipalities. The method has produced highly accurate hindcast results, particularly for the thermal expansion component of rise, and predicts a total rise of 0.50 meter to 1.4 meters (20 to 55 inches) by 2100. Rahmstorf cautions that delayed positive feedbacks might result in the method underestimating the contribution from land ice, resulting in total rise of over 1.4 meters. In spite of this caveat, the Science Panel believes that the Rahmstorf method is robust and 1.4 meters a reasonable upper limit for projected rise.

Pfeffer et al (2008) attempted to constrain the upper limit of land ice contribution to sea level by investigating the physical ability of glaciers and ice sheets to discharge into the ocean. The research was intended to provide a basis and methodology for incorporating land ice contributions into calculations of future global MSL. The research concluded that a range of 0.80 meter to 2 meters is a more plausible range than the figures presented by the IPCC. A 2-meter rise is considered very unlikely, but still possible, and could only occur with rapidly accelerated and very high rates of warming and ice sheet melting.

A one meter (39 inch rise) is considered likely in that it only requires that the linear relationship between temperature and sea level that was noted in the 20th century remains valid for the 21st century (Rahmstorf, 2007). This level of rise is consistently encapsulated within all of the projections reviewed, and is not located at the upper or lower extremes of the projections. Given the range of possible rise scenarios and their associated levels of plausibility, the Science Panel recommends that a rise of 1 meter (39 inches) be adopted as the amount of anticipated rise by 2100, for policy development and planning purposes.

Confidence level or margin of error for the reported ranges and rate curves

Confidence levels and margins of error are not calculated for the individual rate curves because the curves are considered to be the upper and lower boundaries of sea level over the next 90 years. It is important to understand that the curves were generated using a constant acceleration rate to reach the selected endpoints derived from the literature, and are not projections of actual sea level at specific future dates. As a consequence, it is not accurate to interpolate quantities of sea level rise for specific years since we do not know whether RSL acceleration will be constant over the next 90 years. The curves are primarily intended to illustrate the expectation of increased acceleration.

The Science Panel does not believe, based on the data available at this time, that it is appropriate to attempt to quantify confidence intervals or margins of error beyond those inherent in the chosen scenarios, as informed by the published literature. Nevertheless, the Science Panel is confident that the curves presented constrain the plausible range of sea level by 2100 as accurately as is possible at this time.

Recommendations for improved sea-level rise monitoring in North Carolina

All of the historical tide gauge records over the last century and geologic evidence over the last several centuries offer undisputable evidence that sea level has been steadily rising in North Carolina, and based on multiple indicators suggesting that global climate is warming, the Panel believes that an acceleration in the rate of SLR is likely.

To justify actions that may become necessary if SLR accelerates, it is recommended that the long-term tidal observations be maintained and new stations added to the long-term record to provide better geographic coverage of our coast. The state should insure that our existing tide stations are maintained for the future and that new, better-distributed water level gauges are maintained or installed to develop long-term records. Several agencies have already installed short-term gauges that should be considered for funding support and conversion to long-term operations. In other areas new water level gauges should be installed to achieve comprehensive geographic coverage. In addition, the state should consider installing tide monitoring stations in the estuarine system, and establishing a program for continuously monitoring and measuring land subsidence on the coastal plain.

Recommendations for updating this report

Predicting sea level rise in North Carolina for the next century is now and will be for an extended period, an inexact exact science. Immediate actions should be guided by what we know best, the historical sea level and storm records combined with reasonable safety factors. With improvements in data collection, climate science and modeling, sea level decadal to century-scale predictions should improve in the future. The Panel recommends a general reassessment of the planning predictions every five years or more frequently should any significant breakthroughs develop.

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Errata. Table 1 showed a period of data for the Oregon Inlet Marina station of 1977-1880, 1994-2002. The table has been corrected to show a period of 1977-1980, 1994-2002.