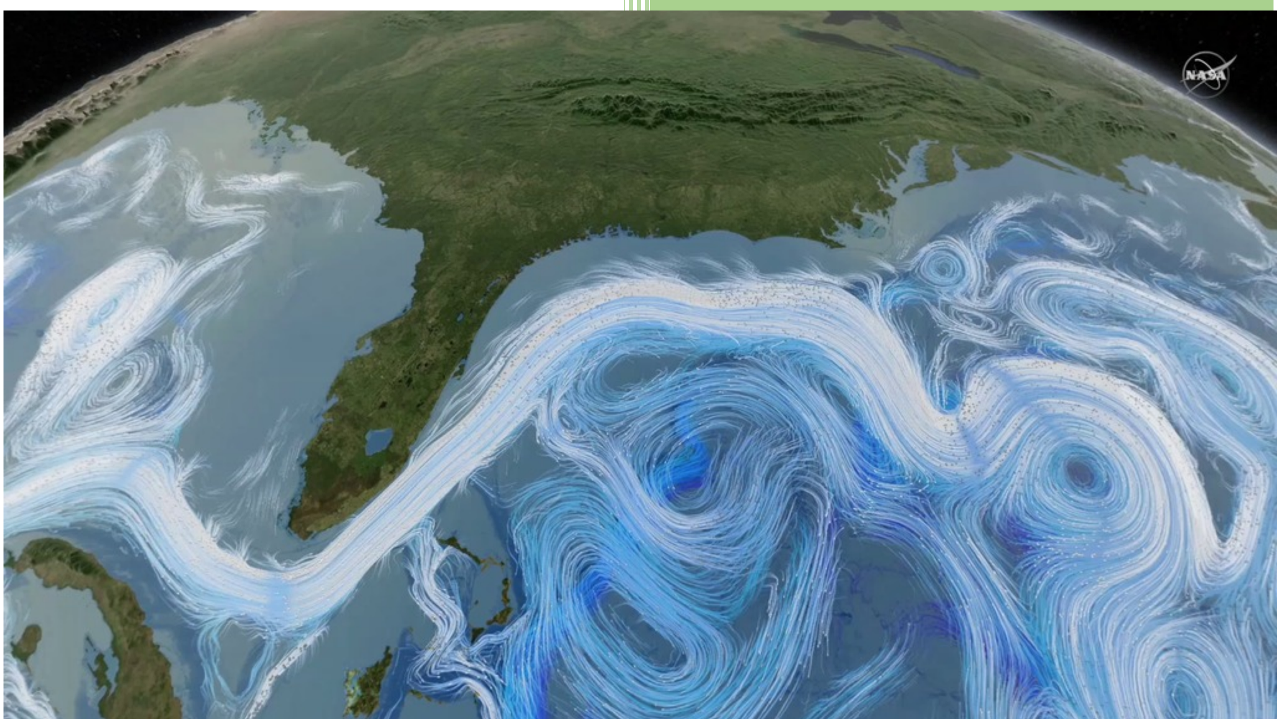
May 2017

Effects of Gulf Stream Variations on Sea Levels along the Eastern Coast



FAU
FLORIDA CENTER FOR
ENVIRONMENTAL STUDIES
Charles E. Schmidt College of Science
Florida Atlantic University

Workshop Summary Document

Florida Center for Environmental Studies

FLORDA ATLANTIC UNIVERSITY

5/9/2017

Florida Atlantic University's Center for Environmental Studies presents

Effects of Gulf Stream Variations on Sea Levels along the Eastern Coast

Venue: B-1 Auditorium, South Florida Water Management District
3301 Gun Club Road, West Palm Beach, Florida 33406
May 9, 2017

Workshop Summary Draft

On May 9, 2017, Florida Atlantic University's Center for Environmental Studies convened a one-day workshop, *Effects of Gulf Stream Variations on Sea Levels along the Eastern Coast* in the B-1 Auditorium of the South Florida Water Management District.

Attendees (list of abbreviations follows):

Len Berry (FAU)	Santee Lee (AOML)	Serena Hoermann (FAU CES)
Ricardo Domingues (AOML)	Francisco Calderon (MB)	Jenifer Barnes (SFWMD)
David Enfield (NOAA)	Ben Kirtman (UM)	Tibebe Dessalegne (SFWMD)
Michael Rittenhouse (WPB)	Tal Ezer (ODU)	Joel VanArman (SFWMD)
Mike Sukup (FIU)	Lauren Thead (WPB)	Jayantha Obeysekera (SFWMD)
Angela Montoya (DERM)	Anton Post (FAU HBOI)	
Albert Lee (BC)		

Phone-In Participants:

Will Beach (USACE)	Glenn Landers (USACE)	Larry Atkinson (ODU)
William Sweet (NOAA)	Keren Bolter (SFRPC)	

After a warm welcome to participants in the room and those attending via live streaming, **Dr. Leonard Berry, Emeritus Professor of Geosciences at Florida Atlantic University**, identified the workshop's objectives: to 1) share what we know and 2) identify what information is missing and how best to fill these gaps. The end product of this workshop will be a summary paper and guidelines for future action.

Dr. Jayantha Obeysekera (South Florida Water Management District – SFWMD) set the stage for discussion by stressing **the importance of even small sea level changes on water control structures.** SFWMD collects water level data from their control structures, which gives greater detail than the widespread tide gauges. Control structure data collected since 1985 shows an uptick in 2010 with changes in the Gulf Stream, although not in 2005. After 2012, the mean monthly water levels have increased regionally, and interior ground water levels measured by the US Geological Survey have also increased. Sea level rise, water table rise and storm surge are a triple threat in raising water levels.

Discussion: Where do SFWMD responsibilities end and local governments begin? The primary (major) drainage canals and structure are managed, operated and maintained by the SFWMD *to provide flood control, water quality, water supply and environmental resource protection. Secondary drainage networks are managed by local drainage districts, local governments or counties. The tertiary drainage features serve local neighborhoods and are managed by private interests. All three networks work together during storm events or droughts to optimize performance.*

ABBREVIATIONS

ADCIRC	ADvanced CIRCulation model (used for predicting storm surge and flooding)
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Ocean Current
AOML	Atlantic Oceanographic and Meteorological Laboratory
BC	Broward County
CES	FAU's Florida Center for Environmental Studies
CESM	Community Earth Systems Model
CMIP5	Coupled Model Inter-Comparison Project Phase 5
DERM	Miami-Dade County Department of Environmental Resource Management
EMIC	Earth Systems Models of Intermediate Complexity
ENSO	*el nino* southern oscillation
FAU	Florida Atlantic University
FEMA	Federal Emergency Management Agency
FIU	Florida International University
GRACE	Gravity Recovery and Climate Experiment (measurements of earth mass variability)
HBOI	FAU's Harbor Branch Oceanographic Institute
HRC model	High resolution current
IPCC	Intergovernmental Panel on Climate Change
LRC model	Low resolution current
MB	City of Miami Beach
NOAA	National Oceanographic and Atmospheric Administration
ODU	Old Dominion University
RCP	Representative Concentration Pathways (future greenhouse gas level scenarios)
RSMAS	University of Miami, Rosensteil School of Marine and Atmospheric Sciences
SFRPC	South Florida Regional Planning Council
SFWMD	South Florida Water Management District
Sv	Sverdrup (a unit of flow)
UM	University of Miami
USACE	United States Army Corps of Engineers
WPB	City of West Palm Beach

PRESENTATIONS

In a series of 20-minute presentations followed by discussion, researchers shared information on the current state of knowledge on sea levels on the US Eastern Coast and identified the main factors influencing this - particularly the role of oceanic circulation and the implications for future projections of sea level rise.

Dr. Shimon Wdowinski (Florida International University)

In a pre-recorded presentation, Dr. Wdowinski reported on his paper with Phillip Thompson (University of Hawaii) and Gary Mitchum (University of South Florida), ***Decadal-scale variations***

in the coupling between sea level along the Florida Atlantic coast and the strength of the Florida Current.

The Virginia Beach tide gauge shows an acceleration of sea level rise since 2006 with an increasing trend, while there has been a gradual decrease in the Florida Current since 2000. Park and Sweet (2015) show a correlation between coastal flooding and weaker current. Ezer and Atkinson (2014) also observe a short term correlation between coastal flooding and current strength. Wdowinski pointed out that there is considerable slope in sea level across the Gulf Stream. Levels along the US east coast are 3-5 feet lower than without the Gulf Stream.

Comments: (Ezer) These measurements were taken along the coast vs. across the coast, which makes a difference when comparing to other studies. There has been a continuous decline in Gulfstream flow since 2004. (Enfield) The time series and correlation diagram shows low coupling in 2004 vs high negative coupling in later years. Surprising that it covers all frequencies. If coupling due to frequencies of annual and higher, you would not expect to see that. High coupling is due to the trend after the mid 2000's and that there isn't much coupling at the higher frequency. Spectral analysis might be useful – look at the coherent spectrum and see where that stops --at what point is the coupling reduced or augmented? (Ezer) Some data on this are available that I will discuss. (Kirtman) Need to state the null hypothesis – ENSO correlations occur with many parameters (rainfall etc. with low frequency modulations. These are tantalizing results, but should we expect low frequency modulations over time? Do we accept these low frequency correlations? Is there AMO-ENSO modulation occurring? Was there a change in the Atlantic Multidecadal Oscillation (AMO) in 2004? Has this occurred in the past? (Lee AOML) Are there ENSO links to global rainfall?

Dr. Tal Ezer (Old Dominion University)

Dr. Ezer's presentation focused on **the link between the Gulf Stream and sea level along the US East Coast based on observations and modeling,** including the long term impact of the Gulf Stream on sea level rise trend as well as shorter-scale changes.

He noted the strong difference in acceleration of sea level rise north of Cape Hatteras as compared to the acceleration south of the Cape. Long-term variations of the Gulf Stream (see Ezer et al., JGR, 2013) appear to show a shift from a 6-8 yr oscillation cycle to a pronounced weakening trend since ~2004. South of the Cape, where the Gulf Stream is closer to the coast, variations are somewhat smaller than those to the north, where the Gulf Stream is farther from the coast, but the dynamics there also involve Gulf Stream meanders, eddies and the influence of the southward flowing slope current. There is a strong correlation between changes in the Gulf Stream transport and variations in sea level, sea level will rise when the Gulf Stream is weakening; this correlation exists for a wide range of scales, from daily changes to seasonal and decadal. Land subsidence also plays a role in increasing local sea level rise- this is especially evident in places like Norfolk, VA.

Offshore hurricanes, even if not making landfall seem to disrupt the Gulf Stream thermal structure and often cause a significant weakening of the Gulf Stream flow- this was evident for example, during Hurricane Joaquin (2015) and Hurricane Matthew (2016); in the latter, the transport of the Florida current (Gulf Stream) decreased by ~50% and as a result, in addition to direct storm surge, Gulf Stream's weakening contributed to higher than normal sea level from the Florida coast to Atlantic City NJ.

All these factors demonstrate a statistically significant link between a weakening Gulf Stream and higher coastal sea level and thus a potential for predicting sea level increases during storms or other events that can be detected by the Florida Current cable measurements- this capability was recently demonstrated (see Ezer and Atkinson, Ocean Dynamics, 2017). Numerical models of the Gulf Stream (see Ezer, Ocean Dynamics, 2016) can also help to better understand the Gulf Stream-sea level connections and how to use this information to study the Gulf Stream's impact on the coast.

Ezer also demonstrated a statistical method of predicting the number of hours of future flooding, which show significant acceleration in flooding hours everywhere. The Miami record shows an extremely large sea level rate in recent years that if continue could significantly accelerate flooding even beyond other locations, however, due to the relatively short record in Miami, the projected sea level acceleration is less accurate than in longer records.

Comments: (Obey) The Gulf Stream effect on sea level variability is on the order of 15-25% at Virginia Key. It's hard to talk about short-term changes in acceleration. We need to focus on long-term records. (Berry) How do we measure the strength of the Gulfstream current? Some direct flow measurements have been made since 1982 (35 years). We also have altimeter data since about 1997 (20 years). There is thus a combination of flow measured underwater and estimated base on sea level from above. There is a time lag between when minimum transport velocities occur in the Florida current and when they occur further north. Northern stations show more effect than southern stations. Large scale changes in the gulf stream generates waves and these are also affected by the coast and by coastal waves.

Dr. William Sweet (NOAA)

Dr. Billy Sweet addressed **tidal flood factors in the South East Atlantic including Gulf Stream**. He distinguished between global, regional and local sea level rise parameters. While the increased input from melting glaciers and ice caps will affect the global picture, ocean and other dynamics such as the Gulf Stream will have regional importance. The circulatory component is significant, and has not been sufficiently addressed in the downscaling of global models. Observations indicate an east coast slowdown of the global system. This is real and measurable. The fall season shows higher than normal sea level maxima. For every 1 sverdrup (Sv) of slowdown there is a 2 cm rise in the maximum. Sea level rise scenarios capture the AMOC slowdown but the magnitude is greater north of Cape Hatteras. The variability south of the Cape is apparent in the specific high-tide flooding probabilities.

Comments: (phone comment) From 1994 to present, a shift in the Gulf Stream has resulted in a 2.1 cm decrease. (Ezer) Sea level rise is not linear – the probability statistics depend on the *length of the record. Virginia key has a short record. Especially for lower probability events, the statistical results can be quite different.*

Dr. Ben Kirtman (University of Miami)

Ben Kirtman explored the potential for a flood prediction system which would forecast flood potential from days to decades. He described the Ocean Eddy resolving model which attempts to include the Gulf Stream, but the goal is an output which couples all flooding possibilities in an holistic model.

The CMIP5 (Coupled Model Intercomparison Project) model includes the ocean component at 10 km resolution. Current work is testing the model against historical data up to one year, in the future to five years. At present, researchers are focusing on data from Brazil and examining rainfall changes associated with those current patterns. Processes in the deep ocean seem to play a role, and warmer sea surface temperatures along the coast may mean higher rainfall or more intense rainfall.

Comments: (Ezer) The HRC model does not adequately represent the area north of Cape Hatteras. It may be suitable for South Florida but not for the mid-Atlantic (associated with the Gulf Stream separation problem). (Kirtman) The models range from a resolution of 100 KM (LRC) to 50 KM to 25 KM (HRC) in the atmosphere. The change in scale from 100-50 KM results in huge improvement, whereas the change from 50 to 25 KM is not so much. In the oceans, changing from 100 KM to 25 KM does not improve the model very much, whereas the change from 25 to 10 KM is much better. For the oceans, we would like to see 1/25^th^ of a degree. CMIP6 models are all using better resolution.

Ricardo Domingues (University of Miami/NOAA)

Ricardo Domingues NOAA described the AMOL observing system in East Coat. Most efforts are focused on understanding the role of currents, weather, and other factors on sea level rise. Domingues pointed out basic underlying differences in sea level, for example, up to a one meter difference in sea level between Florida and the Bahamas. Satellite observing systems show a strong correlation between sea level and the Florida Current (Gulf Stream) - 5 to 10 cm negative relationship in Florida i.e. higher, and 5 cm decrease in the Bahamas, which means a slower Gulf Stream correlates to a higher sea level in Florida and lower in the Bahamas. The best long-term record of Gulf Stream data is from telephone cables, the longest in the world.

This record shows a long-term pattern of high flows in the summer and low in fall/winter with variations from year to year. But changes in seasonality account for a large part of total variability. A new study shows that changes in the Gulf Stream correlate to westward propagating signals from the open ocean. The signals behave like first baroclinic modes.

Year to year changes with seasonality have links with coastal sea level changes. Data indicates that sometimes the water column is either colder or warmer than normal. This expansion and contraction may have an impact on sea level. See AMOL website with sea level indicator related to Florida Current. http://www.aoml.noaa.gov/phod/indexes/index.php

Discussion: (Ezer) Do Rossby waves affect sea level rise or do they affect the Gulfstream, which in turn affects sea levels? (Domingues) Ongoing experiments are trying to separate these effects. Coastal wave effects and temperature variation also need to be considered. (Obey) Are there multi-year decadal patterns? Could el Niño play a role? Are there effects from the Gulf of Mexico? (Ezer) Gulfstream changes after hurricanes. (Domingues) We have not yet looked at that specifically, but it could be done.

David Enfield (formerly NOAA/AOML)
David Enfield presented research from **Bakker et al. (2017): Recent work on the impact of mitigation on projected decline of the AMOC.**
The research assessed the fate of the Atlantic Meridional Overturning Circulation (AMOC) decline scenario with continued warmth and Greenland ice melt. Using the AMOCMIP ensemble of models, the AMOC showed a 15-20% decline even with mitigation.
A whole series of questions from the models included:

1. Does the Florida Current vary proportionally to the AMOC, which is also influenced by wind stress and other factors?
2. How does sea level respond to Florida Current transport decline?
3. What fraction of sea level rise was due to Florida Current, or what are the other factors?

Only high resolution models incorporating all factors will resolve these issues.

Comments: (Ezer) Measurements only go back to 2004--a very short period. From 2009-2010 we saw a 20-30% decline in AMOC due to inter-annual variation. High inter-annual variability limits the ability to predict changes and thus makes it problematic to predict a 40-60% decline over next 60 years. (Kirtman) How did they account for ice melt? EMIC models include ice melt, but global climate models do not. Adding ice melt as a hosing component might be appropriate, but a value of 0.1 Sv may be more realistic. It would be useful to correlate ice melt rates to GRACE measurements (satellite-based) of mass loss. This might also help to estimate ice melt plus ice discharge.

WRAP-UP AND DISCUSSION ITEMS

The main takeaways include:

- The Gulf Stream is an important component of sea level rise, and changes in the rate of sea level rise on the East Coast of the US.
- The Gulf Stream appears to influence not only long-term variation but also seasonal and short-term variation.
- Although we still don't know in sufficient detail many components of this relationship, the AMOC monitoring and research ongoing at ODU and UM could provide some answers fairly soon.

- Better regionally focused inclusive models are needed, as well as continued observational data and analysis.
- In general, the influence of a weakened Gulf Stream will accelerate sea level rise differentially along the East Coast with Cape Hatteras being an important dividing line for this factor.
- A small group (10-12 people) should carry this effort forward and continue work on Gulf Stream effects.
- Larry Atkinson / ODU offered the use of his website to encourage cooperation between researchers on this topic. (https://www.odu.edu/impact/initiatives/resiliencecollaborative)
- Communication of these and future findings to decision makers in clear, understandable ways is important.

DISCUSSION

Providing better information: (Larry Atkinson) ODU's website provides a sounding board for this issue (https://www.odu.edu/impact/initiatives/resiliencecollaborative). Improved public outreach regarding climate change/ sea level rise is needed to explain how things that affect us locally are related to events happening globally. (Glenn) We understand some aspects of seasonal variation along the coast, for example that the peak tidal events in the hurricane season are somewhat compensated by the Gulfstream effects. We need to get these messages out. Summer melting is related to the speed.

Improving system designs: (USACE staff on phone) This information has exciting research implications. For the design of structures, we need to understand probabilities for surges, waves, changes in means, etc. We need to be able to consider the full range of reasonably-probable conditions. Better flooding indicators should be provided to characterize local effects such as elevations and durations of expected high tides, etc. How high can we expect tides to occur locally? (Brian, Ryan?). Further study is needed to determine sea level rise impacts on storm surge. Need 1000 years of tropical storms, etc. We do not have adequate maps of current surge risks or frequencies. FEMA is working on this using ADCIRC and historical storm data, and hopes to have results in 1-2 years. (Obey) In the SFWMD, sea level rise is affecting operations. Some gates can't open now. High resolution models are needed to predict ocean effects. Are Gulfstream changes permanent or temporary? How can we use his information for planning purposes?

Improved predictions: There is a need for better rainfall and sea level rise predictions. (Bolter) Predictability is an important issue. We know the King Tide days for 2017, so we can provide some warning of likely extreme conditions. How do we better package this and other types of warnings for use by local governments? Ft. Lauderdale has a "King Tide Tool Kit" and Miami Beach also provides this kind of information. People should be advised of these risks. The 2015 Climate Compact projection document includes a section on the Gulf Stream. Kirtman has also provided materials. Perhaps there should be a speaker on this topic at the Climate Compact Conference this year. An important piece of information is to Identify differences in elevations for coastal communities. We also need to know about tipping points (thresholds) above which damages are likely to increase very rapidly and how to help citizens and local governments determine when, where, and how much this may affect specific areas. It would be very useful to provide charts that show with water levels over time and correlate this to maps and pictures showing likely impacts.

Gulfstream conditions and effects: (Obey) Has the Gulfstream affected king tide conditions in recent years? Is there basin specific information about the westward propagating waves and their land effects? Can we add this information to our predictive tools. (Enfield) We are hampered by how much variability occurs on top of trends. Also, we haven't adequately addressed thermos-steric effects and their causes Can they be predicted? (Lee) Who is watching all these factors and considering them together in order to generate predictions? The existing communication mechanisms do not seem to be effective.

Combined effects of weather and sea levels: (Glenn) We also need to emphasize the inland impacts of sea level rise as well. Hurricane Sandy provided some great lessons. The storm occurred close to high tide and thus was an example of compounded effects. Combined effects of warm water, waves, tides, storms, surges, etc. can create extreme events.

Closing remarks: (Berry) This meeting was well prepared and provided good overviews of the issues, but we need to follow up. Ten to twelve people should carry this effort forward and continue work on Gulfstream effects. Also, we need to work on communication. Results from this meeting will be available in PDF formats and recordings. The Florida Climate Institute, Climate Compact and Center for Environmental Studies should all be involved.

For more information, please contact Leonard Berry at berry@fau.edu or 561-297-2935.