the open coast. The Intracoastal Waterway together with the open coast bounds the barrier islands while further landward is the inland floodplain.

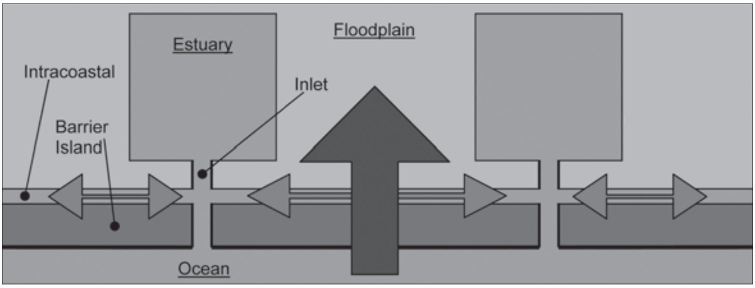

Figure 1. Local plan view of Intracoastal Waterway and other coastal features (labeled). Arrows indicate perpendicular surge overflow (↑) and along-channel surge conveyance (↔).

Challenges in meshing the Intracoastal include how to define the elements and nodes across the channel (Figure 2a). In the conceptual diagram, element(s) of fixed size are assigned to describe three different channel widths. Nodes that are inside the channel (below bank elevation) remain fully wetted over the duration of the surge event whereas nodes wet and dry at the bank elevation. Figure 2b depicts the tradeoff between mesh resolution and representation of a given channel. In the conceptual diagram, *high-resolution* represents the actual channel width and a trapezoidal cross-section (three elements/four nodes across the channel with the exterior nodes at the bank elevation and the interior nodes at the bottom depths) and *low-resolution* artificially increases the channel width and represents the channel cross-section as a V-notch (two elements and three nodes across the channel with the exterior nodes at the bank elevation and the interior node at the invert depth). The channel is artificially widened for the *low-resolution* mesh so that its cross-sectional area of flow would be equivalent to the *high-resolution* mesh.

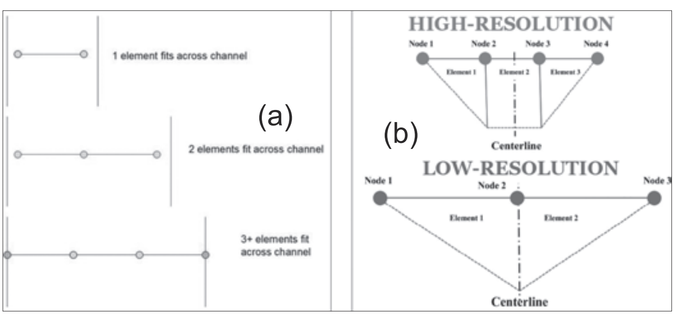

Figure 2. **(a)** Three different channel widths represented by fixed-size elements; and **(b)** *high-resolution* channel representation (actual channel width and trapezoidal cross-section) and *low-resolution* channel representation (artificially increased channel width and V-notch cross-section).

The objective of this paper is to study the Intracoastal in a storm surge setting from the dual perspective of the associated longwave physics and mesh resolution (as related to channel configuration). Two questions are examined: (i) is there a frictional component that the Intracoastal provides to the storm surge as it propagates perpendicularly over its channel and into the inland floodplain; and (ii) how does the Intracoastal transmit storm surge within its channel and into the adjacent estuaries? These questions will be answered in the context of Florida's Intracoastal Waterway.

2. LITERATURE REVIEW

Longwave physics in the coastal setting include the omnipresent astronomic tides and meteorologically driven (event-based) storm surge. With respect to the astronomic tides, the Intracoastal can influence circulation within the adjacent estuaries (cf. Bacopoulos and Hagen 2009 for an example in southeastern Florida) and can also be a factor with regard to tidal inlet instability (cf. Davis and Zarillo 2003 for examples in the Gulf coast and Cleary and FitzGerald 2003 for an example in North Carolina). The Intracoastal can also have an influence on salinity distribution (cf. Cobb et al. 2008 for an example in southern Louisiana).

Ramsey III et al. (2011) determined flooding caused by Hurricane Rita (2005) pushed salinity waters north into the western coastal Louisiana marshes beyond the Gulf Intracoastal Waterway (GIWW). Neyland (2007) concluded that the GIWW acted as a barrier to the storm surge and protected the northern sectors of the marsh and remarked (p. 5) that "it remains unclear whether the storm surge was stopped by the levee protecting the GIWW or spilled over into the GIWW."

The Interagency Performance Evaluation Taskforce (2006) published a performance evaluation of the New Orleans and southeast Louisiana hurricane protection system in response to Hurricane Katrina (2005). In it, they documented how the GIWW and Mississippi River Gulf Outlet (MRGO; an open hydraulic channel very similar to the GIWW) were able to funnel and accumulate storm surge inland to levels that it would overtop the levee banks. This was found to be particularly true where levee alignments make acute angles on the flood side and force wave run-up to move laterally along the levee and converge toward the apex of the levee alignment (Lopez 2009). Sills et al. (2008) presented an overview of New Orleans levee failures related to storm surge flooding by Hurricane Katrina. They found interior flooding to be caused by breaching and overtopping of the levees, GIWW, and MRGO with about two-thirds of the flooding caused by breaching and about one-third caused by overtopping. Ebersole et al. (2010) cited (p. 103) the "presence of channels (the GIWW and MRGO) which created hydraulic connectivity between water bodes" as an influential factor (amongst others) to variability in surge conditions (both peak surge and hydrograph shape) around St. Bernard polder (southeast Louisiana).

Review of the literature leads to the implication that the Intracoastal is hydrodynamically important in a couple of ways: (i) bank elevations can directly influence the propagation of storm surge as it propagates perpendicularly over the channel (Figure 1, uni-directional arrow); and (ii) along-channel conveyance of the storm surge by the Intracoastal can directly influence the amount of water mass available to flood and inundate the local floodplain (Figure 1, bi-directional arrows).

3. REGION OF INTEREST

The region of interest is the Intracoastal Waterway in north Florida which extends through the coastal watersheds of St. Johns, Flagler, and Volusia counties and includes Matanzas Inlet to the north and Ponce de Leon Inlet to the south. This coastal region is formally known as the Northern Coastal Basin which encompasses over 1760 km^2 of coastal lowlands interspersed with numerous creeks and small rivers (some of the more notable ones include: Tolomato River, Matanzas River, Pellicer Creek, and Halifax River) draining east to form a series of shallow bays and lagoons (Haydt and Frazel, Inc. 2003). The area is prone to strong hurricanes from the Atlantic which cause flooding damage to homes and buildings. Local residents and commercial interests are directly impacted by insurance rates as related to established floodplains (hurricane-induced flooding).

4. STORM OF INTEREST

The storm of interest is Hurricane Dora (August 28–September 16, 1964). Hurricane Dora was a moderately powerful Category 2 hurricane with maximum sustained winds of 200 km/hr (125 mph), precipitation counts of 200 mm (8 in), and storm tides of 2–3 m (5–8 ft) that struck northeastern Florida (the first tropical cyclone on record to landfall in north Florida). Hurricane Dora made landfall on St. Augustine, Florida (Figure 3), just after midnight on September 10th with minimum central pressure of 957 hPa (28.52 in).

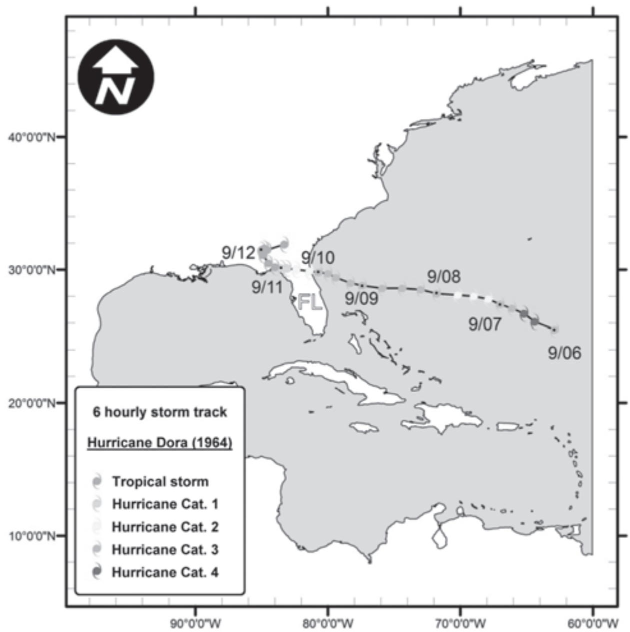

Figure 3. Hurricane Dora (1964)—6 hourly storm track with landfall as Category 2 at St. Augustine, Florida at approx. 0000 hrs. on Sept. 10th.

In their preliminary report on Hurricane Dora, the U.S. Weather Bureau (1964) cited (p. ii) that "extensive wind-induced river flooding occurred in Jacksonville along the north bank of the St. Johns River" and that "in addition to flooding along lakes and streams, many poorly-drained areas were completely inundated in north Florida." They also cite (p. iv) highest tide—at Daytona Beach, 2 m (7 ft) at 2200 hours on September 10th—and at Fernandina Beach, 3 m (10 ft) between 2300 and 0900 hours on September 10th – 11th. In his account of Hurricane Dora, Longshore (2008) cited (p. 143) that "extensive flooding topped seawalls along the banks of the Halifax and San Sebastian Rivers, submerging the streets and lower stories of entire neighborhoods," and that "parts of U.S. Highway A1A between Salt Run and St. Augustine Beach were completely washed out."

5. FINITE ELEMENT MESH

Hagen et al. (2006) provides a large-scale finite element mesh for the western North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea. A finite element mesh for the local region of interest is generated using elements sized at 60 m for the Intracoastal Waterway and connecting creeks and streams, 100 m in the adjacent intertidal zones (coastal wetlands and forests), and 250 m in the upland areas. These two finite element meshes are appended to one another to generate a comprehensive finite element mesh that contains the large-scale coastal and ocean region as well as the local region of interest at a high resolution (Figure 4).

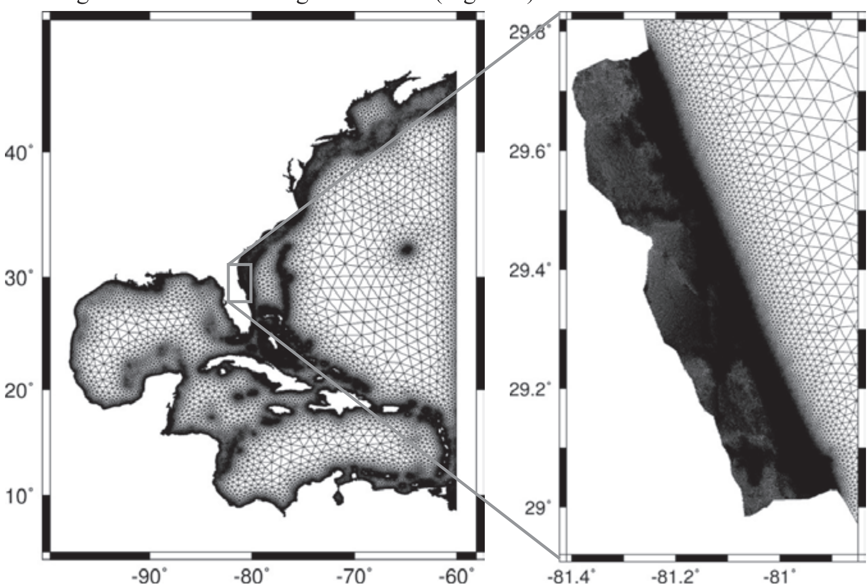

Figure 4. Large-scale finite element mesh with Intracoastal Waterway in north Florida at high resolution.

6. DATA AND NUMERICAL CODE

Data, with respect to the local region of interest, are described as follows. Bathymetric data are from surveys (circa 2001) by the St. Johns River Water Management District (John and Morris 2003) and include the tidal inlets (Matanzas and Ponce de Leon) and Intracoastal Waterway. Topographic data are from LIDAR flown in 2006 and 2007 and include bare earth and vertical features (National Geophysical Data Center 2011). Landuse/landcover (LULC) data are from NOAA's Coastal Change Analysis Program (CCAP) 2006 era land cover data of the southern United States (NOAA CCAP 2011). Meteorological forcing data are provided as a nested set of winds and atmospheric pressures with the first set encompassing the full ocean basin at resolution of 0.25° and the second set honing in on the local region of interest at resolution of 0.05° (Oceanweather, Inc. 2011).

The numerical code employed for storm surge simulation is ADCIRC (ADvanced CIRCulation) which solves, via finite element method, the shallow water equations (Luettich et al. 1992). The version of ADCIRC employed uses the LULC data for the assignment of surface attributes onto the mesh nodes. The three surface attributes include Manning's *n*, surface canopy, and directional upwind roughness lengths (Atkinson et al. 2011). Winds are incorporated into ADCIRC as surface stresses using the formulation of Garratt (1977). A wind drag multiplier of 1.09 is used to convert the 30-minute average winds, as originally generated, to 10-minute average winds (Hagen et al. 2011)—this 9% increase meant to account for the higher wind unsteadiness experienced at shorter time scales (Powell et al. 2006).

7. METHODOLOGY

First, the historical storm track of Hurricane Dora (1964) is shifted south by 0.375° and 0.875° to focus surge-driven flooding on the local region of interest. Second, the Intracoastal Waterway is re-meshed to generate alternative resolutions/descriptions of the channel configuration. Re-meshing applies the following steps: (i) start with the control mesh (Figure 4) which resolves the Intracoastal Waterway at 60 m resolution; (ii) strip out the Intracoastal Waterway from the control mesh and save the void as a map; (iii) strip out a layer, 4 elements in, around the void and save this void as a separate map (for transition); (iv) mesh the void of the Intracoastal Waterway with different uniform resolution (120, 90, 30, and 15 m); and (v) mesh the transition void so that elements transition from 60 m in the floodplain to the Intracoastal resolution (120, 90, 30, or 15 m). This procedure generates a total of five finite element meshes: very low-resolution mesh at 120 m; low-resolution mesh at 90 m; control mesh at 60 m; high-resolution mesh at 30 m; and very high-resolution mesh at 15 m. The five finite element meshes are visualized in Figure 5 as are the components of the re-meshing procedures. Third, the re-meshed finite element meshes are applied in ADCIRC storm surge simulations. Time steps that are applied range from as high as 1.0 to as low as 0.1 based on the CFL stability criterion. Fourth, model output is examined for sensitivity of storm surge response, i.e., MEOW (maximum envelope of water—a worst-case snapshot for a particular storm—cf. National Hurricane Center 2011 for definition) and hydrographs, with respect to the applied re-meshed finite element mesh.

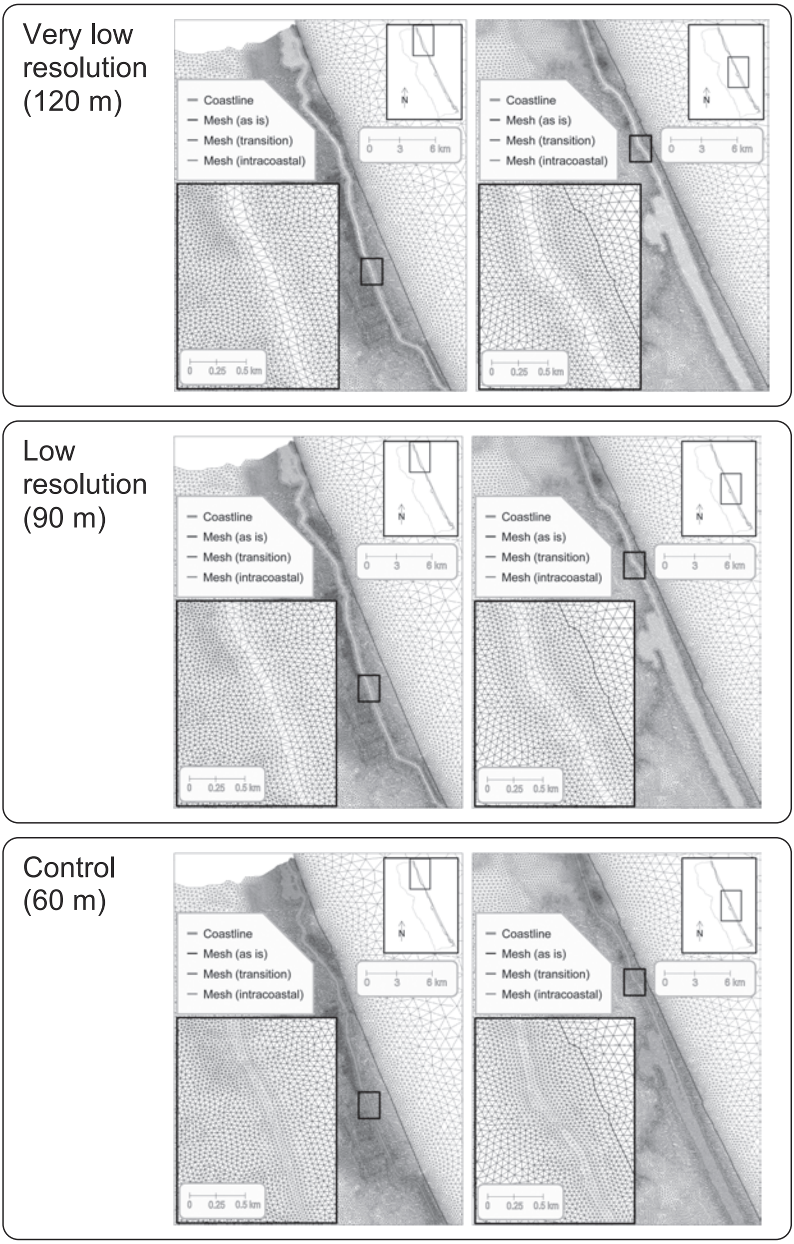

Figure 5. Five finite element meshes for the Intracoastal Waterway in north Florida.

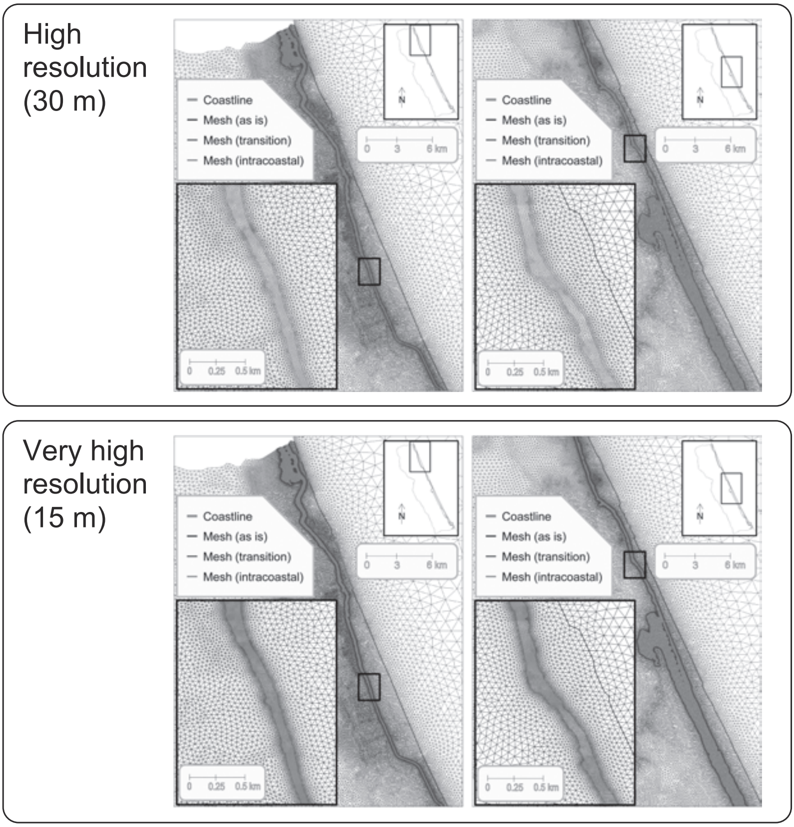

Figure 5. (continued) Five finite element meshes for the Intracoastal Waterway in north Florida.

8. RESULTS

Results include MEOWs and hydrographs. MEOWs are shown as contour plots and hydrographs are shown as time series for stations within the Intracoastal Waterway. Figure 6 shows the MEOWs resulting from application of the five finite element meshes. It is notable that all five MEOWs are very similar in their extent. The MEOWs extend outward from the Intracoastal Waterway. In some local areas, the MEOWs extend inland by as much as 6 km. These observations in the MEOWs hold true regardless of the finite element mesh that was applied. The area extent of flooding is calculated per mesh (except for the very high-resolution mesh on account of suspect noise in the solution) and shows the variability in area extent of flooding to be within 5% (6.5 km^2 variability of 130.9 km^2 area extent of flooding).

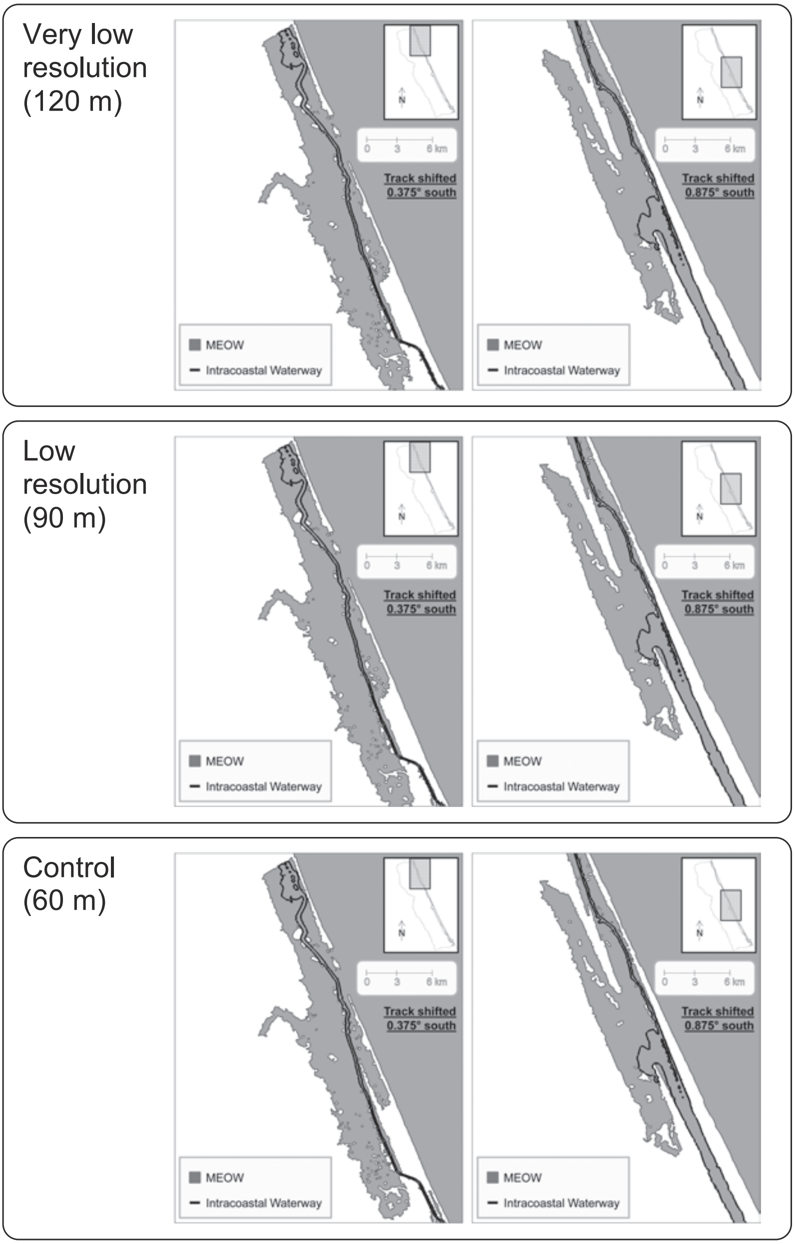

Figure 6. Five MEOWs (maximum envelopes of water) for the Intracoastal Waterway in north Florida.

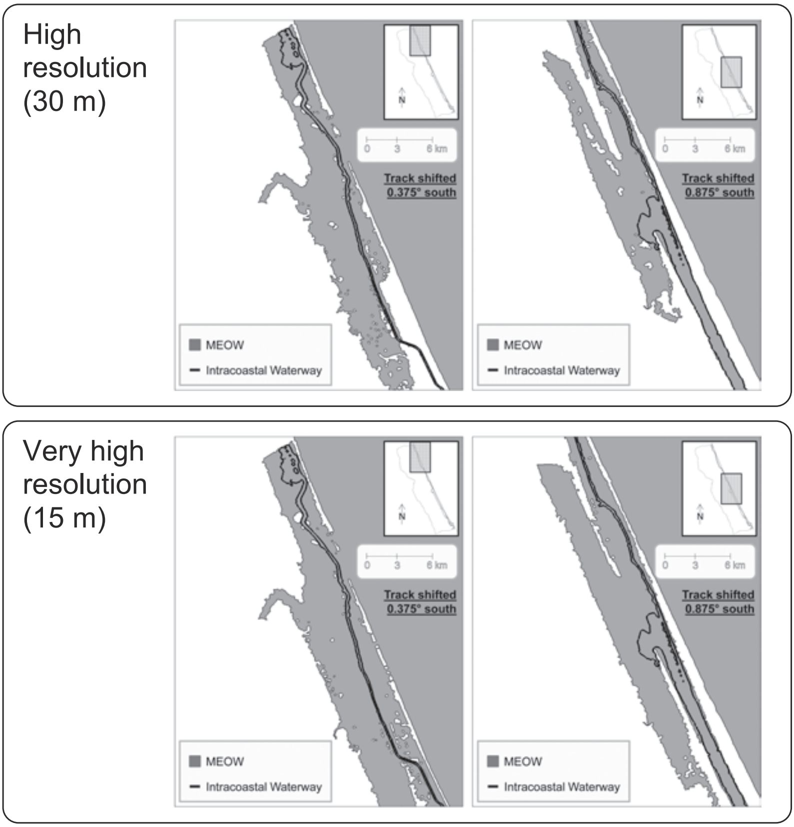

Figure 6. (continued) Five MEOWs (maximum envelopes of water) for the Intracoastal Waterway in north Florida.

Figure 7 shows hydrographs resulting from application of the five finite element meshes. The hydrograph resulting from application of the very high-resolution mesh (15 m) is not shown on account of there being noise in the solution. (This will be a subject of future work.) Trends among the four hydrographs shown are similar with respect to the rising limb, peak surge, and maximum wind drawdown. However, there are differences in the falling limb and surge backfill.

Recall the only difference in the model setup and application is with the applied finite element mesh. To that end, differences in the resulting MEOWs and hydrographs can be attributed to the differences in the applied finite element meshes.

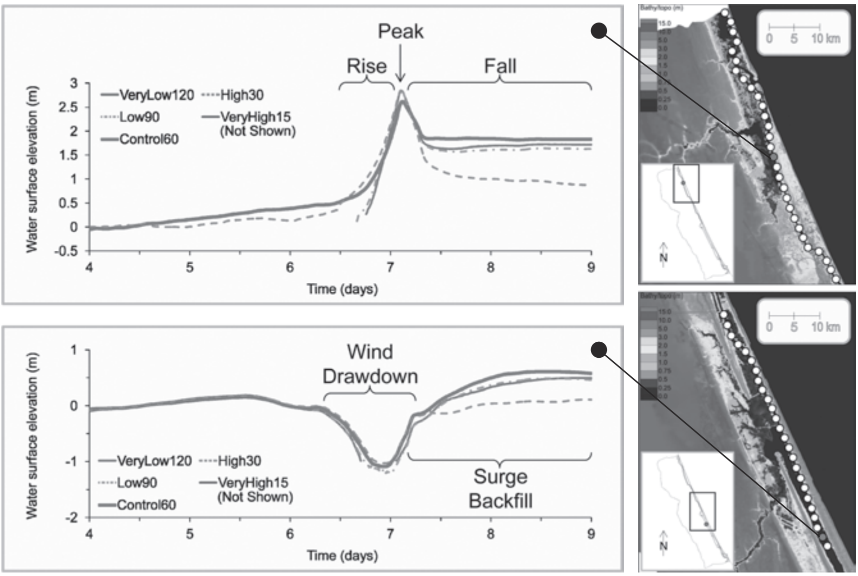

Figure 7. Hydrographs at stations within the Intracoastal Waterway.

9. CONCLUSIONS AND FUTURE WORK

Changing the resolution of the Intracoastal Waterway within the finite element mesh caused minor impact on the simulated MEOW extent. This implies that the configuration of the Intracoastal Waterway has an inconsequential effect on the extent of surge-driven inundation within the floodplain. Future work will quantify the convergence of the solutions and the frictional component of the Intracoastal. Changing the resolution of the Intracoastal Waterway within the finite element mesh caused a measureable impact on the simulated hydrographs, namely with the shape of the falling limb/surge backfill. This implies that the configuration of the Intracoastal Waterway has a discernible effect on the conveyance of surge receding from the floodplain and thus on the residence time of floodwaters within the floodplain. Future work will quantify volume of flooding water and will combine those volume calculations with calculated volume of discharge through the channel to better understand the surge conveyance properties of the Intracoastal.

10. ACKNOWLEDGEMENT

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11. REFERENCES

Atkinson, J., Roberts, H., Hagen, S. C., Zou, S., Bacopoulos, P., Medeiros, S., Weishampel, and Cobell, Z. (2011). "Deriving frictional parameters and