ADDENDUM TO THE
NORTH CAROLINA SEA-LEVEL RISE ASSESSMENT REPORT (NCSLRAR) OF 2010
April 4, 2012
(Corrected April 20, 2012, see Errata on page 9).

Background

The North Carolina Sea-Level Rise Assessment Report was published in March 2010 and is available at http://dcm2.enr.state.nc.us/news/2010%20Releases/slrreport.html. The Science Panel on Coastal Hazards prepared the report in consultation with additional coastal scientists working in the State and invited by the Division of Coastal Management to participate in the process.

In the Fall of 2011, the Science Panel on Coastal Hazards was asked to review the initial report and answer the following questions:

- **Why does the report apply the Duck gauge, which has the highest rate and shortest record, to the entire coast? Why not use Wilmington for the south?**
- **Why is acceleration expected this century when past data shows none?**
- **Why does the report accept the IPCC's AR4 emissions and temperature projections but not its SLR projections?**
- **How does updated work by Rahmstorf, Church & White, and others affect the Panel's assessment?**

In the following sections, these questions are addressed individually.

**Why does the report apply the Duck gauge, which has the highest rate and shortest record, to the entire coast? Why not use Wilmington for the south?**

There are four long-term (period greater than 30 years) tide gauges currently operational along the North Carolina Atlantic coast: Duck (established 1977), Oregon Inlet Marina (established 1974), Beaufort (established 1964), and Wilmington (established 1908). NOAA reports sea level trends for Oregon Inlet, Beaufort, Wilmington, and Southport (established 1974, removed 2008). These stations (Oregon Inlet, Beaufort, Wilmington, and Southport) fit the stated criteria of consisting of data records longer than 30 years as of 2006 (http://tidesandcurrents.noaa.gov/sltrends/index.shtml).

The Duck gauge was chosen to evaluate sea level trends for three reasons: (1) because it is on the open coast, (2) it is the least disturbed by anthropogenic processes, and (3) it has a solid, well-documented installation and continuous operational history. The Duck gauge has never been abandoned and with time, will improve as a long-term source of relative SLR data.

The Wilmington, Beaufort and Oregon Inlet sites have undergone an increase in tidal range due to widening and deepening of nearby navigation channels (Zervas, 2003, 2004); thus the records have added uncertainties that have not been fully quantified. Additional research is needed to evaluate the effects of the channel modifications.
Relative sea-level rise reported by Zervas (2004) is 4.27 ± 0.74 mm/yr and 2.12 ± 0.23 mm/yr at Duck and Wilmington, respectively. The northeast NC coastal segment (north of Cape Lookout, approximately), exhibits relative SLR (RSLR) rates that are higher than those to the south due to several geological factors (underlying geologic framework, isostatic adjustments, etc.) (Peltier, 2004; Mallinson et al., 2005, 2008, 2010; Horton et al., 2009; Kemp et al., 2009). Kemp et al. (2011) incorporate a 1 mm/yr subsidence factor due to glacio-isostatic adjustment (GIA) in their work in North Carolina, to compute a detrended sea-level curve from salt marsh sedimentary sequences. This curve approximates global sea-level rise over the last 2000 years.

The rate that is used clearly impacts the lower estimate (assuming no acceleration) of sea-level rise in 2100 as reported in NCSLRAR. Since the Duck rate is approximately double that of the Wilmington rate, the rise in sea-level is also double for the same time period. The mid-range and upper curves are developed based on projections that assume increased temperature and ice sheet melt will cause an increase in the rise of sea-level to 1 m and 1.4 m by 2100, respectively. The initial rate influences the shape of the curve and thus intermediate (shorter time frame) projections. In future studies, local tide gauge data may be incorporated to establish regional gradients in the rate of relative sea-level rise with greater confidence. The panel may consider how best to present the variation in RSLR within the State’s coastal system in a future revision of the NCSLRAR.

**Why is acceleration expected this century when past data shows none?**

The question of whether or not SLR is currently accelerating is a valid question that warrants continued research and is the primary reasoning behind the Science Panel’s request to update the NC SLR Assessment Report every five years.

The current literature reports a range of global rates of sea-level rise and change in the rate of sea-level rise for different time periods using a variety of data sources and analysis techniques. These are summarized in Tables 1 and 2 below. Change of rate in sea-level rise from a smaller to a larger value in subsequent time periods supports the view that acceleration (positive acceleration) has taken place. Conversely, change in rate of sea level rise from a larger to a smaller value in subsequent time periods supports the view that deceleration (negative acceleration) has taken place.

The longer records (greater than 125 years) uniformly support a positive change in the rate (or acceleration) of sea-level rise. It is generally noted in the literature that an acceleration in the rate of sea level rise occurred between the nineteenth and twentieth centuries. It is also possible to break the tide record into decadal periods and observe a change in the rate of sea-level rise. Both acceleration and slight deceleration have been reported in the literature.

Further, it is important to separate the SLR record from the last century from the expectation of an increase in the rate of acceleration over the next century. Expectations of an increase in the rate of sea-level rise in this century are based primarily on projections of increases in temperature (IPCC 2007) and increasing rates of glacial ice melting (e.g., Wouters et al., 2008, Slobbe et al., 2009, Velicogna 2009, Cazenave and Llovel, 2010, Rignot 2011). Given that the contribution to SLR from land ice loss has increased since 1993, and the thermal models and observations indicate increasing temperatures in the future, it is reasonable to expect an acceleration in the rate of SLR over the next century. However, it is still unclear from the existing data if the expected acceleration has begun.
Table 1. Global Rates of Sea-Level Rise

<table>
<thead>
<tr>
<th>Author</th>
<th>Data Source</th>
<th>Data Period</th>
<th>Rate, mm/yr</th>
<th>Uncertainty ± mm/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gehrels et al., 2008</td>
<td>Foraminiferal</td>
<td>1500-1900 1900-2000</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Kemp et al., 2011</td>
<td>NC data: Salt marsh</td>
<td>BC 100-AD 950 950-1350 1350-1900 1900-present</td>
<td>Stable (0.0 to 0.1) 0.4 to 0.8 Stable to slightly falling (0.0 to -0.2) 1.9 to 2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>sedimentary sequences</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>with GIA adjustment of 1.0 mm/yr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ablain et al., 2009</td>
<td>Satellite altimetry</td>
<td>1993-2008</td>
<td>3.11</td>
<td>0.6</td>
</tr>
<tr>
<td>Cazenave &amp; Llovel, 2010</td>
<td>Tide gauge</td>
<td>1900-1930 1993-2008</td>
<td>1.8</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Merrifield et al., 2009</td>
<td>Tide gauge</td>
<td>1962-1990 1993-2007</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Holgate, 2007</td>
<td>Tide gauge</td>
<td>1904-1953 1954-2003</td>
<td>2.03</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.45</td>
<td>0.34</td>
</tr>
<tr>
<td>IPCC, 2007</td>
<td>Tide gauge</td>
<td>1962-2003</td>
<td>1.8</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Satellite altimetry</td>
<td>1993-2002</td>
<td>3.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 2. Reported Acceleration of Global Sea Level Rise

<table>
<thead>
<tr>
<th>Author</th>
<th>Data Source</th>
<th>Data Period</th>
<th>Acceleration mm/yr²</th>
<th>Uncertainty ± mm/yr²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Church &amp; White, 2006</td>
<td>Tide gauge</td>
<td>1870-2004</td>
<td>0.013</td>
<td>0.006</td>
</tr>
<tr>
<td>Church &amp; White, 2011</td>
<td>Tide gauge</td>
<td>1880-2009 1900-2009</td>
<td>0.009 0.009</td>
<td>0.003 0.004</td>
</tr>
<tr>
<td>Jevrejeva et al., 2008</td>
<td>Tide gauge</td>
<td>Since 1800</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Douglas, 1992</td>
<td>Tide gauge</td>
<td>1905-1985</td>
<td>-0.011</td>
<td>0.012</td>
</tr>
<tr>
<td>Houston &amp; Dean, 2011</td>
<td>Tide gauge</td>
<td>variable 1930 - 2010</td>
<td>-0.0014 -0.0123</td>
<td>0.0161 0.0104</td>
</tr>
</tbody>
</table>

Why does the report accept the IPCC’s AR4 emissions and temperature projections but not the SLR projections?

IPCC AR4 (2007) emissions and temperature projections have been shown to be relatively accurate, with observed temperature increase following the maximum rate of the projected increase (Rahmstorf et al., 2007; Horton et al., 2008). The IPCC decided not to include estimates of future land-based ice loss, primarily from the Greenland and Antarctic ice sheets, in the projections. In addition, the relatively simple treatment of land ice dynamics in the climate models precluded simulation of rapid dynamics. Ice sheets were treated as fixed geographic features that could gain and lose mass through
accumulation and ablation, but would not otherwise change size or undergo variations in flow. It has since been shown that the contribution of melting ice sheets (the cryosphere) to SLR is increasing and will likely be a significant contributor to SLR during the 21st century (Rignot et al., 2011). Thus, our understanding has evolved since 2007, and will continue to evolve as new data become available and vetted through the peer-review process.

**How does updated work by Church & White, Rahmstorf, and others affect the Panel’s assessment?**

Church and White (2006) used a reconstruction of global mean sea level from 1870 through 2004 and found a twentieth century sea-level rise of $1.7 \pm 0.3$ mm/yr and an acceleration of $0.013 \pm 0.006$ mm/yr$^2$. In Church and White (2011) a variety of rates are computed using various sources and time frames. For example, satellite altimeter data for 1993-2009 yielded an estimated $3.2 +/- 0.4$ mm/yr rate while coastal and island sea-level measurements from 1880 to 2009 were used to compute a rate of $1.7 \pm 0.2$ mm/yr between 1900 and 2009 and $1.9 \pm 0.4$ mm/yr from 1961 to 2009. Acceleration from 1880 and 1900 to 2009 is found to be $0.009 \pm 0.003$ mm/yr$^2$ and $0.009 \pm 0.004$ mm/yr$^2$, respectively. Though the rates of sea-level rise are similar in the two papers, the 2011 estimate of acceleration is lower than the 2006 and is more in line with other investigators (Table 2). Further, in the discussion section of the 2011 paper the authors emphasize the importance of maintenance and continuation of the observing network and associated infrastructure needed to update and maintain datasets. They note the increasing importance of GPS measurements at tide-gauge location to provide vertical land motion estimates and the continued need for high quality satellite altimeter observations.

Rahmstorf (2007) developed a semi-empirical relation that connects global sea-level rise to global surface temperature. The rate of sea-level rise is determined to be proportional to temperature ($3.4$ mm/yr of sea-level rise per $1^\circ$C of temperature rise). Using this relationship and applying the IPCC future warming scenarios, 0.5 to 1.4 m of sea-level rise is projected in 2100 above the 1990 level. In Rahmstorf, Perrette and Vermeer (2011) the robustness of the projections is tested by 1) determining the parameters for the semi-empirical relationship between temperature and sea-level rise from a variety of datasets, equations and statistical techniques and 2) by comparing projections from the models for a moderate warming period ($1.8^\circ$C) from 2000 to 2100. Over 20 different model versions were tested and nine different projections were made. Using a $1.8^\circ$C temperature scenario, approximately 1 m of sea-level rise is projected from 2000-2100. Two exceptions are noted. One is that disregarding the correction for water storage lowers the projections by 25 cm. (Note: building artificial reservoirs lowers sea level rise and pumping groundwater raises sea level). Two is the use of the Church and White (2011) data set lowers the projections 30 cm when compared to the use of other datasets (Church and White (2006) and Jevrejeva et al. (2008).

Table 3 presents sea-level rise projections from the literature, including the IPCC (2007), Rahmstorf (2007) and Rahmstorf et al. (2011) as well as others. The Panel’s assessment indicated a range of expected SLR projections over the next century. The updated information on detection of more modest rates of acceleration in the historical record and the updated information based on more refined projection models confirm the Panel’s recommendation for the need to update on a 5 year basis. The analysis and synthesis of data and development of predictive models by the research community, as evidenced in the peer reviewed literature will continue and as a result our understanding of sea level rise and its prediction will improve. Further, comments in Church and White (2011) as well as in Woodworth et al. (2011) support the Panel’s position that high quality data sets with good spatial and temporal coverage are needed to support sea-level rise studies.
Table 3. Projections of global sea level rise.

<table>
<thead>
<tr>
<th>Author</th>
<th>Projected period</th>
<th>Range, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rahmstorf, 2007</td>
<td>1990-2100</td>
<td>50 to 140</td>
</tr>
<tr>
<td>IPCC, 2007</td>
<td>1980-1999 to 2090-2099</td>
<td>18 to 38; 20 to 43; 21 to 48; 20 to 45; 23 to 51; 26 to 59</td>
</tr>
<tr>
<td>(Six scenarios based on different temperature projections.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vermeer &amp; Rahmstorf, 2009</td>
<td>1990-2100</td>
<td>75 to 190</td>
</tr>
<tr>
<td>Rahmstorf et al., 2011</td>
<td>2000-2100</td>
<td>80 to 120*</td>
</tr>
<tr>
<td>Jevrejeva et al., 2010</td>
<td>2000-2100</td>
<td>60 to 160</td>
</tr>
<tr>
<td>Horton et al., 2008</td>
<td>2000-2100</td>
<td>47 to 100</td>
</tr>
<tr>
<td>Grinsted et al., 2009</td>
<td>2000-2100</td>
<td>90 to 130</td>
</tr>
<tr>
<td>Jevrejeva et al., 2012</td>
<td>2000-2100</td>
<td>57 to 110</td>
</tr>
</tbody>
</table>

*If ice discharges were to scale up in the future, it would add 10 to 20 cm to the upper bound of sea-level rise in the IPCC projections (IPCC, 2007).

**Exceptions as noted from Rahmstorf et al. (2011) are described in the above paragraph.

Summary

It is helpful to put the North Carolina SLR Assessment Report into perspective. Many scientific organizations in the United States and worldwide have issued statements regarding the importance of global climate change. An acceleration in the rate of sea level rise is an explicit or implicit concern of all. These include 1) American Association for the Advancement of Science (AAAS, 2006); 2) Research Council of the National Academies (2011); 3) Geological Society of America (GSA, 2010); 4) American Geophysical Union (AGU) 2012; and 5) European Geosciences Union (EGU, 2005).

In addition, SLR assessments produced by expert panels in other states reference numbers very similar to those in the North Carolina SLR Assessment Report. Maine is establishing plans to deal with the impacts of a 0.5, 1.0 and 2.0 m rise by 2100 (EPA, 1995). Delaware is adopting management plans for sea-level rise scenarios of 0.5, 1.0 and 1.5 m by 2100 (DNREC, 2009). The Louisiana Applied Coastal Engineering and Science (LACES) Division produced a comprehensive report in which they recommend that Coastal Protection and Restoration Authority staff assume a SLR of 1 m by 2100 for the Gulf coast, with lower and upper bounds of 0.5 and 1.5 m (LACES, 2012). The California State Lands Commission is preparing for a projected sea-level rise of 1.4 m (55 inches) by 2100 (CSLC, 2009). Southeast Florida is projecting a 9 to 24 inch rise by 2060 (SEFRCCC, 2011). Further, the U.S. Army Corps of Engineers requires that potential sea level rise changes must be considered in all USACE coastal activities (USACE, 2011). These states and organizations are concerned with the implications of a rising sea level, even if the magnitude of the rise is uncertain.

This document is intended to clarify the questions asked about the Science Panel’s first SLR Assessment Report. Based on this review, the broad recommendations of the original report stand. As recommended, the next anticipated update is in 2015.
References


Additional Bibliography on Sea Level Rise:


Other Assessment Reports:

http://www.floridaoceanscouncil.org/reports/Climate_Change_and_Sea_Level_Rise.pdf

http://www.seclimate.org/pdfpubs/201108mitchum_sealevel.pdf


http://www.lacpra.org/assets/docs/LACES/LACEStech02_06_12.pdf

http://epa.gov/climatechange/effects/coastal/sap4-1.html

http://epa.gov/climatechange/effects/coastal/pdfs/SAP_4-1_SynthesisandAssessmentProduct.pdf

Significant links:

http://sealevel.colorado.edu/

http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/

http://climate.nasa.gov/keyIndicators/index.cfm#seaLevel

http://rads.tudelft.nl/rads/rads.shtml

http://www.aviso.oceanobs.com/


http://grace.jpl.nasa.gov/

http://www.psmsl.org/

http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/LSA_SLR_timeseries_global.php

http://tidesandcurrents.noaa.gov/sltrends/index.shtml

Errata:

1. The acceleration reported for Church and White 2006 in Table 2 was erroneously reported as 0.13 mm/yr². The correct acceleration is 0.013 mm/yr².
2. Corrected a formatting error in the References section for Holgate et al. 2007.