The role of meteorological forcing on the St. Johns River (Northeastern Florida)

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SUMMARY

Water surface elevations in the St. Johns River (Northeastern Florida) are simulated over a 122-day time period spanning June 1–September 30, 2005, which relates to a particularly active hurricane season for the Atlantic basin, and includes Hurricane Ophelia that significantly impacted the St. Johns River. The hydrodynamic model employed for calculating two-dimensional flows is the ADCIRC (Advanced Circulation Model for Oceanic, Coastal, and Estuarine Waters) numerical code. The region of interest is modeled using three variations of an unstructured, finite element mesh: (1) a large-scale computational domain that hones in on the St. Johns River from the Western North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea; (2) a shelf-based subset of the large domain; (3) an inlet-based subset of the large domain. Numerical experiments are then conducted in order to examine the relative importance of three long-wave forcing mechanisms for the St. Johns River: (1) astronomic tides; (2) freshwater river inflows; (3) winds and pressure variations.

Two major findings result from the various modeling approaches considered in this study, and are applicable in general (e.g., over the entire 122-day time period) and even more so for extreme storm events (e.g., Hurricane Ophelia): (1) meteorological forcing for the St. Johns River is equal to or greater than that of astronomic tides and generally supersedes the impact of freshwater river inflows, while pressure variations provide minimal impact; (2) water surface elevations in the St. Johns River are dependent upon the remote effects caused by winds occurring in the deep ocean, in addition to local wind effects. During periods of calm weather through the 122-day time period, water surface elevations in the St. Johns River were generally tidal in response, with amplitudes exceeding 1 m at the mouth and diminishing to less than 10 cm 150 km upriver. Considering an extreme storm event, the timing of Hurricane Ophelia occurred during the neap phase of the tidal cycle and at the mouth of the St. Johns River, the wind-driven storm surge was near equal to the tidal component, each contributing about 0.5 m to the overall water surface elevation. However, 150 km upriver, meteorological forcing dominated, as over 90% of the total water surface elevation was driven by winds and pressures. The simulation results replicate these behaviors well. As a supplement, it is shown that applying a hydrograph boundary condition, generated by a large domain, to a localized domain is highly beneficial towards accounting for the remote wind forcing.

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Introduction

In the following paper, we present an application of the ADCIRC (Advanced Circulation Model for Oceanic, Coastal, and Estuarine Waters) numerical code towards a simulation of the water surface elevations in the St. Johns River for a 122-day time period spanning June 1–September 30, 2005. Numerical experiments are conducted using three model domains of different extents in order to investigate the relative importance of three long-wave forcing mecha-
active hurricane season for the Western North Atlantic Ocean, and includes Hurricane Ophelia, which significantly impacted the St. Johns River. Further, the distinctive configuration of the St. Johns River, coupled with its large drainage basin (22,000 km², encompassing most all of Northeastern Florida; cf. Bergman (1992)) which provides significant freshwater influxes, makes it a unique system in which to study the long-wave components of the storm tide.

The storm tide consists of several components (Graber et al., 2006): astronomic tides, wave setup, wave run-up, inverse barometer effect, and wind-driven storm surge. Of these storm tide processes, the long-wave components involve the astronomic tides, the inverse barometer effect (caused by pressure variations), and wind-driven storm surge. In addition, freshwater river inflows may act to increase water surface elevations within the estuary during a storm tide event. Understanding the impact of these various long-wave forcing mechanisms on water surface elevations in the estuary is especially important for maintenance purposes (e.g., channel/inlet stability) and local emergency response (e.g., hurricane-induced flooding).

The wind and pressure effects caused by a hurricane approaching the East Coast of the United States extend well beyond the radius of maximum wind (Hsu and Yan, 1998). These large-scale features of the hurricane provide a meteorological influence not only over the region of interest (locally), but also away from the region of interest (remotely). This dual nature of the meteorological forcing has been studied using analytical methods (e.g., see Wong and Moses-Hall (1998)); however, the simplifications made in this study are not pertinent to the complex estuaries observed in reality. Therefore, numerical models have been applied to real Coastal systems (Peng et al., 2006 [Charleston Harbor]; Shen et al., 2006 [Chesapeake Bay]) in order to further shed light on the local and remote effects of the meteorological forcing.

With the implementation of numerical models it becomes necessary to adequately discretize the computational domain for the region of interest, with sufficient resolution and a consideration of boundary conditions. Blain et al. (1994) studied hurricane-induced storm surge in the Gulf of Mexico and concluded that a large domain modeling approach facilitates simple boundary condition specification and minimizes the influence of boundary conditions on storm surge generation in Coastal regions. On the other hand, for a localized domain, particular care needs to be taken with respect to the proper specification of open-ocean boundary conditions (Mathew et al., 1996). In addition to the consideration of domain size, adequate grid resolution is crucial for the numerical simulation of storm surge in Coastal regions (Westerink et al., 1992). These constraints make nested models (Peng et al., 2006) and unstructured grid models (Shen et al., 2006) favorable choices for simulating the storm tide along Coasts and within estuaries.

The St. Johns River (Fig. 1), located in Northeastern Florida, is the longest river (500 km) contained wholly within the State of Florida. The river bottom (or channel invert) drops only 2.2 cm per km of length (slope = 0.000022); the St. Johns River has a flat bottom with little inclination along its longitudinal axis. With regards to the river’s hydraulics, the near flat bathymetric profile of the St. Johns River permits tide-induced flow reversal to extend 170 km upstream from its mouth at Mayport. Tidal flow in the St. Johns River is further complicated by the addition of freshwater river inflows, which become significant during and after storm events (Bergman, 1992). Further, while wind waves are known to be prevalent during storm events, especially along the Coast and at the inlet of the estuary (Funakoshi et al., 2008), the long-wave dynamics of the storm tide can be considered to dominate water surface elevations in the St. Johns River during meteorological episodes.

2005 Atlantic hurricane season

The 2005 Atlantic hurricane season was the most active Atlantic hurricane season in recorded history, producing a record 28 tropical and subtropical storms, of which a record 15 became hurricanes. We simulate water surface elevations in the St. Johns River over a 122-day time period spanning June 1–September 30, 2005, where this simulation timeframe is chosen to include most of the 2005 Atlantic hurricane season. We did not simulate the entire hurricane season due to the availability wind/pressure data; however, included in the 122-day simulation timeframe is an extreme meteorological event for the St. Johns River, Hurricane Ophelia (September 6–23, 2005). In fact, the slow and erratic track of Hurricane Ophelia provided a persistent strong wind as the storm paralleled the East Coast of the United States from Florida to North Carolina between September 7 and 16, 2005 (Beven and Cobb, 2005).

Hydrodynamic model

Tidal and storm surge computations are performed using ADCIRC-2DDI (http://www.adcirc.org/), the depth-integrated option of a set of two- and three-dimensional, fully nonlinear, hydrodynamic codes named ADCIRC (Luetich et al., 1992). ADCIRC-2DDI solves the vertically integrated equations of mass and momentum conservation, subject to the hydrostatic pressure approximation. Herein, we assume that pressure gradients do not contribute appreciably to the storm surge, and that the storm surge can be modeled sufficiently as a barotropic process. Of course, when interested in velocities, the baroclinic component should be considered in addition to the barotropic component; however, in the following study, our interest will be on elevations, and we thus neglect baroclinic effects in the modeling approach. We leave the inclusion of baroclinic effects to future communication, where such an analysis would contain comparisons between observed and computed velocities.
For the applications presented in this paper, the hybrid bottom friction formulation is used, baroclinic and advective terms are neglected, and the lateral diffusion/dispersion terms are enabled, leading to the following set of balance laws in primitive, nonconservative form, expressed in a spherical coordinate system (Kolar et al., 1994a):

\[
\frac{\partial \zeta}{\partial t} + \frac{1}{R \cos \phi} \left( \frac{\partial \phi}{\partial \zeta} \right) = 0
\]

(1)

\[
\frac{\partial U}{\partial t} - \left( \tan \frac{\phi}{R} + \frac{f}{R} \right) V = -\frac{1}{R \cos \phi} \frac{1}{\rho_0} \left( p_s + g \left( \zeta - h \right) \right)
\]

(2)

\[
\frac{\partial V}{\partial t} + \left( \tan \frac{\phi}{R} + \frac{f}{R} \right) U = -\frac{1}{R \cos \phi} \frac{1}{\rho_0} \left( p_s + g \left( \zeta - h \right) \right)
\]

(3)

where depth-integrated momentum dispersion in the longitudinal and latitudinal directions, respectively, is given by (Blumberg and Mellor, 1987; Kolar and Gray, 1990):

\[
M_{\phi,\theta} = \frac{E_0}{R^2} \frac{1}{\cos^2 \phi} \frac{\partial^2 (U, V)}{\partial \phi^2} + \frac{\partial^2 (U, V)}{\partial \phi^2}
\]

(4)

and \( t \) = time; \( \lambda, \phi \) = degrees longitude (East of Greenwich positive) and latitude (North of equator positive), respectively; \( U, V \) = depth-integrated velocity in the longitudinal (traversing meridians of longitude/East–West movement) and latitudinal (traversing parallels of latitude/North–South movement) directions, respectively; \( H \) = total height of the vertical water column, \( h + \zeta \); \( h \) = bathymetric depth, relative to mean sea level (MSL); \( \zeta \) = free surface elevation, relative to MSL; \( R \) = radius of the Earth; \( f = 2 \Omega \sin \phi \) = Coriolis parameter; \( \Omega \) = angular speed of the Earth; \( p_s \) = atmospheric pressure at the free surface; \( \rho_0 \) = reference density of water; \( g \) = acceleration due to gravity; \( \alpha \) = effective Earth elasticity factor; \( E_0 \) = horizontal eddy viscosity; \( \alpha_s, \alpha_a \) = applied free surface stress in the longitudinal and latitudinal directions, respectively; \( \tau \) = quadratic bottom stress; \( \eta \) = Newtonian equilibrium tide potential (Reid, 1990). It is also relevant to note that the wetting and drying algorithm contained within ADCIRC-2DDI is implemented to allow for the simulation of flood inundation and recession in nearshore and inland regions; however, we remark that our present discretization of the St. Johns River does not include major regions of wetting and drying. In fact, the computational mesh is designed to describe hydrodynamics within the river banks, and wetting and drying is very minimal in the simulations presented. We note that recent advancements have improved the wetting and drying algorithm within ADCIRC, and it would be interesting to apply the improved algorithm to the numerical experiments conducted herein. However, such application should also work with an updated version of the computational mesh, one which contains major regions of wetting and drying, and we leave this to be the subject of future work.

Eqs. (1)–(3) are reformulated into a Generalized Wave Continuity Equation (GWCE) to provide highly accurate, noise free, finite element-based solutions to the shallow water equations (Luettich et al., 1992). The GWCE is derived by combining a time-differentiated form of the primitive continuity equation and a spatially differentiated form of the primitive, conservative momentum equations, and adding to this result, the primitive continuity equation multiplied by a constant in time and space, followed by a transformation of the advective terms into nonconservative form. The GWCE is solved in conjunction with the primitive, nonconservative momentum equations using a standard Galerkin finite element method on linear, triangular finite elements in space, and a three-time-level implicit scheme in time. Considerably more detailed presentations of ADCIRC-2DDI are given by Luettich et al. (1992), Kolar et al. (1994a) and Westerink et al. (1994).

**Meteoroological forcing**

Storm surge is a meteorologically induced, long-wave motion, which results from the combined action of extreme wind stress and, to a lesser degree, reduced atmospheric pressure on shallow shelf seas. All of the necessary wind- and pressure-field data (which are applied in this study) corresponding to the 122-day simulation timeframe (June 1–September 30, 2005) were computed using the Interactive Objective Kinematic Analysis (IOKA) system (Cox et al., 1995) in which tropical storm winds and local measurements are blended into a synoptic-scale wind and pressure-field provided by the National Center for Environmental Protection Global Forecast System (NCEP GFS).

A tropical wind field model, herein referred to as TC96 (Thompson and Cardone, 1996), governed by vertically averaged equations of motion that describe horizontal airflow through the planetary boundary layer (Cardone et al., 1994) was applied to each tropical system within the computational domain. Following the assumption that the structure of the tropical cyclone changes relatively slowly over time, TC96 calculates snapshots (in time) that represent distinct phases of the storm’s evolution. TC96 is driven by the National Hurricane Center/Tropical Prediction Center track and intensity information as well as by data obtained from hurricane hunter aircraft and analyzed by the Hurricane Research Division Wind Analysis System (Powell et al., 1998). An exponential pressure law is employed in order to determine a radially symmetric pressure-field centered at the eye of the storm (Holland, 1980).

Local wind measurements from Jacksonville International Airport, Jacksonville Naval Air Station, Mayport, and St. Augustine were assimilated into the IOKA system to provide local-scale wind response over the St. Johns River. Fig. 2 shows the time history of winds at the Jacksonville Naval Air Station compared to the NCEP GFS winds before IOKA assimilation. Wind and pressure data were derived on an hourly basis at the ADCIRC nodal locations. The IOKA process was carried out on an analysis grid of 28-km spacing, in general, except to depict the cyclone winds at higher resolution, where the cyclone model-generated winds in the inner core of the tropical cyclone (overlaid at higher spatial resolution of 2 km spacing) before the wind fields were interpolated to the ADCIRC nodes. The IOKA process adds resolution over that provided by the NCEP GFS winds by virtue of the analyst assisted kinematic analysis process and the assimilation of all in situ marine and Coastal data including the three land stations cited above. Certainly, there are parts of the ADCIRC mesh where the nodal spacing is finer than the resolution of the wind and pressure-fields, but in such areas the resolution of the mesh is dictated by factors other than meteorological forcing, such as water depth variations, Coastal configuration and, of course, the geomorphology of the river itself.

Wind speeds and atmospheric pressures were then processed for each specified time step, using the quadratic drag law proposed by Garratt (1977) to transform the wind speeds (acting 10 m above the surface) \( V_{10} \) to wind stresses \( \tau_s \):

\[
\tau_s = \rho_u C_D V_{10}^2 \quad C_D = 0.001(0.75 + 0.067\nu_{10})
\]

where \( \rho_u \) relates to the density of air and \( C_D \) corresponds to a wind speed-dependent wind drag coefficient. (It is noted that wind and pressure effects are treated the same whether onshore or offshore, based on the fact that land-based meteorological data was used towards the generation of the wind forcing.) An inverted barometer
Effect is applied in order to transform the atmospheric pressures (in stress units) $p_r$ into equivalent water heights $p_g$:

$$p_g = \frac{p_r}{\rho_w g}$$

where $\rho_w$ relates to the density of seawater and $g$ corresponds to acceleration due to gravity. The inverted barometer effect is incorporated into the governing equations through the barotropic pressure gradient term (that which contains $p_S$) of the shallow water momentum equations (see Eqs. (2) and (3)).

The hindcast includes the time period (September 6–23, 2005) when Hurricane Ophelia was passing offshore to the East of the St. Johns River. At closest approach, the eye was some 250 km away from the St. Johns River with a central pressure of 997 hPa. Local sustained wind response to the storm was in the range of 13–17 m/s, with total rain accumulations upwards of 5 cm locally (Beven and Cobb, 2005).

**Computational domains**

Three computational domains of widely varied sizes are selected (Table 1) to demonstrate the relationship between domain extent and computed storm tide response for the St. Johns River. The Western North Atlantic Tidal (WNAT) model domain serves as the basis for the large-scale modeling approach employed herein (Fig. 3). The WNAT model domain describes the Caribbean Sea, the Gulf of Mexico, and the Western North Atlantic Ocean found West of the 60° West Meridian, and has been shown to perform well in simulations of astronomic tides for the deep ocean and continental shelf margins (Hagen et al., 2006). An unstructured, finite element mesh for the WNAT model domain has been developed using a Localized Truncation Error Analysis (Hagen et al., 2001) to provide increased spatial resolution where the hydrodynamics are known to change rapidly over a short distance (e.g., along the continental shelf break). The Surface-water Modeling System (Zundel, 2005) is then used to incorporate the lower 170 km of the St. Johns River into the WNAT model domain; the resulting mesh is of a large-scale (i.e., ocean-based) and will herein be referred to as OCEAN (Fig. 3).

Table 1 conveys the high gradation of the OCEAN mesh, where elements reduce by nearly four orders of magnitude, from a maximum size of 134.4 km in the deep ocean to a minimum size of 34.6 m in the St. Johns River. In addition, bathymetry described by the OCEAN mesh varies by three orders of magnitude, from a maximum depth of 7620 m in the deep ocean (Table 1) to minimum depths on the order of meters in the St. Johns River.

Element sizes on the order of kilometers define the shoreline of Florida’s East Coast; a transition is specified to allow the element sizes to reduce to about 150 m at Mayport (the inlet which services the St. Johns River). Varied levels of spatial resolution (ranging from 50 to 500 m) are used to represent the shorelines and interior of the St. Johns River (Funakoshi, 2006). Local bathymetry (for all river channels and the inlet) is specified according to data supplied by the St. Johns River Water Management District; depths for the deep ocean and continental shelf margins are based on the WNAT model domain (Hagen et al., 2006). All bathymetry is referenced from NAVD88 (North American Vertical Datum of 1988).
Three computational domains are applied in various numerical experiments. First, an inlet-based mesh (herein referred to as INLET; see Fig. 4) is constructed with its open-ocean boundary located just outside of the inlet (extending radially outward from Mayport with a radius of approximately 10 km) to be representative of the localized modeling approaches used by many practicing Coastal engineers for storm tide simulation in the St. Johns River. Second, a shelf-based mesh (herein referred to as SHELF; see Fig. 5) is constructed as a superset of the INLET mesh, with its open-ocean boundary located on the continental shelf (extending radially outward from Mayport with a radius of approximately 350 km) in order to examine uniquely the impacts of the deep ocean and the continental shelf on storm tide generation for the St. Johns River. An ocean-based mesh (herein referred to as OCEAN; see Fig. 3) is constructed as a superset of the SHELF mesh, which homes in on the St. Johns River from the Western North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea.

**Code initialization and methodology**

The model parameters and applied boundary conditions are specified as follows: simulations begin from a cold start; 122 days (June 1–September 30, 2005) of real time is simulated; applied boundary forcings are ramped over a period of 15 days; a time step of 2 s is used to ensure model stability (Luettich et al., 1992); a no-flow boundary condition is specified along all land boundaries. To facilitate the finite element-based solution to the shallow water flow boundary condition is specified along all land boundaries. To examine uniquely the impacts of the deep ocean and the continental shelf on storm tide generation for the St. Johns River. An ocean-based mesh (herein referred to as OCEAN; see Fig. 3) is constructed as a superset of the SHELF mesh, which homes in on the St. Johns River from the Western North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea.

The hybrid bottom friction formulation is employed with the minimum bottom friction factor $C_{f, \text{min}} = 0.0025$, break depth $H_{\text{break}} = 10$ m, and the two dimensionless parameters $\theta = 10$ and $\gamma = 1/3$:

$$
\tau_z = C_f \sqrt{U^2 + V^2} \frac{H}{V} ; \quad C_f = C_{f, \text{min}} \left[ 1 + \left( \frac{H_{\text{break}}}{H} \right)^\theta \right]^\gamma
$$

where $\tau_z$ = quadratic bottom stress (see Eqs. (2) and (3)). The hybrid bottom friction formulation provides a depth-dependent bottom friction coefficient to allow, in general, for larger values in shallower waters and smaller values in deeper waters. Across the wide range of depths within the model domain (varying by over three orders of magnitude), the hybrid bottom friction formulation results in a quadratic bottom friction relationship in deep waters and pseudo-Manning's bottom friction behavior in shallow waters. The “pseudo” modifier is used here to imply the more linear behavior, typical of that associated with a Manning's bottom friction, which results from the hybrid bottom friction formulation in shallow waters. The break depth is specified domain-wide, at a depth of 10 m (Luettich et al., 1992), where this setting defines the delineation from deep to shallow water. The hybrid bottom friction formulation is justified since roughness naturally increases in the shallowest of waters.

Seven principal tidal constituents ($K_1, O_1, M_2, S_2, N_2, K_s, Q_1$) are used as tidal elevation forcings along the open-ocean boundary: the OCEAN mesh applies these tidal boundary conditions along the 60° West Meridian; the open-ocean boundaries of the SHELF and INLET meshes are forced with harmonic data (corresponding to these same seven principal tidal constituents) extracted from the OCEAN mesh application. Freshwater river inflows (resolved at 30-min time intervals) are applied at five locations along the St. Johns River (Fig. 1), where these data (collected from the United States Geological Survey) represent streamflow and precipitation received from the drainage basin of the St. Johns River. Meteorological inputs (winds and pressures) are updated every 30 min, where these forcing data are applied over the surface of the model domain. A hydrograph boundary condition is applied (see Table 2) along the open-ocean boundaries of the SHELF and INLET meshes, where the associated forcing data are extracted from the OCEAN mesh application.
mesh application. Model performance is evaluated at four National Ocean Service (NOS) gaging stations located along the St. Johns River (Fig. 1).

A total of sixteen simulations are performed (Table 2) in order to explore the relative importance of three long-wave forcing mechanisms for the St. Johns River: (1) astronomic tides; (2) freshwater river inflows; (3) winds and pressure variations. Foremost, the first four experiments presented in Table 2 are analyzed with respect to the simulation of astronomic tides. Intercomparing Experiments 1–3 (which apply the OCEAN, SHELF, and INLET meshes, respectively, in tide-only simulations) will reveal the influence of domain size on computed tidal behavior. Comparing Experiments 3 and 4 (which apply the INLET mesh is tide-only simulations, without and with the advective terms enabled, respectively) to one another will reveal the influence of advection on computed tidal behavior.

Following, the INLET mesh is applied with freshwater river inflows as boundary forcings, supplementary to the imposed tidal elevations (see Experiment 5), in order to explore the role of watershed drainage to the storm tide. Then we wish to examine the relative contribution from arising from the meteorological forcing. The three model domains (INLET, SHELF, OCEAN) are applied with winds and pressures as surface forcings and with freshwater river inflows and astronomic tides as boundary forcings (see Experiments 6–8). Experiments 6–8 also offer the opportunity for us to explore the impact of domain size on the computed water surface elevations; the consideration here is that domain size can be thought of as a model parameter, which we will show can be significant in describing the storm tide in the estuary.

Next, we wish to examine the applicability of using a hydrograph boundary condition to force the SHELF and INLET meshes. The SHELF and INLET model domains are applied with winds and pressures as surface forcings and with freshwater river inflows
Simulation results and discussion

Astronomic tides

Tidal fluctuations provide a major contribution to the long-wave motion of the storm tide (Graber et al., 2006), and thus, we are motivated to verify the numerical model towards simulating the astronomic tides within the St. Johns River. The OCEAN model domain is applied with freshwater river inflows and astronomic tides as boundary forcings and with winds and pressures applied uniquely (see Experiments 12 and 13) in order to assess the individual contributions of winds and pressures on the storm tide. In addition, we wish to examine the nonlinear interaction between winds and pressure variations. The OCEAN model domain is applied without any boundary forcings, but with different surface forcings in order to simulate the wind-only, pressure-only, and wind–pressure combined responses in water surface elevations (Experiments 14–16).

Table 2

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This table presents the sixteen simulations performed in this study, detailing the domain type, advection settings, forcings applied, and whether surface or boundary conditions were used. Each experiment explores different combinations of forcings to assess their impact on water surface elevations.

The harmonic analysis utility contained within ADCIRC-2DDI (Luetich et al., 1992) is applied to the last 45 days of the simulated water surface elevations in order to determine the harmonic information relating to 23 tidal constituents (with frequencies ranging from fortnightly to eighth-diurnal speeds). Harmonic tidal constituents are sourced from NOS, derived from the application of the OCEAN mesh in Experiment 1. We compare the harmonic tidal constituents of the historical tidal constituent dataset. The next steps involve assessing the tidal performance of the various simulations through the use of tidal resynthesis (35 historical; 23 model). Table 3 provides a means by which to quantitatively assess the tidal performance of the various simulations. The RMS error is calculated using the formula:

$$\text{RMS} = \sqrt{\frac{1}{N} \sum (\text{Hist}_i - \text{Mod}_i)^2}$$

where $\text{Hist}_i$ relates to the historical tidal elevation at time $i$, $\text{Mod}_i$ corresponds to the model tidal elevation at time $i$, and $N$ refers to the total number of data points used in the error estimation.
computational meshes in terms of water surface elevations, with respect to the extent of the computational domain. First, we note that a vast majority of the RMS errors shown in the top three rows of Table 3 are less than 10 cm, demonstrating that the astronomic tides are faithfully simulated by the numerical model, regardless of the domain extent used. While the RMS errors presented in the top three rows of Table 3 demonstrate a high reliability for all three computational domains (OCEAN, SHELF, INLET) to simulate astronomic tides in the St. Johns River, the OCEAN mesh application yields the best solution for three (I-295 Bridge, Red Bay Point, Buffalo Bluff) of the four NOS gaging stations. It is entirely sufficient to apply a localized domain for the simulation of astronomic tides; however, this modeling approach requires the prescription of appropriate boundary conditions, which are typically derived from a large-scale tidal simulation. In our large-scale simulation of astronomic tides only, the OCEAN mesh is used, which also contains the high-resolution description of the St. Johns River. We have not demonstrated the utility of an alternative large-scale mesh (e.g., one that provides a coarse representation of the St. Johns River, or even one that neglects the St. Johns River altogether) for the generation of shelf- or inlet-based tidal boundary conditions. With our interest in water levels, we argue that the high-resolution of the estuary is insignificant with respect to the mass balance of the regional system, whereby tidal elevations

Fig. 6. Tidal resynthesis plots for: (a) Mayport, (b) I-295 Bridge, (c) Red Bay Point, and (d) Buffalo Bluff. The model results being shown here correspond to the simulation output (astronomic tides) attained from the OCEAN mesh application in Experiment 1 of Table 2.
occurring on the shelf or at the inlet (where the large-scale model output will be used as boundary forcings for the localized domains) will not be a function of the local description of the St. Johns River. On the other hand, we would expect that the high-resolution of the estuary to be significant with respect to the momentum balance of the regional system, whereby tidal velocities occurring offshore will be a function of the local description of the St. Johns River.

Advection relates to a horizontal motion, where in shallow water Coastal systems, the spatial change in the horizontal motion \( \nabla \mathbf{u} \) may be affected by the horizontal motion itself \( \mathbf{u} \), and vice versa:

\[
(\mathbf{u} \cdot \nabla) \mathbf{u}
\]

where the advective terms (expressed in a spherical coordinate system) can be included on the left-hand sides of the shallow water momentum equations (see Eqs. (2) and (3)) in order to describe the advective processes occurring in the astronomic tides:

\[
\frac{1}{R \cos \phi} \frac{\partial U}{\partial \phi} + \frac{1}{R} \frac{\partial U}{\partial \phi}
\]

(11)

\[
\frac{1}{R \cos \phi} \frac{\partial V}{\partial \phi} + \frac{1}{R} \frac{\partial V}{\partial \phi}
\]

(12)

Experiments 3 and 4 of Table 3 provide a means by which to quantitatively assess the tidal performance of the INLET mesh in terms of water surface elevations, with respect to the enabling/disabling of the advective terms in the shallow water momentum equations (see Eqs. (2) and (3)). Vast improvement is observed across all four NOS gaging stations when advection is enabled in the tidal simulations (see Experiments 3 and 4 of Table 3), where greater improvement (about a 50% reduction in RMS error) is attained further upstream (e.g., at Buffalo Bluff) and less improvement (about a 15% reduction in RMS error) is attained further downstream (e.g., at Mayport), indicating that highly advective flows exist throughout the St. Johns River and contribute to the astronomic tides. In a shallow water Coastal system with considerable length such as the St. Johns River (about 170 km), horizontal motions in the astronomic tides have a greater potential to be affected by the spatial gradient in the horizontal motion, and vice versa. Further, while we show that advection improves the simulated water levels, it must also be recognized that advection would contribute to the simulated flow field.

### 122-Day simulation timeframe

**Freshwater river inflows**

The vast size of the drainage basin (22,000 km², encompassing most all of the Northeastern Florida) results in dramatic influxes of freshwater into the St. Johns River during and after storm events (Bergman, 1992). Experiment 5 applies the INLET mesh with freshwater river inflows as boundary forcings, supplementary to the imposed tidal elevations, in order to explore the contributing role of watershed drainage to the storm tide. Fig. 7 displays water level plots for the four NOS gaging stations where historical data/model output comparisons are performed; the model results being shown in these water level plots correspond to the simulation output (astronomic tides and freshwater river inflows) attained from the INLET mesh application in Experiment 5. Observed and computed water levels are shown for a 15-day period (September 3–18, 2005) of the 122-day simulation timeframe, to include the effects of Hurricane Ophelia (Fig. 7). All graphical plots of the simulation results are shown for the 15-day period of Hurricane Ophelia (September 3–18, 2005), which begins before the start of the official storm track (September 6, 2005). We choose to show simulation results prior to the official start date since the historical data show a meteorological response during this time; plus, we are interested in observing the capabilities of the different model implementations to capture this meteorological response.

There is an apparent meteorological influence caused by Hurricane Ophelia (Fig. 7), and it is clear that the numerical model is insufficient (to simulate the associated response in water levels) when the only forcing mechanisms applied are astronomic tides and freshwater river inflows. In fact, an intercomparison of the RMS errors presented in Experiment 5 of Table 3 (unnamed versus parenthesized) highlights the meteorological influence of Hurricane Ophelia over the 9-day period spanning September 6–15, 2005. For example, an RMS error of approximately 20 cm is computed (across all four NOS gaging stations) when the entirety of the 122-day simulation timeframe is evaluated. A significantly greater RMS error (of approximately 50 cm) is computed (across all four NOS gaging stations) when the 9-day period (of the 122-day simulation timeframe) that includes Hurricane Ophelia (September 6–15, 2005) is evaluated.

While the volume of freshwater river inflow entering the St. Johns River is significant in terms of hydrologic runoff, it can be considered minor when compared to the scales of the river geometry (e.g., overall storage capacity) and the hydrodynamics of interest (e.g., astronomic tides). For example, over the 15-day period associated with Hurricane Ophelia (September 3–18, 2005), we calculate the discrete flux entering the model domain, in the form of freshwater river inflow, as a total volume of 0.03 km³. Applying this total volume over the surface area of the St. Johns River (about 600 km²) all at once would result in an instant water level rise of just over 5 cm. The minimal influx of hydrologic runoff is for Hurricane Ophelia, which did not make a direct landfall on the state of Florida; freshwater river inflows should not necessarily be neglected, for example, with more significant rainfall events (e.g., Tropical Storm Fay in 2008).

**Local winds and pressure variations**

It is demonstrated that astronomic tides and freshwater river inflows alone are insufficient towards simulating water surface elevations over the 122-day simulation timeframe, especially for...
the 9-day period (September 6–15, 2005) that includes Hurricane Ophelia (Fig. 7 for graphical results; see Experiment 5 of Table 3 for quantitative results). It then behooves us to apply a meteorological forcing over the localized domain, where winds and pressure variations are applied over the surface (and astronomic tides and freshwater river inflows are applied along the boundary) of the INLET mesh (Experiment 6). Fig. 8 displays water level plots for the four NOS gaging stations where historical data/model output comparisons are performed; the model results being shown in these water level plots correspond to the simulation output (astronomic tides, freshwater river inflows, and local winds and pressure variations) attained from the INLET mesh application in Experiment 6. Observed and computed water levels are shown for a 15-day period (September 3–18, 2005) of the 122-day simulation timeframe, to include the effects of Hurricane Ophelia (Fig. 8).

There is an apparent meteorological influence caused by Hurricane Ophelia (Fig. 8), and it is clear that local winds and pressure variations must be applied collectively with astronomic tides and freshwater river inflows in order to more adequately simulate the associated response in water levels. Moreover, an intercomparison of the RMS errors presented in Experiments 5 and 6 of Table 3 further highlights the importance of incorporating local winds and pressure variations into the storm tide simulation. For instance, when the 9-day period (of the 122-day simulation timeframe) that includes Hurricane Ophelia (September 6–15, 2005) is evaluated,
the inclusion of local winds and pressure variations yields a reduction in the RMS error (across all four NOS gaging stations) from 50 to 25 cm (see parenthesized values in Table 3; Experiment 5 versus Experiment 6). In fact, when the entirety of the 122-day simulation timeframe is evaluated, the inclusion of local winds and pressure variations yields a reduction in the RMS error (across all four NOS gaging stations) from 20 to 15 cm (see unformatted values in Table 3; Experiment 5 versus Experiment 6). While the surrounding topography reduces the wind effect locally over the St. Johns River, its extended length and vast surface area permits significant wind-driven motions to develop. Indeed, the large-scale of the meteorological forcing excites a circulation throughout the entirety of the St. Johns River, one which exceeds the motions induced by hydrologic runoff.

**Domain size**

While all three computational domains (OCEAN, SHELF, INLET) are suitable for simulating astronomic tides in the St. Johns River, the influence of domain size on computed storm tide behavior is an important consideration (Blain et al., 1994). Consider our interest towards simulating water levels in the St. Johns River, where we differentiate this study from that of Blain et al. (1994) by assessing the impact of domain size on computed storm tide elevations not just along Florida’s East Coast, but also 170 km upriver.

![Fig. 8. Water level plots for: (a) Mayport, (b) I-295 Bridge, (c) Red Bay Point, and (d) Buffalo Bluff. The model results being shown here correspond to the simulation output (astronomic tides, freshwater river inflows, and local winds and pressure variations) attained from the INLET mesh application in Experiment 6 of Table 2. A 15-day period of the 122-day simulation timeframe is displayed to contain the effects of Hurricane Ophelia (September 3–18, 2005).](image-url)
Our next goal, then, is to apply the SHELF and OCEAN meshes with the following forcing mechanisms (Experiments 7 and 8): astronomic tides and freshwater river inflows along the boundary; winds and pressure variations over the surface. The INLET mesh application of Experiment 6 serves as the basis to which the SHELF and OCEAN mesh applications of Experiments 7 and 8 will be compared. Since the OCEAN, SHELF, and INLET meshes have identical discretizations over corresponding regions, and because the numerical simulations all employ the same model parameters and meteorological forcing, any observed differences between the respective model results can be attributed to domain size.

An intercomparison of the RMS errors presented in Experiments 6–8 of Table 3 demonstrates the relative performance of the INLET, SHELF, and OCEAN meshes towards simulating the storm tide in the St. Johns River. Foremost, the SHELF mesh application produces virtually the same model response as that produced by the INLET mesh (see Table 3; Experiment 6 versus Experiment 7). Despite the minor difference in computed RMS errors (less than 10%) for Mayport, it is concluded that the continental shelf features described by the SHELF mesh (and not described by the INLET mesh) provide no significant advantage to the storm tide simulation. It then motivates us to evaluate the performance of the OCEAN mesh application in Experiment 8. Interestingly, over the 9-day period (of the 122-day simulation timeframe) that includes Hurricane Ophelia (September 6–15, 2005), a 30% reduction in RMS error is observed (across all four NOS gaging stations) between the OCEAN

![Fig. 9. Water level plots for: (a) Mayport, (b) I-295 Bridge, (c) Red Bay Point, and (d) Buffalo Bluff. The model results being shown here correspond to the simulation output (astronomic tides, freshwater river inflows, and local and remote winds and pressure variations) attained from the OCEAN mesh application in Experiment 8 of Table 2. A 15-day period (of the 122-day simulation timeframe) is displayed to contain the effects of Hurricane Ophelia (September 3–18, 2005).](image-url)
and INLET mesh applications (see parenthesized values in Table 3; Experiment 6 versus Experiment 8). In fact, when we consider the full 122-day simulation timeframe, the OCEAN mesh application provides the best solution for all cases considered thus far (see unformatted values in Experiment 8 of Table 3).

The length scales of a hurricane approaching the East Coast of the United States (upwards of about 500 km) far exceed the length scales of the open-ocean boundaries of the INLET and SHELF meshes (approximately 10 and 350 km, respectively). On the contrary, the vast expanse of the OCEAN mesh allows for it to fully encompass the large-scale features of the hurricane. Further, the large size of the OCEAN mesh permits for a simulation of the storm tide as the hurricane develops in the deep ocean, propagates onto the continental shelf, and enters the estuary. By comparison, the smaller sizes of the INLET and SHELF meshes yield them incapable of describing the storm tide dynamics in the deep ocean and over the continental shelf.

Our model results align with the findings of previous works, where a localized domain will underestimate the peak elevation of the storm tide (Fig. 8). The studies of Blain et al. (1994), Peng et al. (2006) and Shen et al. (2006) reveal the need to employ a large-scale computational domain in order to more fully simulate the storm tide. Importantly, we differentiate our study from those of Peng et al. (2006) and Shen et al. (2006) by employing the WNAT model domain as the basis of the OCEAN mesh. While Peng et al. (2006) and Shen et al. (2006) extend the computational domain to encompass the region of interest and only a small portion of the deep ocean, we extend the OCEAN mesh out to the 60° West Meridian to comprise a large expanse of the deep ocean. Fig. 9 displays water level plots for the four NOS gaging stations where historical data/model output comparisons are performed; the model results being shown in these water level plots correspond to the simulation output (astronomic tides, freshwater river inflows, and local and remote winds and pressure variations) attained from the OCEAN mesh application in Experiment 8. Observed and computed water levels are shown for a 15-day period (September 3–18, 2005) of the 122-day simulation timeframe, to include the effects of Hurricane Ophelia (Fig. 9). It is clear that the OCEAN mesh not only captures the peak elevation of the storm tide, but also adequately simulates the rising and falling limbs of the storm surge hydrograph (Fig. 9). While we show that local wind effects are significant towards affecting water surface elevations in the St. Johns River (see Fig. 8 for graphical results; see Experiment 6 of Table 3 for quantitative results), the winds acting over the deep ocean have the potential to influence the storm tide not just when it is directly impacting the St. Johns River, but also as it approaches the region of interest from the deep ocean.

Hydrograph boundary condition

Computer limitations typically force many practicing Coastal modelers to select a localized domain for storm tide simulation in estuaries such as the St. Johns River. While the local wind and pressure effect can be included in the localized modeling approach, the impact due to winds and pressure variations occurring in the deep ocean can only be incorporated via a boundary condition. We note that while our large-scale simulations of the storm tide (i.e., the OCEAN model domain) employ the high-resolution description of the St. Johns River, it would be sufficient to apply an alternative large-scale mesh, which coarsely represents (or even neglects) the St. Johns River, for the generation of shelf- or inlet-based tidal boundary conditions (Salisbury and Hagen, 2007). We then test the facility of the OCEAN mesh towards providing a hydrograph boundary condition to use for the SHELF and INLET meshes. This hydrograph boundary condition contains the astronomical tides and the remote effects of the meteorological forcing. In the storm tide simulations that follow, a hydrograph boundary condition (generated by application of the OCEAN mesh) is applied along the open-ocean boundaries of the SHELF and INLET meshes (Experiments 9 and 10) in order to test this modeling approach.

The model response resulting from the SHELF mesh application (when using the hydrograph boundary condition) virtually mirrors that attained by the OCEAN mesh application (see Experiments 8 and 9 of Table 3). The same holds true when the INLET mesh is applied with the hydrograph boundary condition (see Experiments 8 and 10 of Table 3). Only when the SHELF and INLET meshes are applied with the hydrograph boundary condition (generated by application of the OCEAN mesh) is the storm tide most fully captured. It becomes clear that storm tide elevations in the St. Johns River are driven by the combined (local and remote) effects of the meteorological forcing. While the astronomical tides are a deterministic process, storm surge generated in the deep ocean and on the continental shelf is a stochastic process. Therefore, we suggest the use of a large-scale computational domain (with the forcing boundaries removed as far as possible from the region of interest) in order to more fully simulate the history of the storm tide event. An alternative modeling approach which employs model output (generated by a large domain) along the open-ocean boundaries of more localized domains is sufficient to account for the remote effects of the meteorological forcing.

Advection

The simulation results presented thus far suggest the following: (1) meteorological forcing for the St. Johns River is equal to or greater than that of astronomic tides and generally supersedes the impact of freshwater river inflows; (2) water surface elevations in the St. Johns River are dependent upon local meteorological effects, in addition to remote effects. Moreover, we have demonstrated the utility of the hydrograph boundary condition (generated by application of the OCEAN mesh) when it is applied along the open-ocean boundary of the INLET mesh (see Experiments 8 and 10 of Table 3) towards capturing the remote effects caused by the winds blowing in the deep ocean. We are now interested in examining the contribution of advection to the overall storm tide elevation.

An additional simulation was performed using the INLET mesh (in the same implementation as that used in Experiment 10), however, with advection enabled (Experiment 11). We learn that the influence of advection (see Eq. (10)) on the storm tide is minimal (see Experiments 10 and 11 of Table 3), relative to the dominance of the meteorological response. Whereas advection has the potential to influence water surface elevations along the entire 170-km length of the St. Johns River under purely tidal conditions, advection contributes little during a storm tide event, where the meteorological forcing and freshwater river inflows tend to dominate. For example, when the difference in computed RMS errors for Buffalo Bluff in Experiments 3 and 4 of Table 3 (of 5.78 cm) is compared to the tidal range at this upstream location (of approximately 30 cm; see Fig. 6d), we observe that advection can contribute to nearly as much as 20% of the tidal signal. On the other hand, when the difference in computed RMS errors for Buffalo Bluff in Experiments 10 and 11 of Table 3 (of 0.37 cm when the 9-day period [of the 122-day simulation timeframe] that includes Hurricane Ophelia [September 6–15, 2005] is considered) is compared to the peak storm tide elevation at this upstream location (of approximately 80 cm; see Fig. 7d), we observe that advection contributes to only 0.46% of the overall water level.

Pressure variations

The meteorological forcing, as it exists in nature, and the manner in which it is applied in this study, consists of two components: winds (see Eq. (5)) and pressure variations (see Eq. (6)). To this end, the OCEAN mesh was applied in two additional simulations using
different implementations of the boundary conditions to represent individually the wind and pressure variation components of the meteorological forcing (Experiments 12 and 13).

It is found that the wind component of the meteorological forcing dominates (see Experiments 8, 12, and 13 of Table 3). For example, when the entirety of the 122-day simulation timeframe is evaluated, the RMS errors computed (across all four NOS gaging stations) for Experiments 8 and 12 (refer to unformatted values) vary minimally (less than 2%), while the RMS errors computed (across all four NOS gaging stations) for Experiments 8 and 13 (refer to unformatted values) vary greatly (upwards of 30%). This same trend (where the wind component of the meteorological forcing dominates) holds true when the 9-day period (of the 122-day simulation timeframe) that includes Hurricane Ophelia (September 6–15, 2005) is evaluated; however, it also becomes clear that a greater portion of the meteorological forcing results from pressure variations during meteorological episodes (see parenthesized values in Experiments 8, 12, and 13 of Table 3).

This observed trend in the dominance of the wind forcing (over pressure effects) follows with our understanding of the meteorological forcing, where hurricane winds are known to have a broad impact over a significantly large expanse (Hsu and Yan, 1998), in comparison to hurricane-induced pressure effects which provide an isolated impact to the local area over which the storm center is positioned (Blain et al., 1994). Further, since hurricane winds are incorporated into the numerical model through use of a wind

Fig. 10. Water level plots for: (a) Mayport, (b) I-295 Bridge, (c) Red Bay Point, and (d) Buffalo Bluff. The solid curve corresponds to the simulation output (local and remote winds and pressure variations, applied collectively) attained from the OCEAN mesh application in Experiment 14 of Table 2. The dashed curve corresponds to a linear superposition of the simulation output (local and remote winds and pressure variations, applied individually) attained from the OCEAN mesh applications in Experiments 15 and 16 of Table 2. A 15-day period (of the 122-day simulation timeframe) is displayed to contain the effects of Hurricane Ophelia (September 3–18, 2005).
stress (see Eq. (5)), the large-scale of the hurricane winds are inherently described in the storm tide simulation. The inverted barometer effect associated with pressure variations results in a water level rise of no more than 3 m (about 1 m of increase per 100 hPa deficit) over the local area where the storm is centered (Reid, 1990). Consider that the lowest pressure experienced by Hurricane Ophelia over its entire history was about 25 hPa below ambient pressure (Beven and Cobb, 2005). For this worst case scenario, we can estimate a pressure-induced rise in water level (based on the inverted barometer effect) to be about 7.5 cm. Based on this estimation, we expect the wind forcing to be the dominant driver of water level changes during meteorological episodes.

The local and remote effects of the meteorological forcing are identified as significant towards simulating water levels in the St. Johns River, and while it is shown that pressure variations provide a minimal impact over the 122-day simulation timeframe, pressure effects should be considered during hurricane events. For the 9-day period (of the 122-day simulation timeframe) that includes Hurricane Ophelia (September 6–15, 2005), winds and pressure variations act simultaneously to provide completely the meteorological influence. We are still interested in examining the level of nonlinear interaction that exists between the winds and pressure variations. Therefore, we conduct three final experiments, which employ the OCEAN mesh with different applied surface forcings in order to simulate the wind-only, pressure-only, and wind–pressure combined responses in water surface elevations (Experiments 14–16).

Fig. 10 displays water level plots for the four NOS gaging stations where historical data/model output comparisons are performed, based on the simulation output (local and remote winds and pressure variations, applied collectively) from the OCEAN mesh application of Experiment 14 (winds + pressures) and a linear superposition of the simulation output (local and remote winds and pressure variations, applied individually) from the OCEAN mesh applications of Experiments 15 and 16 (winds only + pressures only). Observed and computed water levels are shown for a 15-day period (September 3–18, 2005) of the 122-day simulation timeframe, to include the effects of Hurricane Ophelia (Fig. 10). Foremost, the simulation results presented in Fig. 10 correspond to meteorologically induced water level responses and do not include the effects of astronomic tides and freshwater river inflows. An intercomparison between these meteorologically induced water level responses and the historical NOS data further reveals the contributing role of the meteorological forcing to water surface elevations in the St. Johns River. In addition, it is noteworthy that the linear superposition of the wind– and pressure-only model responses (Experiments 15 and 16) matches almost exactly with the wind–pressure combined model response (Experiment 14). While the nonlinear interaction between the winds and pressure variations is shown to be virtually nonexistent for the 9-day period (of the 122-day simulation timeframe) that includes Hurricane Ophelia (September 6–15, 2005), this may not necessarily be the case for scenarios involving landfalling hurricanes, where there would be a greater potential for local wind and pressure effects to interact with each other.

Summary and conclusions

Presented herein is an application of the ADCIRC (Advanced Circulation Model for Oceanic, Coastal, and Estuarine Waters) numerical code towards a simulation of the water surface elevations in the St. Johns River (Northeastern Florida) for a 122-day time period spanning June 1–September 30, 2005. Three different model domains provide a high-resolution description of the St. Johns River, but with different placements of the open-ocean boundary. Various implementations of the model domains use different combinations of boundary and surface forcings with respect to astronomic tides, freshwater river inflows, winds and pressure variations. The role of advection, as it contributes to the astronomic tides and storm tide elevations in the St. Johns River, is explored.

We show that meteorological forcing for the St. Johns River is equal to or greater than that of astronomic tides and generally supersedes the impact of freshwater river inflows, while pressure variations provide a minimal influence. To this end, astronomic tides and winds are identified as necessary long-wave forcing mechanisms to include for a robust numerical model of the St. Johns River. We demonstrate that for Hurricane Ophelia (which did not make a direct landfall on the study area) pressure variations induced a negligible effect on water levels in the St. Johns River; we do not present the following herein, but acknowledge that for scenarios involving landfalling hurricanes, pressure effects could become quite significant. Further, the water level responses to winds and pressure variations may be linearly superimposed (for the cases considered in this study), suggesting that the interaction between the winds and pressure variations is weakly nonlinear.

Although one’s work may be focused on a single estuary, the storm tide dynamics occurring far away from the estuary (in the deep ocean and on the continental shelf) must be considered when one is interested in water levels inside of the estuary. By holding all relevant variables constant throughout our numerical experiments (e.g., identical discretizations over corresponding regions, same model parameters and meteorological forcing), we show that winds and pressure variations acting over the continental shelf and deep ocean are major contributors to the storm tide. To this end, regardless of whether a numerical model locates its open-ocean boundary at the inlet or on the continental shelf, it will perform well given a hydrograph boundary condition (generated by a large-scale [i.e., ocean-based] computational domain) that includes the astronomic tides and the remote effects of the meteorological forcing. Blain et al. (1994) have shown that use of a hydrograph boundary condition is necessary towards simulating Coastal storm surge in the Gulf of Mexico; we expand on this modeling approach by demonstrating its applicability to the river/estuary systems located along Florida’s East Coast. We exploit the WNAT model domain and have it serve as the basis for the OCEAN mesh, where its large expanse provides us with the capability to describe the storm tide as it progresses from the deep ocean into the St. Johns River.

We restate the fact that none of the numerical models presented in the paper have been calibrated. Calibrating the numerical model prior to testing for domain size and boundary condition specification would fold in relevant features of the storm tide and would thus, invalidate the simulation results. Our message here is to test the numerical model under various implementations to learn about the impacts of domain size, forcing mechanisms, nonlinearities (e.g., advection), etc. We suggest that calibration occurs after model testing, so that the necessary model features (learned from the earlier testing) are identified and incorporated, prior to any parameter adjustment. To exemplify this point, our top-performing storm tide model (the OCEAN mesh with all forcings applied; Experiment 8) will become the starting point now for our calibration, which will focus initially on two model parameters; the bottom friction and wind drag coefficients.

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