On the impact of the AMOC on sea level rise: new evidence that a slowdown of the Gulf Stream is responsible for accelerating sea level rise along the U.S. mid-Atlantic coast

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* “Norfolk has been ranked second only to New Orleans among U.S. coastal cities threatened by flooding”
Floods in Norfolk, Virginia

Minor flood: high tide (~4ft; 8-25-2012)

Major flood: Hurricane Sandy (~7ft; 10-29-2012)

Storm surge+tide prediction underestimated water level by 1 foot! Why?
Top storm surges in Norfolk, VA

- 1-Chesapeake Potomac Hurricane
- 2-Hurricane Isabel
- 3-Veterans Day Nor-easter
- 4-Hurricane Irene
- 5-Ash Wednesday Storm
- 6-Hurricane Sandy
- 7-Hurricane of 1936
- 8-Thanksgiving Nor-easter
- 9-Twin Nor-easter #2
- 10-Columbus Day Nor-easter
- 11-Nor-easter of 1978
- 12-Nor-easter of 1956
- 13-2nd Hurricane of 1933
- 14-Twin Nor-easter #1
- 15-Hurricane Floyd
- 16-Hurricane Flossy
- 17-Hurricane Donna

Graph showing storm surges with MHHW and MLLW marks.

SLR = 1.5 ft/century
- What causes this dramatic increase in flooding?
- If sea level is rising at a linear rate (~4.5 mm/y) why is the response so non-linear?
Mean SLR in Norfolk is \(~50\%\) higher than global SLR from altimeter data and \(~200\%\) higher than global SLR from tide gauge data. Until recently, land subsidence was blamed for the high local SLR (Boon et al. 2010). But this may be only part of the story...
• Why is local SLR along the US East coast different than global SLR?
• Is linear SLR rates accurately represent the underlying dynamics?
Global vs. Local Sea Level Rise:

Local (relative) SLR = 

Global SLR ± Land Subsidence/Uplift ± Ocean Dynamics

thermal expansion
melting ice sheets & glaciers
volume change
Three separate studies published within months in 2012 all indicate a “hotspot of accelerated SLR” in the mid-Atlantic coast.

Hotspot of accelerated sea-level rise on the Atlantic coast of North America

Asbury H. Sallenger Jr*, Kara S. Doran and Peter A. Howd

Evidence of Sea Level Acceleration at U.S. and Canadian Tide Stations, Atlantic Coast, North America

John D. Boon


Is sea level rise accelerating in the Chesapeake Bay? A demonstration of a novel new approach for analyzing sea level data

Tal Ezer¹ and William Bryce Corlett¹,²

Empirical Mode Decomposition Hilbert-Huang Transformation, EMD/HHT [Huang et al., 1998]
Decadal & multi-decadal cycles are separated from the trend

Example of EMD analysis for Baltimore: separating the SL record into oscillating modes and a trend

\[ \eta(t) = \sum_{i=1}^{N} c_i(t) + r(t) \]
Projections based on EMD analysis + bootstrap simulations (take into account only local statistics of the data)

Projections based on the National Climate Assessment (NRC-1, NRC-2, NRC-3 (USACE 2011))
Mean Sea Level Rise Rates (from linear regression)

linear local land subsidence +
linear global SLR

North of Cape Hatteras

South of Cape Hatteras
Sea Level Rise Acceleration (from EMD analysis) eliminates the long-term geological land movement and oceanic multi-decadal variations.
Why is SLR accelerating north of CH? Does the Gulf Stream play a role? We proposed that weakening Gulf Stream is contributing to sea level rise.
The fascination of the public with possible Gulf Stream slowdown is partly due to science fiction movies …. but,

- does the Gulf Stream really slowing down?
- and if so, what are the impacts?
Why would the AMOC affect coastal sea level rise?

- North Slope Current
- Gulf Stream
- Gulf Stream East
- Cooling
- Cold & Dense Arctic Waters
- Sink into the deep North Atlantic
- AMOC
- U.S. East Coast
- Deep Gulf stream
- North Atlantic Deep Water

Approximately 1 meter.
Warmer Climate Scenario

- Weaker Gulf Stream
- Warmer temperatures and melting ice result in less dense water and less sinking
- Rising sea level
- North Atlantic Deep Water
- Warmer Climate Scenario ~1m
- East Up
- U.S. East Coast
- Subtropical Gyre
- Subpolar Gyre
- AMOC

Floods
• NAO
• wind
  • meso-scale
  • seasonal
• Rossby waves
• other forcing...

AMOC

Gulf Stream

Coastal Sea Level

Is there evidence?

• Numerical Models
• Observations

Model results:
- changes in the Gulf Stream transport
  → changes in the sea level across Gulf Stream
  → changes in coastal sea level

Decadal var. in sea level:
- ~10-15 cm north of Cape Hatteras
- ~2-5 cm south of Cape Hatteras

Model experiment: warmer surface temperature in high latitude

Results: 2-3 times larger sea level rise along the western Atlantic (US east coast) than along the eastern Atlantic (European coast)

Why? ocean circulation changes in warmer climate
Model projections of rapid sea-level rise on the northeast coast of the United States

Yin et al. (2009)

Dynamic Sea Level Rise

Projected SLR anomalies from 2000 to 2100
Gulf Stream – Florida Current Correlations

Monthly data: $R=0.13$ (95%)
Low-freq. modes: $R=0.72$ (99.9%)

Is the Gulf Stream getting weaker?
There is evidence that in recent years the Gulf Stream is weakening and potentially shifting offshore.

Change of 12 cm over 10 years \(\rightarrow\) (Six times the global sea level rise!)
EMD/HHT Analysis (last 3-modes):
All sea level records show similar patterns
All sea level records are highly correlated with the Gulf Stream strength.
SLR rates of last decade & GS variability

Sea Level Rise (2002-2011) vs. Correlation with Gulf Stream

Chesapeake Bay stations

- Annapolis
- Solomon Is
- Sewells Pt
- Atlantic Ct

Mid-Atlantic stations

- Lewes
- Kiptopeke
- CBBT
- Duck

GS-SL \leftrightarrow \text{Corr.}
Gulf Stream influence on decadal variability in sea level (note: Bermuda SL in opposite phase to US East coast)

Large FC transport → Large diff Bermuda-US coast → lower coastal sea level
Conclusions

• Variations in coastal sea level records in the Mid-Atlantic region were found to be highly correlated with variations in the Gulf Stream on time scales ranging from a few months to decades.

• There is evidence that weakening of the Gulf Stream since ~2004 may be the cause of recent sea level rise acceleration in the region.

• The proposed mechanism:
  Climate warming and freshening of surface waters in polar regions → slow-down of Atlantic Meridional Overturning Circulation (AMOC) → decrease Florida Current and Gulf Stream transports → decrease surface gradients across the Gulf Stream → increase coastal sea level along the Mid-Atlantic region.

Practical implication: SLR projections must take into account climatic changes in ocean dynamics.
Sea Level Rise Projections for Maryland

Sea level along Maryland’s shorelines could rise 2 feet by 2050

A new report on sea level rise recommends that the State of Maryland should plan for a rise in sea level of as much as 2 feet by 2050. Led by the University of Maryland Center for Environmental Science, the report was prepared by a panel of scientific experts in response to Governor Martin O’Malley’s Executive Order on Climate Change and “Coast Smart” Construction. The projections are based on an assessment of the latest climate change science and federal guidelines.

A slowing Gulf Stream: The working group described several other factors that explain why Maryland can expect its coastal sea level to rise by more than the global average. One is a slowing in the flow of the Gulf Stream current, which travels north from Florida along the East Coast and then east across the Atlantic Ocean. Scientists have collected evidence that indicates a decline in the current’s speed since 2004.
Thank You

Norfolk flooding during Hurricane Sandy, Oct. 2012