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 CO2 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 CO2 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 CO2 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.

# # #

Frank Gorham, Chair NCDENR CRC
Margery Overton, Chair NCDENR CRC Science Panel

April 29, 2015

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).

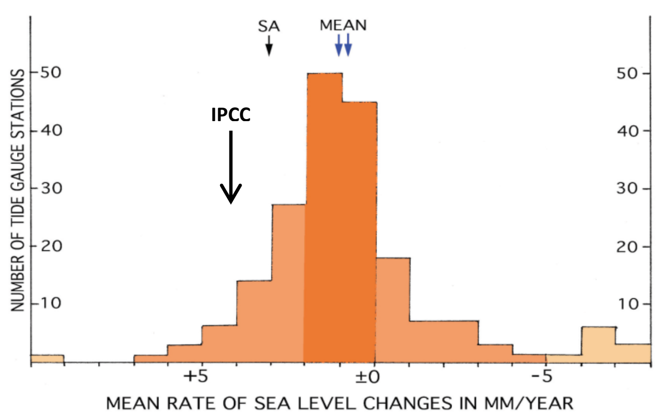

Figure 1. SLR rate distribution of 204 world wild tide gauges used by NOAA
[*Morner,N. 2013,Energy & Environment, 24,509-536*.]

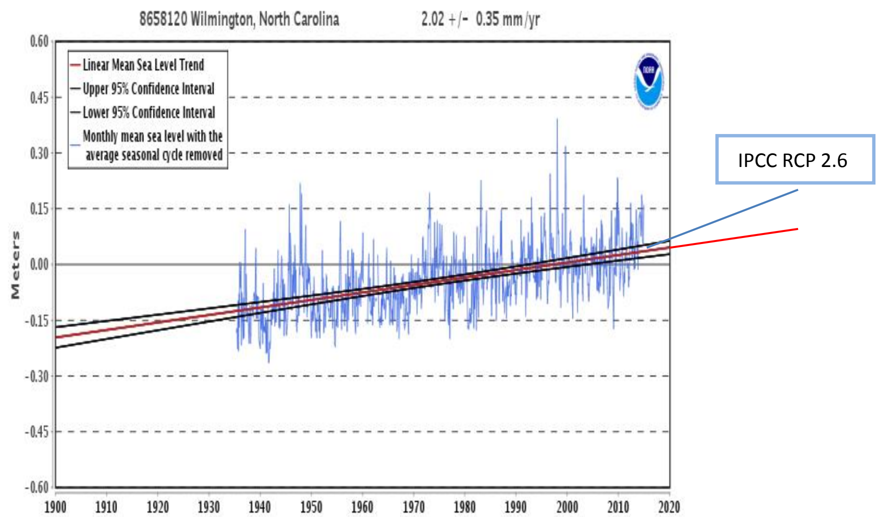

Figure 2. Wilmington tide gauge (NOAA)

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)

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

From: Mike Hayes <mhayes@pinn.net>
To: Miller, Tancred <tancred.miller@ncdenr.gov>
Sent: Sat 4/11/2015 7:37 AM

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.

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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.

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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:”

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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.

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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!

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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

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.

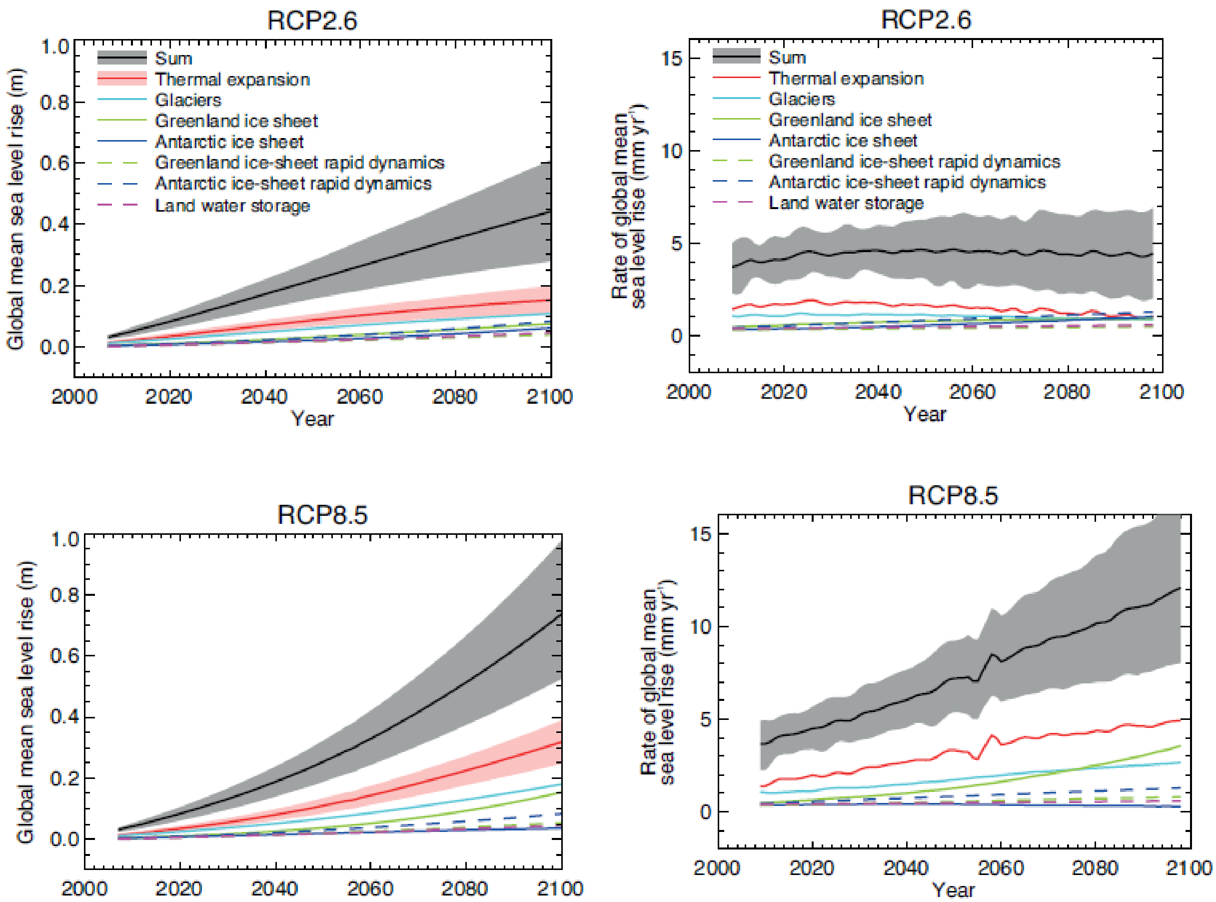


Figure 13.11 | Projections from process-based models of (a) global mean sea level (GMSL) rise relative to 1986–2005 and (b) the rate of GMSL rise and its contributions as a function of time for the four RCP scenarios and scenario SRES A1B. The lines show the median projections. For GMSL rise and the 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.

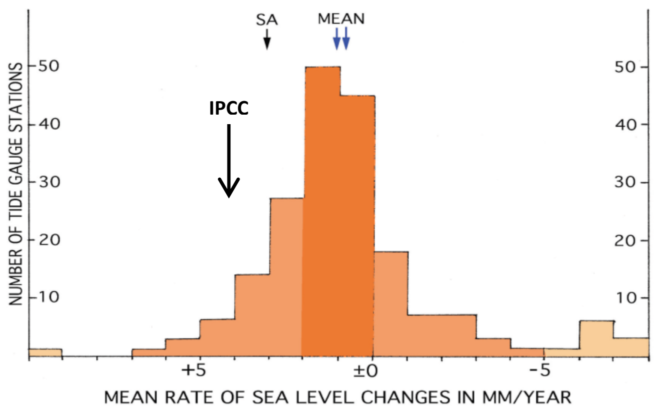
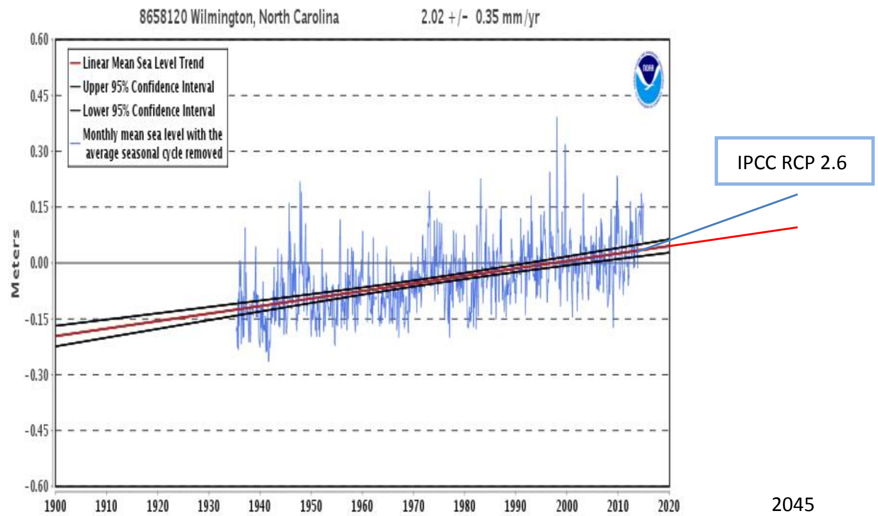


Figure 1. SLR rate distribution of 204 world wild tide gauges used by NOAA
[*Morner,N. 2013,Energy & Environment, 24,509-536*.]

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."

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

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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

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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 $\sim 0.2 \pm 0.2$ mm/yr (e.g., Marple and Talwani, 2004; van de Plassche et al, 2014).

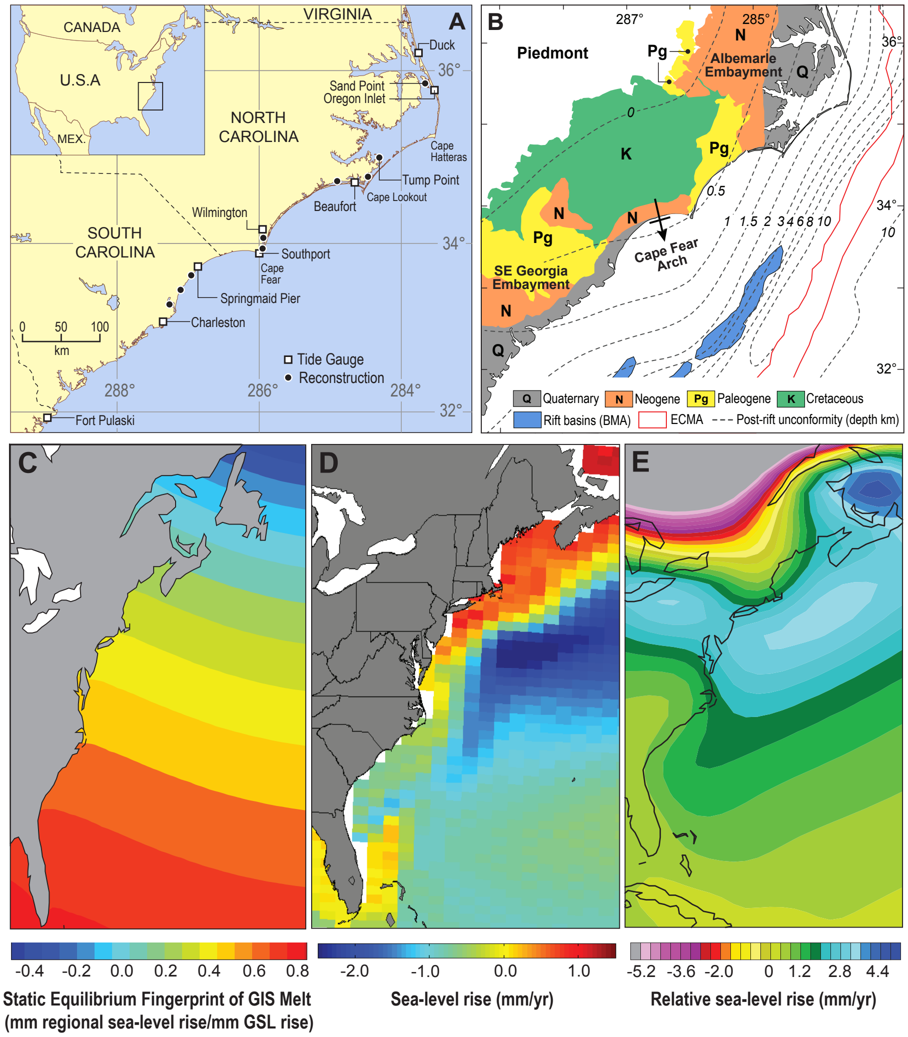

Fig. 1 (A) Location map. (B) Map of regional shallow subsurface geology, post-rift unconformity, and large-scale structural geology (Dillon and P., 1988; Gohn, 1988; Grow and Sheridan, 1988; North Carolina Geological Survey, 2004). (C) Static-equilibrium fingerprint of RSL change from uniform melting 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 include 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 instrumental 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 $\pm$ 1 to $\pm$ 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

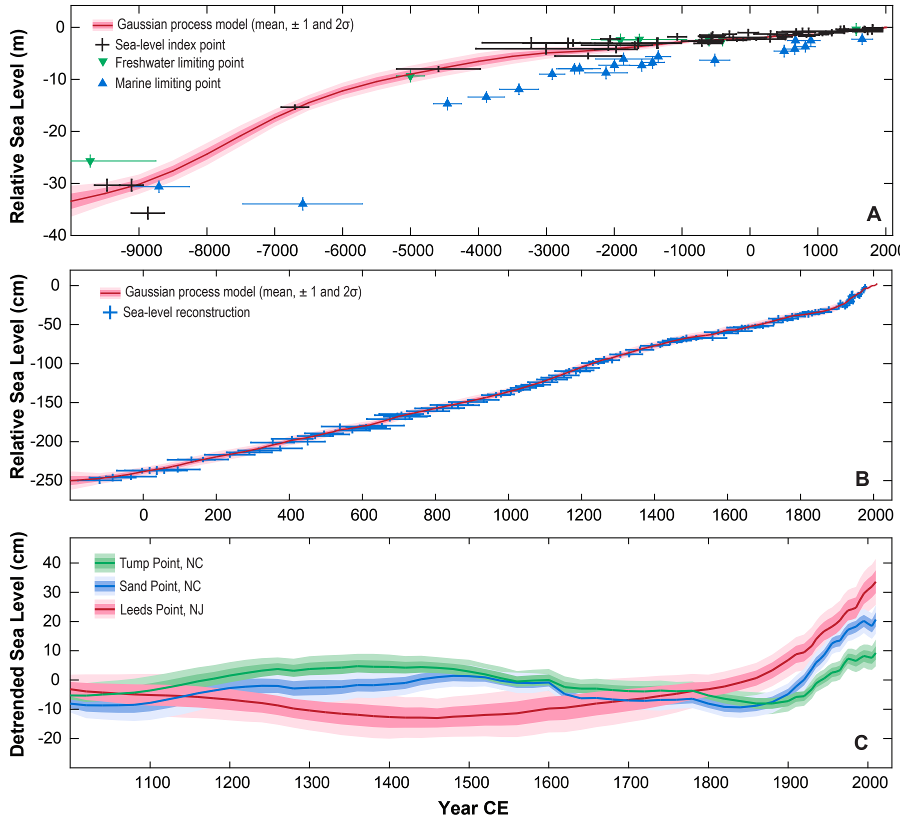

Fig. 2 (a) Holocene RSL in North Carolina, showing a representative GP estimate for central North Carolina (*red*), as well all index points (*crosses*), marine limiting points (*blue upward triangles*), and freshwater limiting points (*green downward triangles*) from North Carolina. Index/limiting points 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.

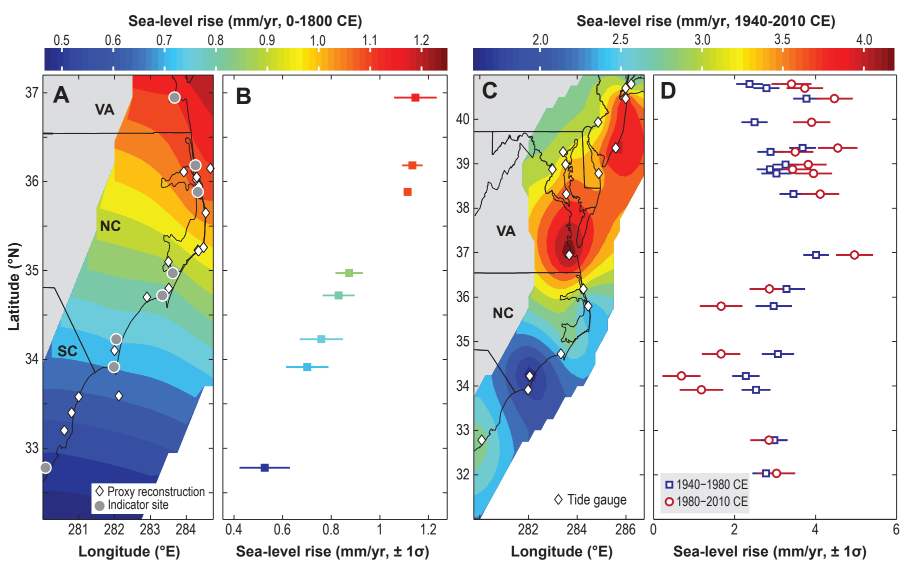

Fig. 3 (a) Pre-Industrial Common Era rate of RSL rise (0-1800 CE; mm/yr). Diamonds: proxy sites; grey circles: selected tide gauges and continuous proxy records (as in Tables S-1 and S-2). Uncolored areas have 1σ uncertainty >0.15 mm/yr. (b) shows estimates at indicated tide-gauge and continuous proxy 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.

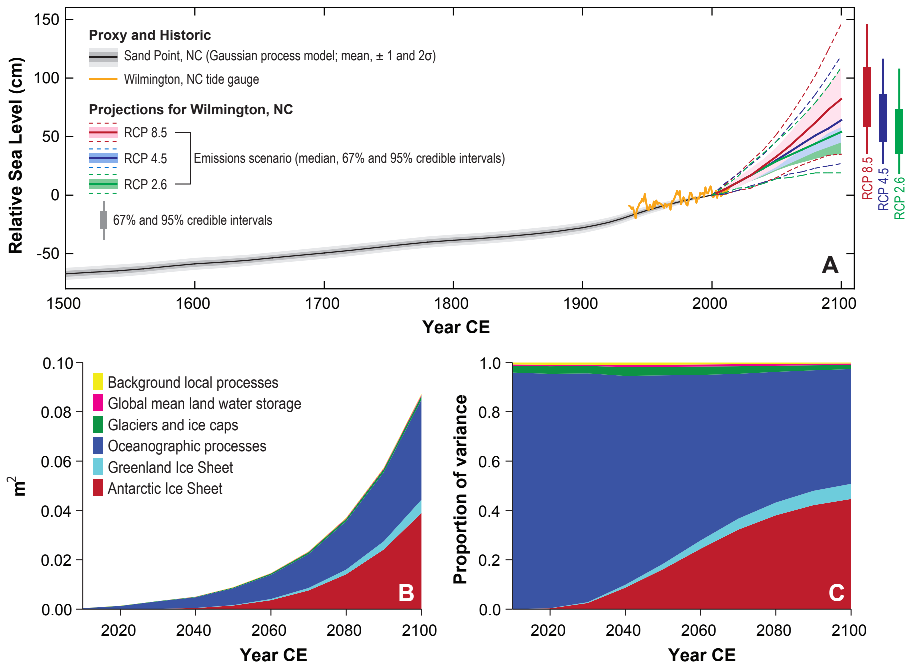

Fig. 4 (a) GP estimate of sea-level at Sand Point (*black*), annual Wilmington tide-gauge data (*orange*), and Kopp et al (2014) projections for RCP 8.5 (*red*), 4.5 (*blue*), and 2.6 (*green*). Shading/dashed lines = 67%/95% credible intervals. Bars and whiskers represent 67% and 95% credible intervals 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 $<\sim$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 contribution 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 $\sim$1.5x by 2050 and $\sim$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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References

Bamber JL, Aspinall WP (2013) An expert judgement assessment of future sea level rise from the ice sheets. Nature Climate Change 3:424–427, doi:10.1038/nclimate1778

Boon JD (2012) Evidence of sea level acceleration at US and Canadian tide stations, Atlantic Coast, North America. Journal of Coastal Research 28(6):1437–1445, doi:10.2112/JCOASTRES-D-12-00102.1

Brain M, Kemp A, Horton B, et al (2015) Quantifying the contribution of sediment compaction to late Holocene salt-marsh sea-level reconstructions (North Carolina, USA). Quaternary Research 83:41–51, doi:10.1016/j.yqres.2014.08.003

Brown LD (1978) Recent vertical crustal movement along the east coast of the united states. Tectonophysics 44(1):205–231

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

Church JA, Clark PU, et al (2013) Chapter 13: Sea level change. In: Stocker TF, Qin D, Plattner GK, et al (eds) Climate Change 2013: the Physical Science Basis, Cambridge University Press

Clark JA, Lingle CS (1977) Future sea-level changes due to West Antarctic ice sheet fluctuations. Nature 269:206–209, doi:10.1038/269206a0

Clark JA, Farrell WE, Peltier WR (1978) Global changes in postglacial sea level: a numerical calculation. Quaternary Research 9(3):265–287

Clark PU, Dyke AS, Shakun JD, et al (2009) The Last Glacial Maximum. Science 325(5941):710–714, doi:10.1126/science.1172873

Collins M, Knutti R, et al (2013) Chapter 12: Long-term climate change: Projections, commitments and irreversibility. In: Stocker TF, Qin D, Plattner GK, et al (eds) Climate Change 2013: the Physical Science Basis, Cambridge University Press

Dillon W, P P (1988) The Blake Plateau Basin and Carolina Trough. In: In: Sheridan RE, Grow JA (eds) The Atlantic Continental Margin: U.S. Geological Society of America, Boulder, CO

Emanuel KA (2013) Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. Proceedings of the National Academy of Sciences 110(30):12,219–12,224, doi:10.1073/pnas.1301293110

Engelhart SE, Horton BP (2012) Holocene sea level database for the Atlantic coast of the United States. Quaternary Science Reviews 54(0):12–25, doi:10.1016/j.quascirev.2011.09.013

Engelhart SE, Horton BP, Douglas BC, Peltier WR, Törnqvist TE (2009) Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic coast of the United States. Geology 37(12):1115–1118, doi:10.1130/G30360A.1

Engelhart SE, Peltier WR, Horton BP (2011) Holocene relative sea-level changes and glacial isostatic adjustment of the U.S. Atlantic coast. Geology 39(8):751–754, doi:10.1130/G31857.1

Ezer T, Atkinson LP (2014) Accelerated flooding along the U.S. East Coast: On the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. Earth's Future 2:362–382, doi:10.1002/2014EF000252

Ezer T, Corlett WB (2012) Is sea level rise accelerating in the Chesapeake Bay? A demonstration of a novel new approach for analyzing sea level data. Geophysical Research Letters 39:L19,605, doi:10.1029/2012GL053435

Ezer T, Atkinson LP, Corlett WB, Blanco JL (2013) Gulf Stream's induced sea level rise and variability along the US mid-Atlantic coast. Journal of Geophysical Research 118:685–697, doi:10.1002/jgrc.20091

Farrell WE, Clark JA (1976) On postglacial sea level. Geophysical Journal of the Royal Astronomical Society 46(3):647–667, doi:10.1111/j.1365-246X.1976.tb01252.x

Foyle AM, Oertel GF (1997) Transgressive systems tract development and incised-valley fills within a Quaternary estuary-shelf system: Virginia inner shelf, USA. Marine Geology 137(3):227–249, doi:10.1016/S0025-3227(96)00092-8

Gohn GS (1988) Late Mesozoic and early Cenozoic geology of the Atlantic Coastal Plain: North Carolina to Florida. In: Sheridan RE, Grow JA (eds) The Atlantic Continental Margin: U.S. Geological Society of America, Boulder, CO

Gregory JM (2010) Long-term effect of volcanic forcing on ocean heat content. Geophysical Research Letters 37(22):L22,701, doi:10.1029/2010GL045507

Grow J, Sheridan RE (1988) U.S. Atlantic Continental Margin: a typical Atlantic-type or passive continental margin. In: Sheridan RE, Grow JA (eds) The Atlantic Continental Margin: U.S. Geological Society of America, Boulder, CO

Hay CC, Morrow ED, Kopp RE, Mitrovica JX (2015) Probabilistic reanalysis of 20th century sea-level rise. Nature 517:481–484, doi:10.1038/nature14093

Horton BP, Peltier WR, Culver SJ, et al (2009) Holocene sea-level changes along the North Carolina Coastline and their implications for glacial isostatic adjustment models. Quaternary Science Reviews 28(17):1725–1736, doi:10.1016/j.quascirev.2009.02.002

Horton BP, Rahmstorf S, Engelhart SE, Kemp AC (2014) Expert assessment of sea-level rise by AD 2100 and AD 2300. Quaternary Science Reviews 84:1–6, doi:10.1016/j.quascirev.2013.11.002

Houser T, Hsiang S, Kopp R, Larsen K (2015) Economic Risks of Climate Change: An American Prospectus. Columbia University Press, New York

Kemp AC, Horton BP, Donnelly JP, et al (2011) Climate related sea-level variations over the past two millennia. Proceedings of the National Academy of Sciences 108(27):11,017–11,022, doi:10.1073/pnas.1015619108

Kemp AC, Horton BP, Vane CH, et al (2013) Sea-level change during the last 2500 years in New Jersey, USA. Quaternary Science Reviews 81:90–104, doi:10.1016/j.quascirev.2013.09.024

Kemp AC, Bernhardt CE, Horton BP, et al (2014) Late Holocene sea- and land-level change on the U.S. southeastern Atlantic coast. Marine Geology 357:90–100, doi:10.1016/j.margeo.2014.07.010

Kienert H, Rahmstorf S (2012) On the relation between Meridional Overturning Circulation and sea-level gradients in the Atlantic. Earth Syst Dynam 3(2):109–120, doi:10.5194/esd-3-109-2012

Konikow LF (2011) Contribution of global groundwater depletion since 1900 to sea-level rise. Geophysical Research Letters 38:L17,401, doi:10.1029/2011GL048604

Kopp RE (2013) Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability? Geophysical Research Letters 40:3981–3985, doi:10.1002/grl.50781

Kopp RE, Mitrovica JX, Griffies SM, et al (2010) The impact of Greenland melt on local sea levels: a partially coupled analysis of dynamic and static equilibrium effects in idealized water-hosing experiments. Climatic Change 103:619–625, doi:10.1007/s10584-010-9935-1

Kopp RE, Horton RM, Little CM, et al (2014) Probabilistic 21st and 22nd century sea-level projections at a global network of tide gauge sites. Earth's Future 2:383–406, doi:10.1002/2014EF000239

Kopp RE, Hay CC, Little CM, Mitrovica JX (2015) Geographic variability of sea-level change. Current Climate Change Reports, doi:10.1007/s40641-015-0015-5

Lautier J (2006) Hydrogeologic framework and ground water conditions in the North Carolina Southern Coastal Plain. North Carolina Department of Environment, Health, and Natural Resources, Division of Water Resources

Marple R, Talwani P (2004) Proposed Shenandoah fault and East-Coast Stafford fault system and their implications for Eastern US tectonics. Southeastern Geology 43(2):57–80

Marzeion B, Jarosch AH, Hofer M (2012) Past and future sea-level change from the surface mass balance of glaciers. The Cryosphere 6:1295–1322, doi:10.5194/tc-6-1295-2012

McHutchon A, Rasmussen C (2011) Gaussian process training with input noise. In: Advances in Neural Information Processing Systems, vol 24, pp 1341–1349

Milne GA, Mitrovica JX (2008) Searching for eustasy in deglacial sea-level histories. Quaternary Science Reviews 27(25–26):2292–2302, doi:10.1016/j.quascirev.2008.08.018

Milne GA, Gehrels WR, Hughes CW, Tamisiea ME (2009) Identifying the causes of sea-level change. Nature Geoscience 2(7):471–478, doi:10.1038/ngeo544

Mitrovica JX, Gomez N, Clark PU (2009) The sea-level fingerprint of West Antarctic collapse. Science 323(5915):753–753, doi:10.1126/science.1166510

Mitrovica JX, Gomez N, Morrow E, et al (2011) On the robustness of predictions of sea level fingerprints. Geophysical Journal International 187(2):729–742, doi:10.1111/j.1365-246X.2011.05090.x

North Carolina Coastal Resources Commission Science Panel on Coastal Hazards (2010) North Carolina Sea-Level Rise Assessment Report

North Carolina General Assembly (2012) House Bill 819 / Session Law 2012-202

North Carolina Geological Survey (2004) Generalized Geologic Map of North Carolina. Digital representation by Medina MA, Reid JC, Carpenter H

Peltier WR (2004) Global glacial isostasy and the surface of the ice-age earth: The ICE-5G (VM2) model and GRACE. Annual Review of Earth and Planetary Sciences 32:111–149, doi:10.1146/annurev.earth.32.082503.144359

Permanent Service for Mean Sea Level (2014) Tide gauge data. URL `http://www.psmsl.org/data/obtaining/`, http://www.psmsl.org/data/obtaining/, accessed 21 January 2014

Poulter B, Feldman RL, Brinson MM, et al (2009) Sea-level rise research and dialogue in North Carolina: Creating windows for policy change. Ocean & Coastal Management 52(3):147–153, doi:10.1016/j.ocecoaman.2008.09.010

Rahmstorf S, Box JE, Feulner G, et al (2015) Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nature Climate Change doi:10.1038/nclimate2554

Rasmussen C, Williams C (2006) Gaussian processes for machine learning. MIT Press, Cambridge, MA

Ray RD, Douglas BC (2011) Experiments in reconstructing twentieth-century sea levels. Progress in Oceanography 91(4):496–515, doi:10.1016/j.pocean.2011.07.021

Rowley DB, Forte AM, Moucha R, et al (2013) Dynamic topography change of the eastern United States since 3 million years ago. Science 340(6140):1560–1563, doi:10.1126/science.1229180

Sallenger AH, Doran KS, Howd PA (2012) Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nature Climate Change 2:884–888, doi:10.1038/nclimate1597

Shennan I, Milne G, Bradley S (2012) Late Holocene vertical land motion and relative sea-level changes: lessons from the British Isles. Journal of Quaternary Science 27(1):64–70, doi:10.1002/jqs.1532

Shepherd A, Ivins ER, Geruo A, et al (2012) A reconciled estimate of ice-sheet mass balance. Science 338(6111):1183–1189, doi:10.1126/science.1228102

Sheridan R (1976) Sedimentary basins of the Atlantic margin of North America. Tectonophysics 36(1):113–132

Stammer D, Cazenave A, Ponte RM, Tamisiea ME (2013) Causes for contemporary regional sea level changes. Annual Review of Marine Science 5(1):21–46, doi:10.1146/annurev-marine-121211-172406

Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society 93(4):485–498, doi:10.1175/BAMS-D-11-00094.1

Tebaldi C, Strauss BH, Zervas CE (2012) Modelling sea level rise impacts on storm surges along US coasts. Environmental Research Letters 7(1):014,032, doi:10.1088/1748-9326/7/1/014032

van de Plassche O, Wright AJ, Horton BP, et al (2014) Estimating tectonic uplift of the Cape Fear Arch (southeast-Atlantic coast, USA) using reconstructions of Holocene relative sea level. Journal of Quaternary Science 29(8):749–759, doi:10.1002/jqs.2746

Van Vuuren DP, Edmonds J, Kainuma M, et al (2011) The representative concentration pathways: an overview. Climatic Change 109:5–31, doi:10.1007/s10584-011-0148-z

Wheeler RL (2006) Quaternary tectonic faulting in the Eastern United States. Engineering geology 82(3):165–186

Yin J, Goddard PB (2013) Oceanic control of sea level rise patterns along the east coast of the United States. Geophysical Research Letters 40:5514–5520, doi:10.1002/2013GL057992

Zervas CE (2004) North Carolina bathymetry/topography sea level rise project: determination of sea level trends. Technical Report NOS CO-OPS 041, National Oceanic and Atmospheric Administration

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.

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

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

$$k_l(\mathbf{x}_1, t_1, \mathbf{x}_2, t_2) = \sigma_l^2 \cdot C_{\frac{3}{2}}(|t_2 - t_1|, \tau_l) \cdot C_{\frac{5}{2}}(r(\mathbf{x}_1, \mathbf{x}_2), \gamma_l) \tag{S-2}$$

$$k_m(\mathbf{x}_1, t_1, \mathbf{x}_2, t_2) = \sigma_m^2 \cdot C_{\frac{3}{2}}(|t_2 - t_1|, \tau_m) \cdot C_{\frac{1}{2}}(r(\mathbf{x}_1, \mathbf{x}_2), \gamma_m) \tag{S-3}$$

$$k_h(\mathbf{x}_1, t_1, \mathbf{x}_2, t_2) = \sigma_h^2 \cdot C_{\frac{3}{2}}(|t_2 - t_1|, \tau_h) \cdot C_{\frac{1}{2}}(r(\mathbf{x}_1, \mathbf{x}_2), \gamma_m) \tag{S-4}$$

(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 $y(\mathbf{x}, t')$ are modeled as

$$y(\mathbf{x}, t') = f(\mathbf{x}, t + \epsilon_t) + w(\mathbf{x}, t') + \epsilon_y + y_0(\mathbf{x}), \tag{S-6}$$

where t' 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

$$k_w(\mathbf{x}_1, t_1, \mathbf{x}_2, t_2) = \sigma_w^2 \delta(t_1, t_2) \delta(\mathbf{x}_1, \mathbf{x}_2) \tag{S-7}$$

$$k_0(\mathbf{x}_1, \mathbf{x}_2) = \sigma_0^2 \delta(\mathbf{x}_1, \mathbf{x}_2), \tag{S-8}$$

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):

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

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 $\mathcal{L}(\mathbf{\Theta}|\mathbf{y}_1)$, 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 $\mathcal{L}(\mathbf{\Theta}|\mathbf{y}_2)$, where $\mathbf{y}_2$ is the complete data set . Finally, all the hyperparameters are locally optimized to maximize the marginal likelihood $\mathcal{L}(\mathbf{\Theta}|\mathbf{y}_2)$. 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 $\tau_l = 14.5$ kyr, $\tau_m = 296$ years and $\tau_h = 6.3$ 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

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

where α_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 $y_j(t)$.

References

Hay CC, Morrow ED, Kopp RE, Mitrovica JX (2015) Probabilistic reanalysis of 20th century sea-level rise. Nature 517:481–484, doi:10.1038/nature14093

McHutchon A, Rasmussen C (2011) Gaussian process training with input noise. In: Advances in Neural Information Processing Systems, vol 24, pp 1341–1349

Rasmussen C, Williams C (2006) Gaussian processes for machine learning. MIT Press, Cambridge, MA

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	32.8	-79.9	0.53 ± 0.21	0.6 ± 0.6	0.4 ± 0.7	1.1 ± 1.1	2.9 ± 0.5
Fort 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	32.8	-79.9	1.7 ± 1.5	2.8 ± 1.1	3.0 ± 0.7	2.9 ± 0.9
Fort 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

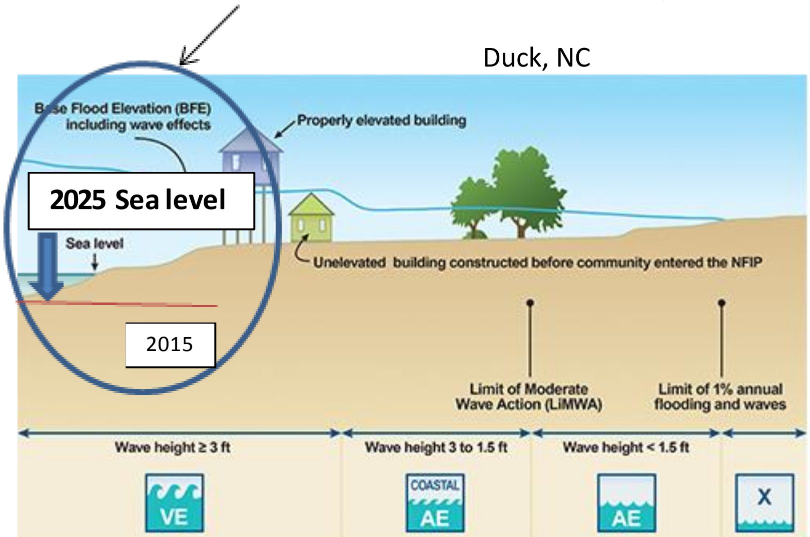
Oc: Oceanographic. GrIS: Greenland ice sheet. AIS: Antarctic ice sheet.
GIC: Glaciers and ice caps. LWS: Land water storage. Bkgd: Background.
All values are cm above 1990–2010 CE baseline. Columns correspond to probability ranges.

Table S-6 Optimized hyperparameters

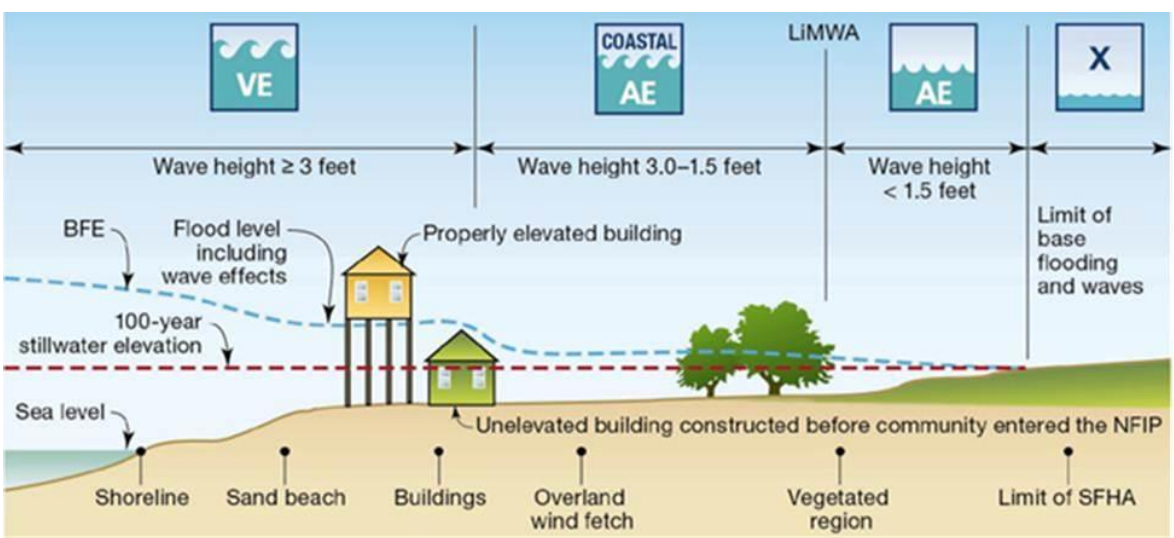
Low frequency			
amplitude	σ_l	19.1	m
time scale	τ_l	14.5	kyr
length scale	γ_l	25.0	degrees
Medium frequency			
amplitude	σ_m	119	mm
time scale	τ_m	296	yr
length scale	γ_m	3.0	degrees
High frequency			
amplitude	σ_h	13.7	mm
time scale	τ_h	6.3	y
length scale	γ_m	3.0	degrees
White noise	σ_w	4.2	mm
Datum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

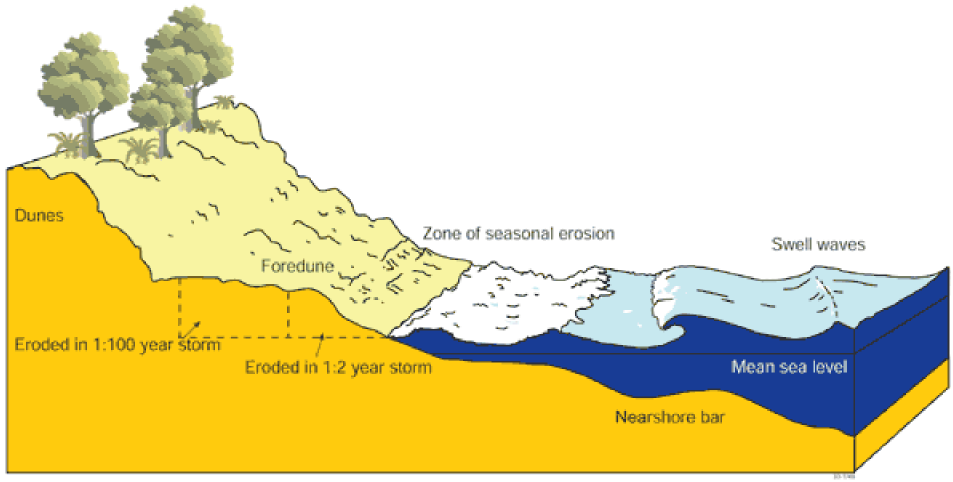
Sea-Level Rise Study Update – Comment
From: Perry, Neil L <nlperry@ncdot.gov>
To: Miller, Tancred <tancred.miller@ncdenr.gov>
Sent: Mon 4/6/2015 4:18 PM

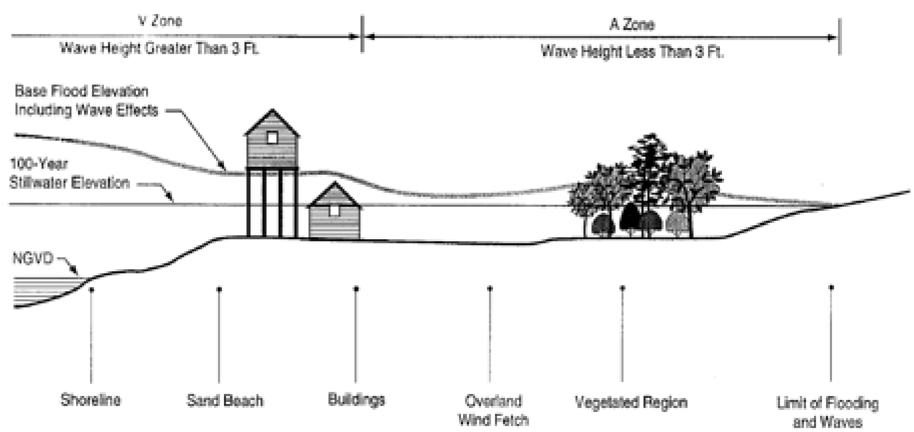
I've read through the updated report and wanted to provide a general comment.
You are **NOT** telling your story in a manner that the general public and general assembly will understand.
The most important information that you are trying to get across needs to be disseminated pictorially. See below.
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.

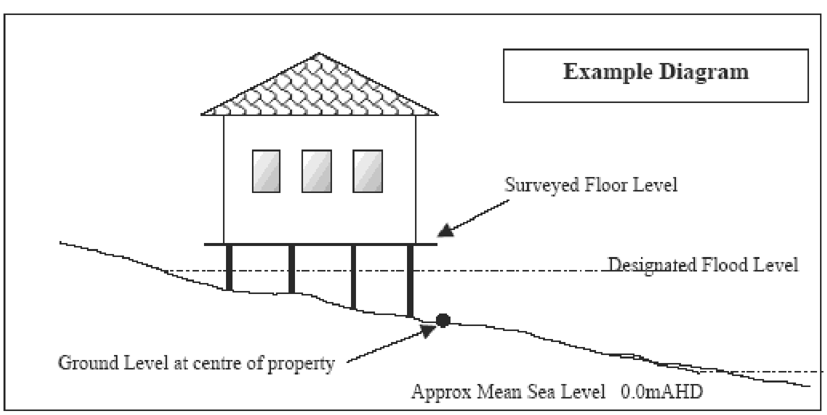


Or use one of the diagrams below or create your own. Point is you HAVE to tell this story pictorially or much of your work will be misunderstood.









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

greetings

From: Mike Hayes <mhayes@pinn.net>
To: Miller, Tancred <tancred.miller@ncdenr.gov>
Sent: Fri 4/10/2015 9:46 PM

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 CO_2. If you are interested I can show you that less CO_2 leaves North America into the Atlantic than comes off the Pacific into North America. Read the previous sentence carefully! Geeze the CO_2 disappeares

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

NC Sea Level Rise Report Is Biased High

From: Michael OBrian <michael_obrian@msn.com>
To: Miller, Tancred <tancred.miller@ncdenr.gov>
Sent: Wed 4/8/2015 5:36 PM

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

Unsolicited Public Comment on the Draft NCDENR Sea-Level Rise Study Update

From: George Mears <ghmears@gmail.com>
To: Miller, Tancred <tancred.miller@ncdenr.gov>
Sent: Mon 4/13/2015 3:22 PM

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.

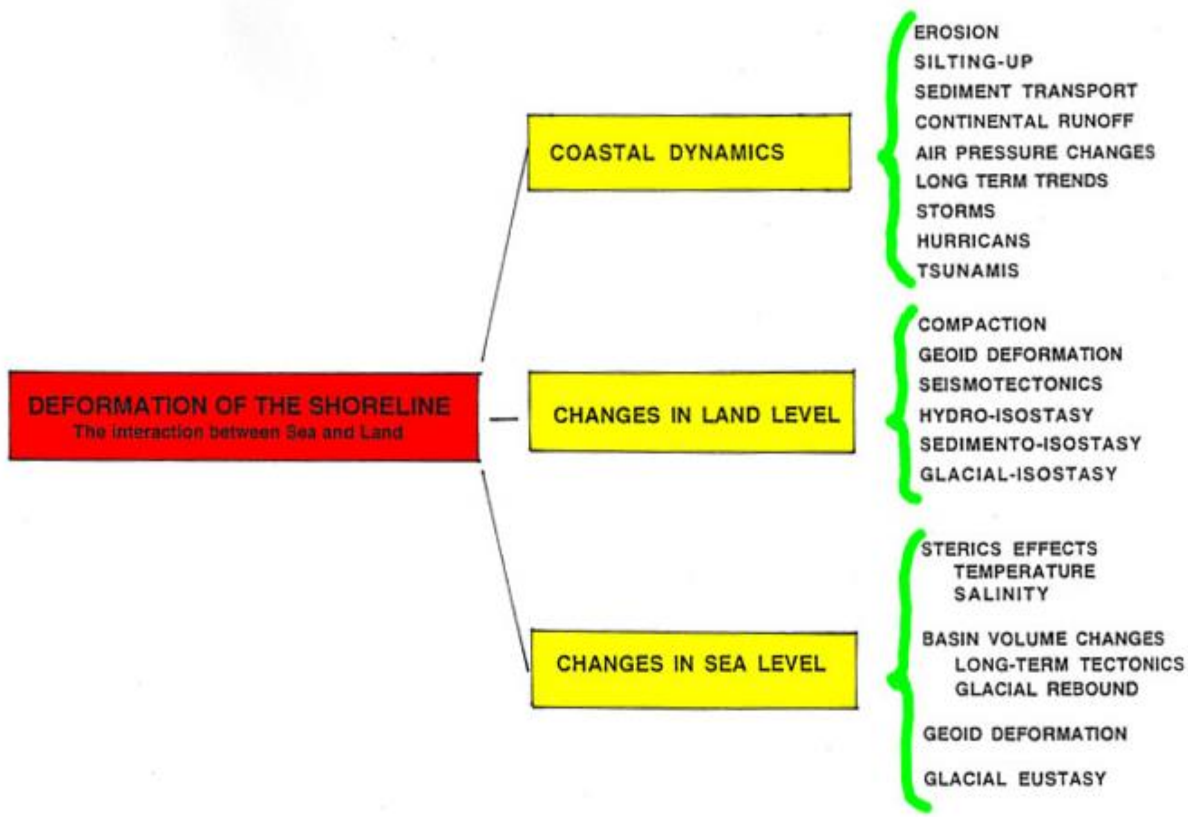
Before becoming an engineer I had over 5,800 flight hours that included several years of flying scientific research missions with John Hopkins, Scripps and Woods Hole, Naval Oceanographic Office scientists studying extreme north and south latitude ice reconnaissance, deep ocean eddy current data collection, 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

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.

Sea Level Rise, etc.

From: Clyde Hunt, Jr <chuntjr@chemstation.net>
To: Miller, Tancred tancred.miller@ncdenr.gov; mike@thenewstimes.com; willokelly@gmail.com; 'Gail Grady' <gail@nc-20.com>
Sent: Thu 6/4/2015 11:09 AM

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.