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USGS science for a changing world

Decadal hindcast of hydrodynamics and barrier island morphology

Caraline Miller[1] (caraline.miller@uga.edu), Matthew Bilskie[1] (mbilskie@uga.edu) & Davina Passeri[2] (dpasseri@usgs.gov)
[1]University of Georgia School of Environmental, Civil, Agricultural and Mechanical Engineering, [2]United States Geological Survey

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1. Abstract

In the northern Gulf of Mexico, storm surge poses a major risk due to the low-lying topography and the high frequency and intensity of tropical cyclones. As climate change increases sea surface temperatures and sea levels, storm surge magnitude is expected to increase nonlinearly because of tropical cyclone intensification, sea level rise, and land use/land cover changes. When barrier islands experience storm surge, they are subject to erosion, flattening, and overtopping, all of which reduce their flood protection benefits to the mainland.

This work is part of a larger USGS-funded project that aims to simulate barrier island morphology into the future, accounting for tropical cyclone-driven storm surge and fair-weather wave and tide action. The project's first stage entails hindcasting 11 hurricanes that made landfall within 200km of Dauphin and Petit Bois Islands (Alabama and Mississippi) between 2005-2020 using ADCIRC+SWAN. Simulated water levels and waves were compared to observations to quantify model errors. After each storm event, storm-induced barrier island morphological changes and the islands' natural recovery are simulated using XBEACH and EDGR models. Prior to the next storm, the ADCIRC+SWAN model topobathy is updated for the study sites based on the XBEACH and EDGR simulations.

The uncertainty of morphological predictions will be quantified based on the hindcast error, climate uncertainty, and other factors. Understanding and minimizing uncertainty will inform restoration and land management initiatives based on the full range of possible outcomes, minimizing risk and damage due to storm surge and maximizing cost efficiency.

2. Objectives

- Simulate morphological changes caused by storms that made landfall within 200km of Dauphin Island, AL between 2005-2020
- Validate the hydrodynamic model by comparing simulated and observed water elevation and wave variables
- Determine the impacts of slight topobathic variations on simulated hydrodynamic model outputs
- Determine the uncertainty of the morphological predictions on Dauphin & Petit Bois Islands between 2005-2020

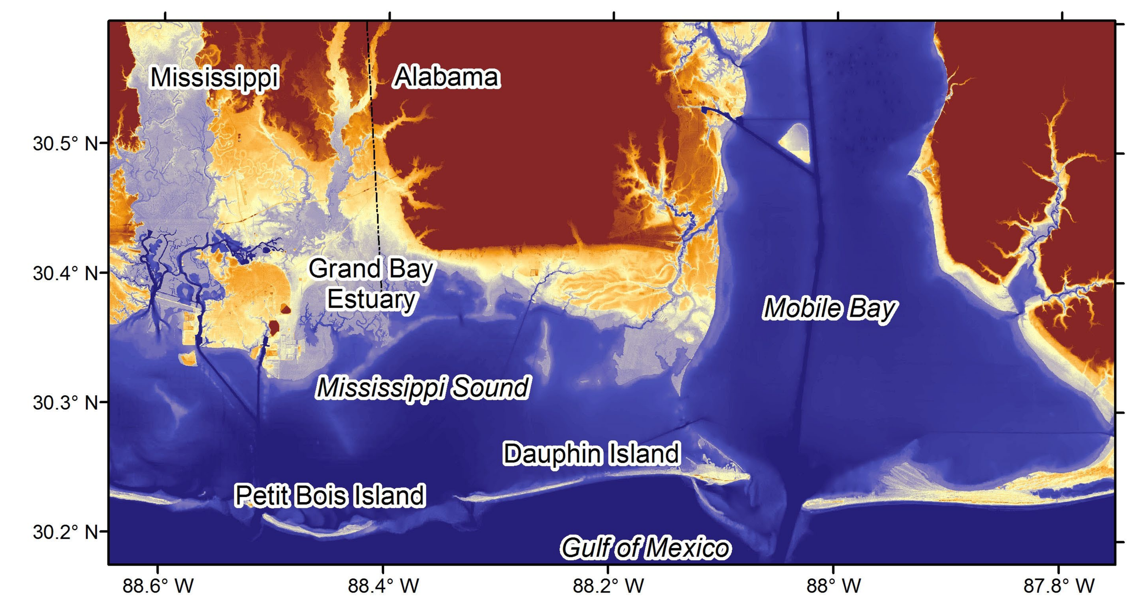


Figure 1: Study Area- Dauphin Island, AL, Petit Bois Island, MS, and West Petit Bois Island, MS (between the P and e of the Petit Bois label)

3. Methods

- Perform ADCIRC+SWAN simulations of 11 storms that made landfall within 200 km of Dauphin Island between 2005-2020 (Figures 3 & 4)
- Error is calculated for hydrodynamic and morphological variables
  - Includes water elevation, and wave variables were compared to NOAA data
  - High Water Mark data was collected from USGS and LSU's SurgeDat database
  - Observed Topobathy data was obtained from USGS, USACE, and/or NASA LiDAR data and was compared to the simulated XBeach DEM for the nearest time-step
- Nearshore hydrodynamics were compared between DEMs (Post-Ivan, XBeach, and LiDAR) to determine the direct impact of slight topographic changes on nearshore hydrodynamics
- Methodological recommendations will be made for future studies that focus on long-term hydrodynamic and morphological forecasting
  - Error and uncertainty of hydrodynamic variables caused by inaccurate and/or outdated topobathy will be discussed
  - Methods for estimating error and uncertainty of XBeach simulation results will be established

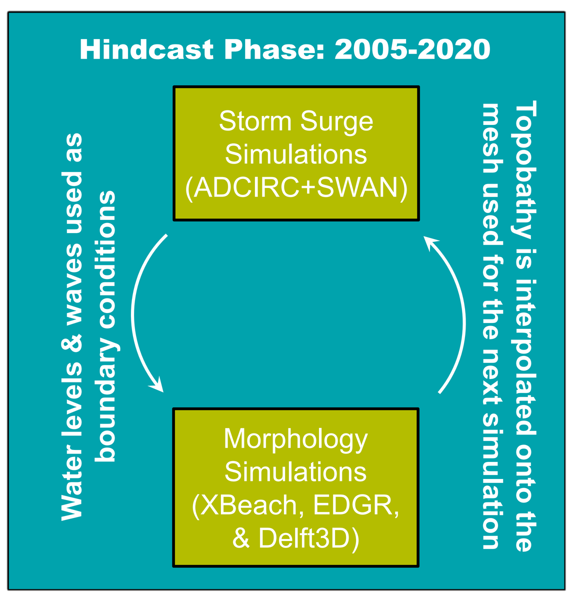


Figure 2: Overview of methods. In addition to being run on the XBeach/EDGR-derived DEM, all storms were also run on a Post-Ivan (2004) DEM and the most up-to-date LiDAR data available at the time of the storm.

#	Storm Name	Year	Classification
1	Arlene	2005	Tropical Storm
2	Cindy	2005	Cat. 1 Hurricane
3	Dennis	2005	Cat. 4 Hurricane
4	Katrina	2005	Cat. 5 Hurricane
5	Ida	2009	Cat. 2 Hurricane
6	Nate	2017	Cat. 1 Hurricane
7	Alberto	2018	Tropical Storm
8	Gordon	2018	Tropical Storm
9	Cristobal	2020	Tropical Storm
10	Sally	2020	Cat. 2 Hurricane
11	Zeta	2020	Cat. 3 Hurricane

Figure 3: Selected storms

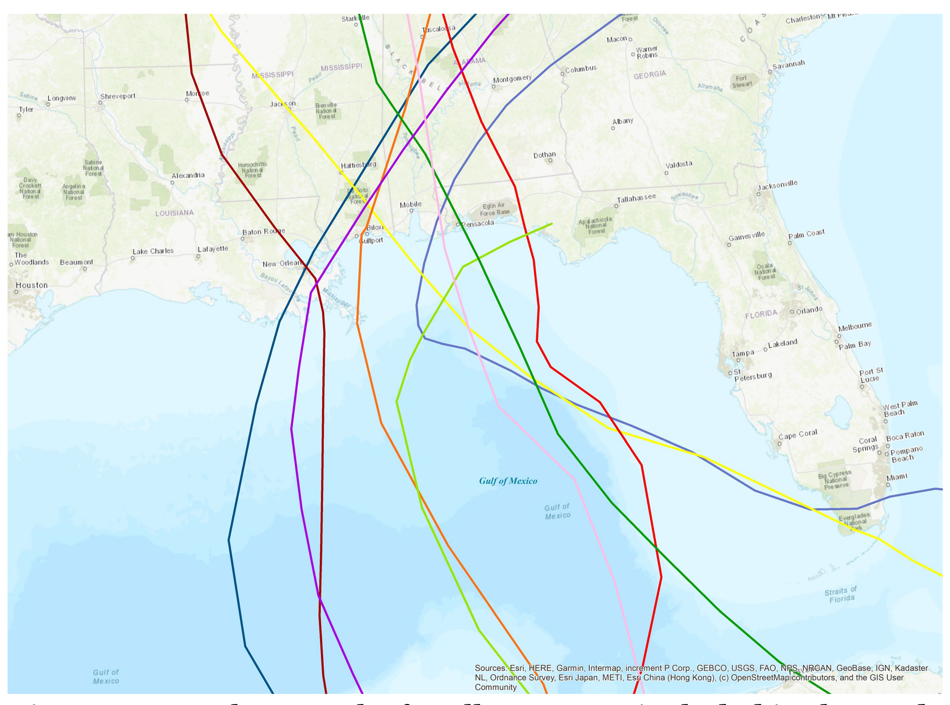


Figure 4: NHC best tracks for all 11 storms included in the study

4. Hydrodynamic Model Validation

- Water surface elevation (WSE), significant wave height, wave direction, and mean & peak wave period were compared to observational data
- RMSE, Mean Normalized Bias, and Scatter Index were quantified at all stations on all DEMs
- Average RMSE for WSE was ≤ 0.20 m for all DEMs (Figure 5)
  - These RMSE values are considered sufficiently accurate (Davis et al., 2019)

	Post-Ivan DEM			XBeach DEM			LiDAR DEM		
Measure	RMSE	MN Bias	Scatter	RMSE	MN Bias	Scatter	RMSE	MN Bias	Scatter
Average	0.20	-0.25	0.33	0.19	-0.25	0.31	0.19	-0.26	0.31
Maximum	0.32	0.08	0.54	0.32	0.07	0.55	0.26	-0.18	0.40
Minimum	0.12	-0.39	0.18	0.12	-0.39	0.17	0.14	-0.39	0.22

Figure 5: Average WSE error statistics for all storms at all stations

- On average, simulations run on the Post-Ivan DEM were less accurate than simulations run on the XBeach or the LiDAR DEM (Figures 4 & 5)
- Offshore differences between DEMs were negligible (Figure 7)

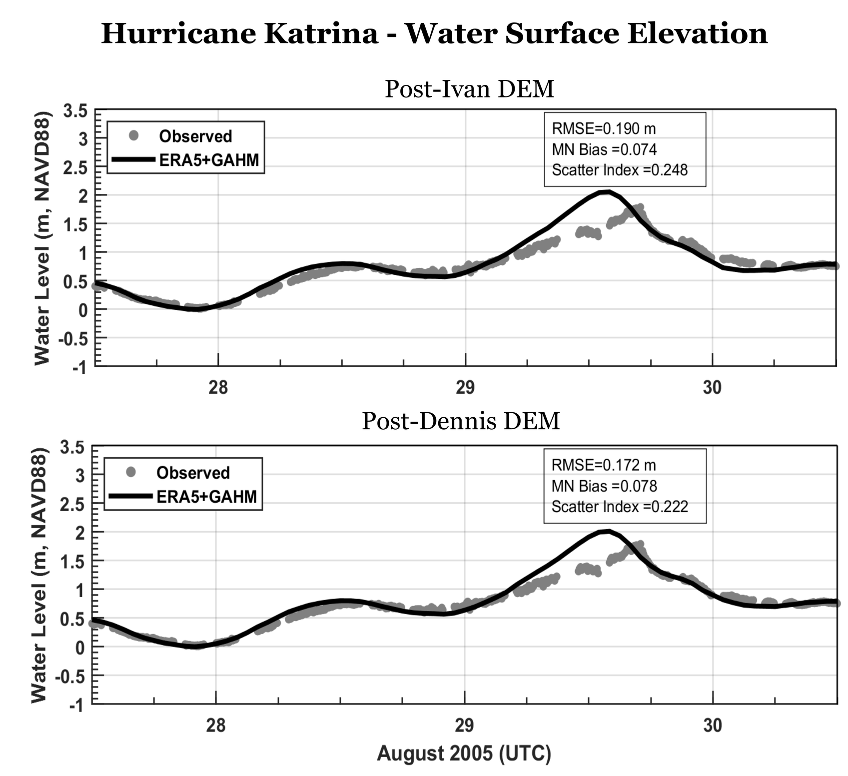


Figure 6: Hydrograph at eastern Dauphin Island (NOAA gauge #8735180) during the peak surge of Hurricane Katrina, using the Post-Ivan (top) and XBeach (bottom) DEM

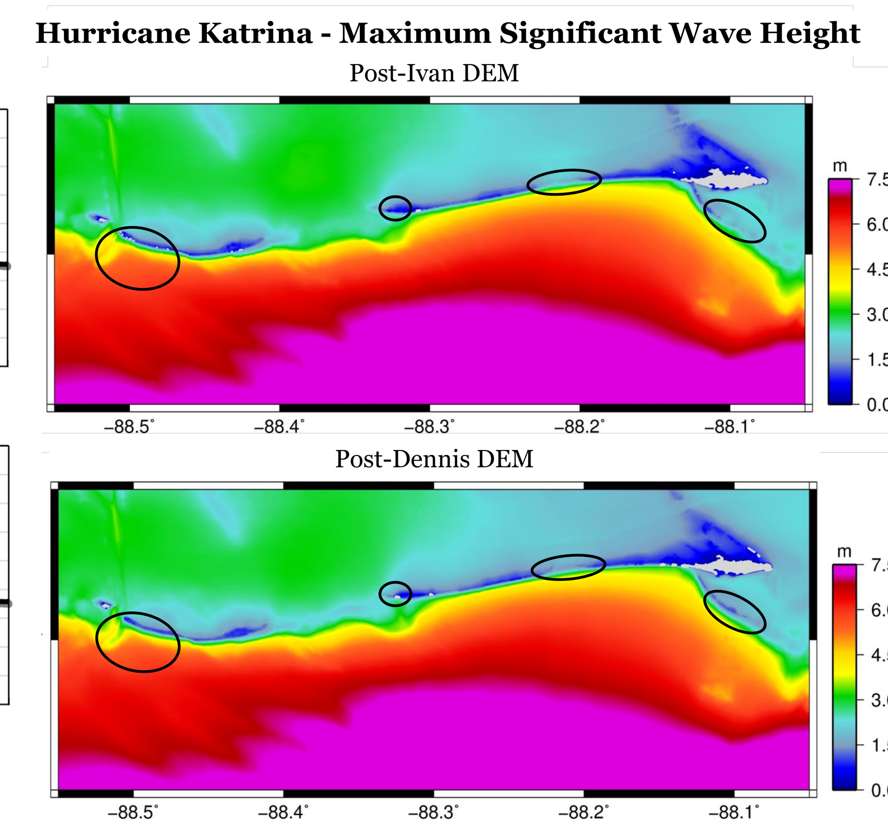


Figure 7: Slight nearshore differences in wave height are present due to topographic differences (see circled areas)

5. Morphology Results

- 0-meter contour lines were established and compared for each DEM
  - Island area and volume within the 0-meter contour were calculated and compared over time, and at corresponding time steps for XBeach/EDGR-derived and LiDAR DEMs
  - Change in contour location was qualitatively compared

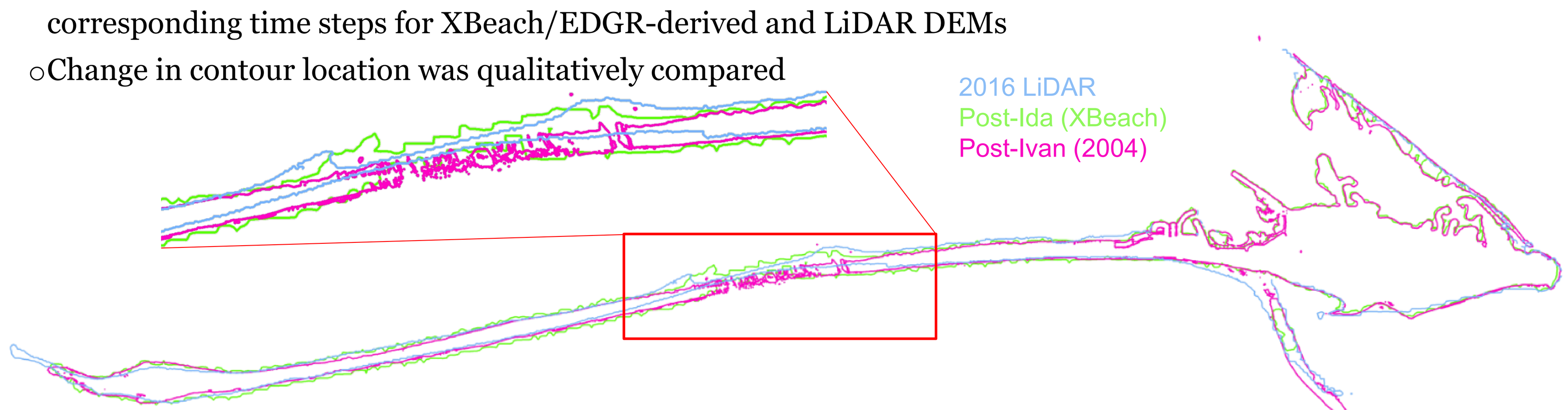


Figure 8: Comparison of the three DEMs used for simulations of Hurricane Nate (2017)- the LiDAR DEM shown in blue, the XBeach-derived Post-Ida DEM shown in green, and the Post-Ivan DEM obtained from 2004 LiDAR data shown in pink.

- Overall elevation and peak dune height were compared at corresponding time steps along 39 cross-shore transects (Figure 9)
  - XBeach tended to oversimplify and flatten the dune profile, underestimating peak dune height (Figure 10) while overestimating total elevation after 2010 (Figure 11)
  - Area beneath each transect was quantified and compared

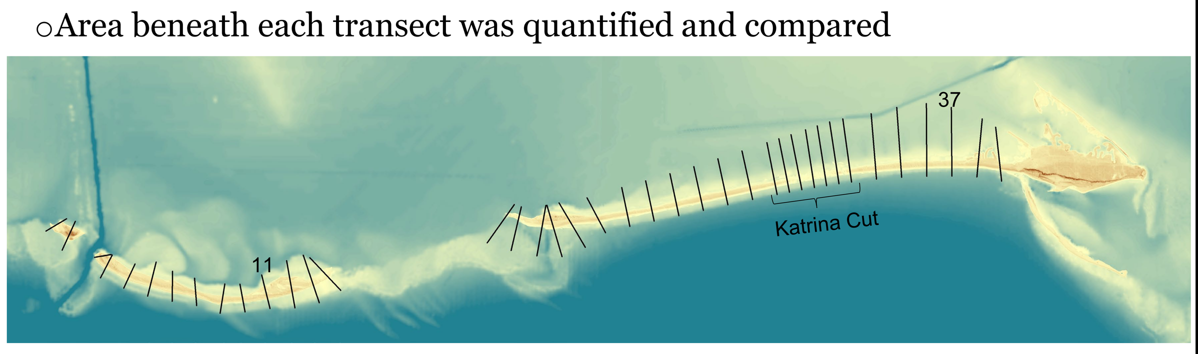


Figure 9: Island transects with 1km spacing (reduced to 0.5km spacing at Katrina Cut) were created to study peak dune heights and dune profiles

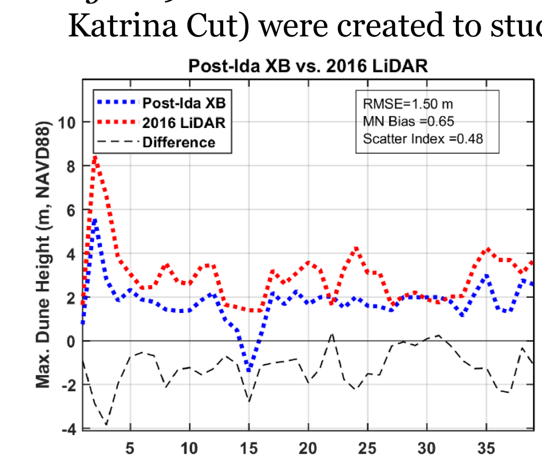
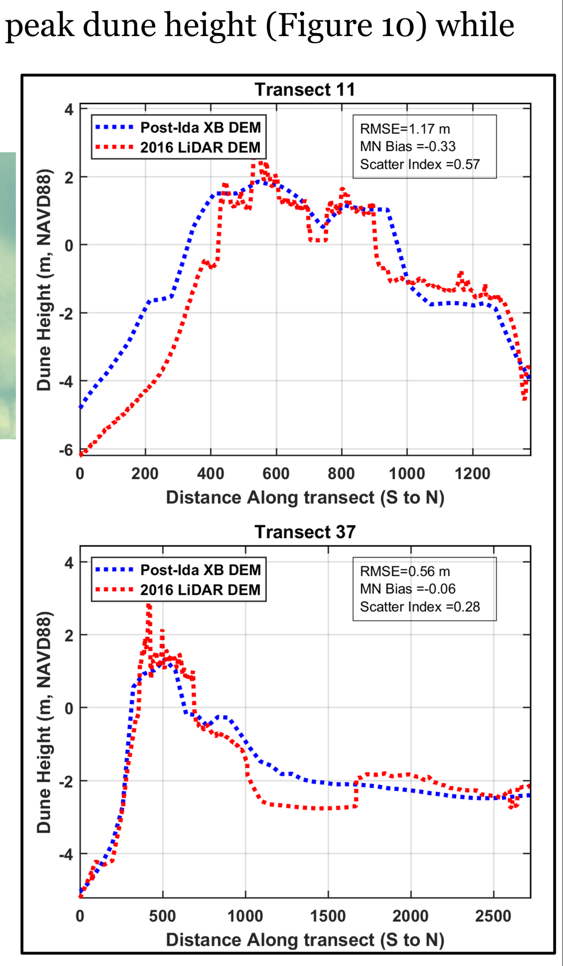


Figure 10 (left): Peak dune heights across all transects for the Post-Ida XBeach DEM (2017) versus the 2016 LiDAR DEM

Figure 11 (right): Dune profiles at Transects 11 and 37. The XBeach DEM oversimplifies the dune profile and tends to overestimate the elevation.



6. Nearshore Hydrodynamic Results

- Hydrodynamic variables were compared at nearshore points for the same storm on each DEM to determine nearshore impacts of topographic differences
  - Endpoints of the cross-shore transects (Figure 9), plus five points nearer to shore on Western Dauphin Island were selected (Figure 12)

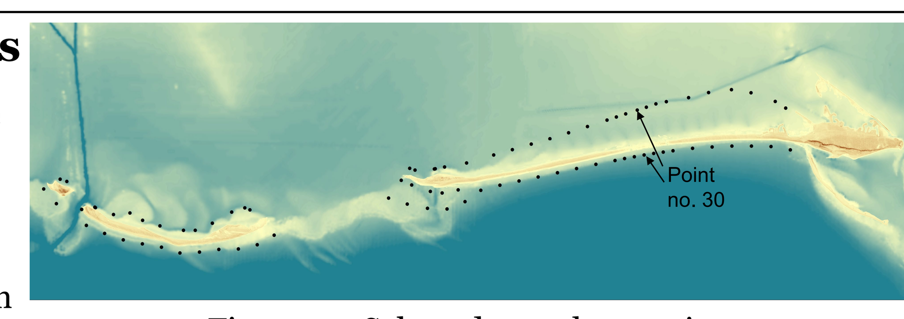


Figure 12: Selected nearshore points

- Differences between DEMs for WSE and significant wave height were negligible (Figure 13)
  - Hydrodynamic variations between DEMs were more pronounced at the western edge of Dauphin Island, eastern Petit Bois Island, and on West Petit Bois Island

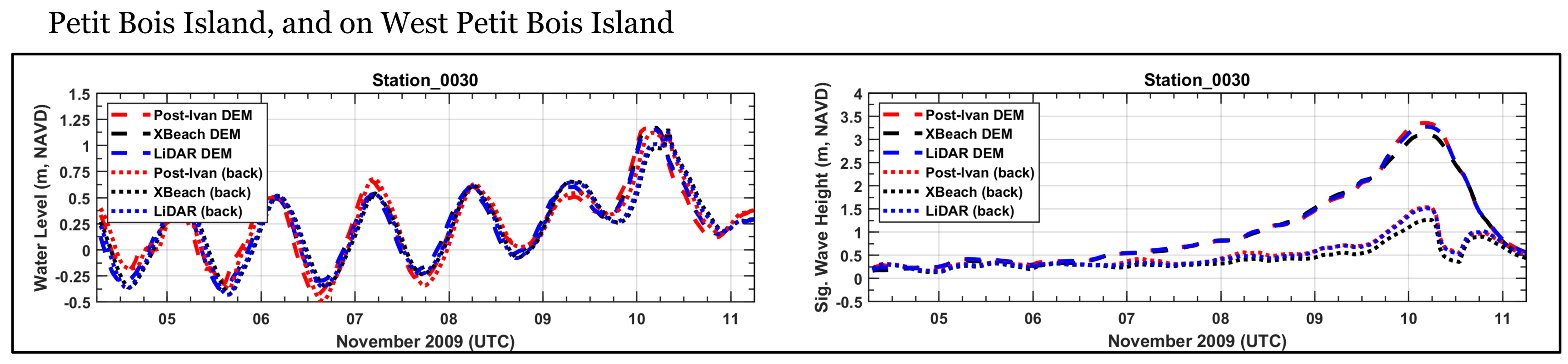


Figure 13: Differences in WSE (left) and significant wave height (right) across DEMs were minimal, though wave attenuation abilities varied noticeably between the three DEMs (dotted versus dashed lines, left graph). Data shown here extracted during Hurricane Ida (2009) from point 30 on the front and back sides of Dauphin Island (Figure 12)

- Wave attenuation and buildup of storm surge on the back side of the islands were also quantified for each DEM
  - Differences between maximum values for corresponding points on the front and back sides of the island were calculated for WSE and significant wave height
- WSE was, on average, 6.0-8.6 cm higher on the back side of the island
  - Differences between DEMs were <2 cm on average, and at most 10.3cm (XBeach vs. LiDAR, Hurricane Gordon)
- Significant Wave Height was reduced by approximately 1.5 m on the back side of the island
  - Post-Ivan and LiDAR DEMs tended to predict the most similar attenuation values (approximately 4 cm difference on average)
  - Differences between DEMs reached as high as 0.584m (Post-Ivan vs. XBeach, Hurricane Nate)
- Two-tailed paired t-tests found that:
  - DEM made a significant ($p \le 0.05$) difference in WSE for Hurricanes Katrina*, Nate**, Sally*, and Zeta*, and Tropical Storms Alberto and Gordon
  - Significant wave height attenuation was significantly different ($p \le 0.05$) between DEMs for all storms *except* Hurricane Zeta* and Tropical Storm Alberto. For Hurricane Cristobal and Tropical Storm Ida, Post-Ivan and LiDAR DEMs did not cause significantly different wave attenuation.

*Only 2/3 DEMs were included in these analyses **Post-Ivan and XBeach DEMs were not significantly different from one another.

Preliminary Findings

- Noticeable differences exist between the Post-Ivan, XBeach/EDGR-derived, and LiDAR DEMs
  - These differences do not significantly impact offshore hydrodynamics
  - However, these differences *do* significantly impact nearshore WSE and significant wave height attenuation
  - Interestingly, WSE of simulations run on XBeach and LiDAR DEMs tend to be most similar, while peak wave height attenuation for simulations run on XBeach and LiDAR DEMs tend to be *least* similar
- Peak dune heights tend to be underestimated by XBeach/EDGR, while overall elevation is over-estimated
  - This, combined with visual analysis of the 0-meter contour lines, suggests that XBeach/EDGR flatten dune profiles and may under-predict dune regrowth during quiescent periods and/or erosion during storms
- Variations between DEMs are more noticeable at dynamic transects near open water, such as on West Petit Bois Island, Eastern Petit Bois Island, and Western Dauphin Island

Future Work

- Regress simulated and observed high water marks to determine impacts of topography on peak surge height
  - Simulated high water marks from simulations that used different DEMs will also be compared
- Study the change in island area over time and across DEMs using the 0-meter contour lines
- Locate areas of erosion, accretion, and island migration
  - Elevation change over time, as well as localized over- or underestimation by XBeach/EDGR, will be studied
- Study relationships between hydrodynamics and morphology
- Identify sources of uncertainty and synthesize methods to quantify uncertainty of the final XBeach DEM
  - This can inform future studies, and influence land management decisions
- Graduate with my M.S. in Environmental Engineering in December!
  - Interests: Nature Based Infrastructure, Coastal Wetlands, Ecological Restoration

Hire me!