Tidal Simulations for the Loxahatchee River Estuary (Southeastern Florida): On the Influence of the Atlantic Intracoastal Waterway versus the Surrounding Tidal Flats

Peter Bacopulos¹ and Scott C. Hagen²

Abstract: Two-dimensional tidal flows within the Loxahatchee River estuary (Southeastern Florida) are simulated in order to assess the effects of incorporating the Atlantic Intracoastal Waterway (AICWW) versus including the surrounding tidal flats in the computational domain. The region of interest is modeled with three variations of an unstructured, finite-element mesh, including a localized mesh with and without tidal flats, and an extended mesh that describes the AICWW. Phase and amplitude errors between model output and historical data are quantified in terms of water surface elevations at five locations within the Loxahatchee River estuary to assess the relative performance of the various computational meshes. While it is shown that the surrounding tidal flats provide some benefit to the numerical model, the hydrodynamics resulting from the inclusion of the AICWW results in a more significant improvement in the simulated water levels—an important modeling consideration that is commonly disregarded in practice. The application of additional boundary conditions enables for both hydrodynamic factors (AICWW; surrounding tidal flats) to be included in the numerical simulation. As a corollary, velocity residuals are computed on a domain-wide basis to reveal significantly different net circulation patterns within the Loxahatchee River estuary, depending on the level of description of the AICWW, and further demonstrate the importance of including the AICWW in the numerical model.

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CE Database subject headings: Coastal environment; Florida; Tidal currents; Finite element method.

Introduction

The flooding and ebbing of water into and out of an estuary at tidal frequencies is an important physical process due to the direct and indirect effects this exchange has on the ecology of the estuary. The tidal current is a reliable transport mechanism for planktonic plant and animal life, as well as for suspended and bedload sediments, in the sense that it is as predictable as it is rigorously periodic. Equally significant is the effect the baseline level of tidally induced transport, or the tidal residual, has on the evolution and distribution of waterborne constituents within the estuary (Nihoul and Ronday 1975; Tee 1976; Zimmerman 1978; Ianniello 1979; Robinson 1981; Friedrichs and Aubrey 1988; Lynch and Naimie 1993; Li and O’Donnell 1997).

The Loxahatchee River estuary, situated on the southeastern coast of Florida (Fig. 1), serves as a natural drainage system for its surrounding watershed, providing a means by which land-derived freshwater may be mixed with seawater (entering through Jupiter Inlet) and carried out to the Atlantic Ocean (McPherson and Sabanskas 1980; McPherson et al. 1982; Russell et al. 1984; South Florida Water Management District 2002). Jupiter Inlet is located along the Atlantic Intracoastal Waterway (AICWW) which acts as an additional hydraulic mechanism driving astronomic tides into and out of the Loxahatchee River estuary; however, the hydrodynamic influence of the AICWW on tidal behavior occurring within the Loxahatchee River estuary has not been studied and documented. Tidal behavior in the Loxahatchee River estuary is further complicated due to the wetting and drying of tidal flats which fringe the upstream river reaches, and the associated storage effects have not been assessed in terms of their impact on the astronomic tides occurring in the Loxahatchee River estuary. To better understand the hydrodynamics of this interconnected coastal system, we are motivated to simulate astronomic tides in the Loxahatchee River estuary and assess the effects of incorporating the AICWW versus including the surrounding tidal flats in the computational domain.

Three different model domains will be employed, all of them with open-ocean boundaries located on the continental shelf. Our question becomes where is it necessary to enforce boundary conditions when using a localized model for an estuary connected to the AICWW: (1) certainly along the open-ocean boundary, to account for the shelf tide and (2) possibly within the AICWW, to account for the tidal influence from the AICWW. The common practice in tide and transport modeling of Florida’s east coast is to employ a single forcing consisting of tidal elevations along the open-ocean boundary only; however, the hydraulic impact of the AICWW goes overlooked with such a modeling approach. To this end, we demonstrate the utility of applying an additional boundary condition, one which is located within the AICWW, in order to account for its hydraulic impact. This additional boundary condition is then applied to a model domain which incorporates the surrounding tidal flats in order to assess the impact of the

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combined hydrodynamic factors (AICWW; surrounding tidal flats).

In the following paper, we describe the development (with respect to domain extent, tidal flats, and alternative boundary-condition locations) of a two-dimensional, depth-integrated tidal model for the Loxahatchee River estuary. Previous modeling studies dealing with the Loxahatchee River estuary focus primarily on the tidal effects resulting from modifications made to the geometry of Jupiter Inlet (Chiu 1975; Russell and Goodwin 1987; Hu 2002), and provide little guidance toward the definition of a computational domain for the Loxahatchee River estuary and no direction regarding the application of boundary conditions within the AICWW. Further, the models employed by Chiu (1975), Russell and Goodwin (1987), and Hu (2002) are confined solely to the local region of interest, excluding major portions of the AICWW, and describe only in-bank tidal flow, neglecting the inundation of tidal flats surrounding the upstream reaches of the Loxahatchee River estuary. The modeling approach employed herein differs from these previous (more pragmatically driven) efforts to provide a modeling tool which is used to assess the impact of the AICWW and the surrounding tidal flats on the tidal behavior occurring in the Loxahatchee River estuary. Our modeling tool also provides an opportunity to assess domain-wide computed velocity residuals in terms of the hydrodynamic influence of the AICWW on net circulation patterns within the Loxahatchee River estuary. It is equally relevant to note that we are not performing a traditional hindcast (i.e., calibrating the numerical model to water surface elevations) in this study; rather, the interest is in understanding the forcing mechanisms (the AICWW versus the surrounding tidal flats) responsible for tidal fluctuations in the Loxahatchee River estuary. For example, bottom friction characterization is intentionally left out of the study so as not to bias the simulation results, where all simulation results presented herein relate to using a standard setting for bottom friction. A standard value $C_{f,min}=0.0035$ (Luettich et al. 1992) is used domain-wide for the minimum bottom friction factor. We also acknowledge that an increased frictional effect should be considered for the surrounding tidal flats, and future work will explore the sensitivity of the tidal response to adjustments in the bottom friction characterization of the surrounding tidal flats; however, our initial interest is to incorporate the additional storage volume into the model domain.

**Data Overview**

Two-year records of water-level data (sampled at 30-min intervals), for five water-level gaging stations found within the Loxahatchee River estuary (see Fig. 1 for respective locations), are obtained from the South Florida Water Management District. These water-level data are harmonically analyzed using T TIDE (Pawlowicz et al. 2002) so that the astronomic tide component of the overall water surface elevation can be extracted. Our interest in this study is on the astronomic tides, and while wind and river discharge are recognized as being important drivers of circulation in the estuary, we isolate attention on tidally driven circulation with respect to influence from the AICWW and surrounding tidal flats. A total of 64 tidal constituents are determined from the harmonic analysis procedure, where the frequencies associated with these 64 tidal constituents range from fortnightly to eighth-diurnal speeds. [See Bacopoulos, P. (2005) for a more complete description of the harmonic analysis of the water-level data for the Loxahatchee River estuary.] The tides within the Loxahatchee River estuary can be classified as microtidal (i.e., the tidal range varies between 1 and 2 m) with a strong semidiurnal character (amplitude of the $M_2$ tidal constituent around 0.315 m; form factor of 0.300). In addition, an $M_2$-$M_4$ amplitude ratio of about 5% indicates a tidal asymmetry (in response to the nonlinear growth of higher harmonics and compounds of the principal astronomic tidal constituents) for the Loxahatchee River estuary.

**Model Description**

Tidal computations are performed using ADCIRC-2DDI, the depth-integrated option of a set of two- and three-dimensional, fully nonlinear, hydrodynamic codes named ADCIRC (Luettich et al. 1992). ADCIRC-2DDI uses the vertically integrated equations of mass and momentum conservation, subject to the hydrostatic pressure approximation. For the applications presented in this paper, a hybrid bottom friction formulation is used, baroclinic terms are neglected, and the advective and lateral diffusion/dispersion terms are employed (when noted), leading to the following set of balance laws in primitive, nonconservative form, expressed in a spherical coordinate system (Kolar et al. 1994a)

\[
\frac{\partial \xi}{\partial t} + \frac{1}{R \cos \phi} \left( \frac{\partial U H}{\partial \lambda} + \frac{\partial (V H \cos \phi)}{\partial \phi} \right) = 0
\]  

\[
\frac{\partial U}{\partial t} + \frac{1}{R \cos \phi} \frac{U}{H} \frac{\partial U}{\partial \lambda} + \frac{1}{V} \frac{\partial U}{\partial \phi} = \left( \tan \phi \frac{H}{R} + f \right) V
\]  

\[
= - \frac{1}{R \cos \phi} \frac{\partial}{\partial \lambda} \left( \frac{p_{t}}{p_{0}} + g \left( \xi - \alpha \eta \right) \right) + \frac{1}{H} M_{s} + \frac{\tau_{t}}{p_{0} H} - \tau_{t} U
\]  

(2)

\[
\frac{\partial V}{\partial t} + \frac{1}{R \cos \phi} \frac{V}{H} \frac{\partial V}{\partial \lambda} + \frac{1}{V} \frac{\partial V}{\partial \phi} = \left( \tan \phi \frac{H}{R} + f \right) U
\]  

\[
= - \frac{1}{R} \frac{\partial}{\partial \phi} \left( \frac{p_{t}}{p_{0}} + g \left( \xi - \alpha \eta \right) \right) + \frac{1}{H} M_{s} + \frac{\tau_{t}}{p_{0} H} - \tau_{t} V
\]  

(3)

where depth-integrated momentum dispersion in the longitudinal and latitudinal directions, respectively, is given by
where \( t \) = time; \( \lambda \) and \( \phi \) = degrees longitude (east of Greenwich positive) and latitude (north of equator positive), respectively; \( U \) and \( V \) = depth-integrated velocity in the longitudinal and latitudinal directions, respectively; \( H \) = total height of the water column; \( h + \zeta \) = 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; \( p_{a} \) = atmospheric pressure at the free surface; \( p_{0} \) = reference density of water; \( g \) = acceleration due to gravity; \( \alpha \) = Earth elasticity factor; \( \nu_{h} \) = horizontal eddy viscosity; \( \tau_{x}, \tau_{y} \) = applied surface stress in the longitudinal and latitudinal directions, respectively; \( \tau_{s} \) = bottom stress; and \( \eta \) = Newtonian tide potential (Reid 1990).

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 (Lynch and Gray 1979; Kinmark 1985; Kolar et al. 1994b). The major advantage in employing the GWCE formulation in the solution algorithm deals with the suppression of nonphysical oscillatory modes, due to its monotonic dispersion relationship (Walters 1983; Atkinson et al. 2004). 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 \( \tau_{0} \) 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 Westernink et al. (1994b).

Frictional closure within the governing equations of ADCIRC-2DDI is achieved through the use of a hybrid formulation of the standard quadratic bottom friction parameterization, which allows for the bottom friction factor to change with respect to bathymetric depth. 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.) A break depth is specified domain-wide, usually 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. In very shallow waters, the hybrid bottom friction formulation is useful particularly when the wetting and drying of elements is implemented since this expression becomes highly dissipative as the water depth becomes small (Grenier et al. 1995). Note that wetting and drying within the ADCIRC code is treated using a thin-layer algorithm (Nielsen and Apelt 2003), which maintains a thin layer of water in nominally dry elements, thereby providing full connectivity within the GWCE, and a mass-conservative scheme.

The quadratic bottom friction function that is used within the hybrid bottom friction formulation is defined as

\[
\tau_{s} = C_{f} \frac{U^{2} + V^{2}}{H} \quad \text{where} \quad C_{f} = C_{f_{\min}} \left[ 1 + \left( \frac{H_{\text{break}}}{H} \right)^{\theta} \right]^{\gamma} \tag{5}
\]

and \( C_{f} \) = bottom friction factor; \( C_{f_{\min}} \) = minimum bottom friction factor that is approached in deep waters when the hybrid bottom friction formulation reverts to a standard quadratic bottom friction function; \( H_{\text{break}} \) = break depth to determine if the hybrid bottom friction formulation will behave as a standard quadratic bottom friction function or increase with depth similar to a Manning’s type bottom friction function; \( \theta \) = dimensionless parameter that establishes how rapidly the bottom friction factor approaches its upper and lower limits; and \( \gamma \) = dimensionless parameter that describes how quickly the bottom friction factor increases as water depth decreases. [Luettich et al. (1992) recommend values of 10 and 1/3 for the two dimensionless parameters of the hybrid bottom friction formulation, \( \theta \) and \( \gamma \), respectively.]

**Mesh Development**

Three different unstructured, finite-element meshes are developed in order to isolate the effects of domain extent on the modeling and simulation of tidal circulation within the Loxahatchee River estuary. All three finite-element meshes employ a shelf-based model domain to describe the continental shelf and the local region of interest, where “shelf-based” is used herein to imply the open-ocean boundary being located on the continental shelf. The three model domains include: (1) limited, which describes only a small portion of the AICWW to the north (5 km) and south (3 km) of the Loxahatchee River estuary, but does not include the tidal flats which fringe the upstream reaches of the Loxahatchee River estuary; (2) limited_TF, which describes the AICWW to the same extent as the limited mesh, but includes the surrounding tidal flats (TF); and (3) extended, which extends the limited mesh to describe the AICWW [through the southern portion of the Indian River lagoon (Smith 1990)] to Fort Pierce Inlet and beyond Lake Worth Inlet, to the north and south, respectively, of the Loxahatchee River estuary.

The limited mesh [Fig. 2(a)] serves as the baseline mesh in the sense that the spatial description of the Loxahatchee River estuary remains constant for all three finite-element meshes. (It is noted that the upstream river reaches of the Loxahatchee River estuary are described upstream limit where tides become insignificant.) The mesh resolution required to adequately describe the Loxahatchee River estuary ranges from 30-m node spacings at Jupiter Inlet to 100-m element sizes in the central embayment and a 30-m nodal density through the upstream river reaches [Fig. 2(b)]. The limited_TF mesh [Fig. 3(a)] is developed by appending tidal flats to the limited mesh, where inland topography is described up to the 1-m contour [Fig. 3(b)]. The 1-m contour is chosen to govern the spatial extent of the TF, due to the fact that the tidal amplitude of the Loxahatchee River estuary peaks at 0.75 m during the spring phase of the spring-neap tidal cycle, and hence, it is ensured that wetting and drying will be constrained to within the model domain. The mesh resolution used to describe the tidal flats is consistent with the element sizes (between 25 and 50 m) of the adjacent coastlines/river banks to which the tidal flats are appended. On average throughout the tidal flats, five elements span in the cross-channel direction.

The extended mesh (Fig. 4) extends the spatial coverage of the...
limited mesh by describing the AICWW and its connection to the Indian River lagoon (Smith 1990) and Lake Worth Inlet, to the north and south, respectively, of the Loxahatchee River estuary. Fort Pierce Inlet serves as the northern boundary of the extended mesh, to allow for description of the southern portion of the Indian River lagoon and St. Lucie Inlet. The southern boundary of the extended mesh lies roughly 20 km south of Lake Worth Inlet. Relative to the limited mesh, an additional 125 km of the AICWW is described by the extended mesh, permitting for the inclusion of three additional inlets (Fort Pierce; St. Lucie; Lake Worth) in the computational domain. The mesh resolution required to adequately describe these additional coastal features is governed by the coastline geometry, using a 25-m nodal density through the narrow channels of the AICWW and allowing for element sizes up to 150 m in areas of open water.

Bathymetry for the Loxahatchee River estuary is supplied by the South Florida Water Management District at a spatial resolution of about 100 m to provide coverage over the spatial extent given by the limited mesh. Bathymetry for the continental shelf is based on the Western North Atlantic Tidal (WNAT) model domain (Hagen and Parrish 2004). An assumed depth of 3.5 m below MSL is used for all regions of the AICWW that lie outside of the bathymetry-data coverage zone (i.e., areas added to the limited mesh to produce the extended mesh), to correspond with dredge-depth requirements set for the Fort Pierce-Miami stretch of the AICWW (Parkman 1983). All bathymetric information is transferred to the mesh points via a linear interpolation scheme.

Code Initialization and Methodology

The following model parameterizations and specifications of the applied boundary conditions remain constant for all tidal simulations presented herein: runs begin from a cold start and at the beginning of a tidal epoch; advective terms [see Eqs. (2) and (3)] are enabled (when noted); no-flow boundary conditions are specified along all land boundaries; the open-ocean boundary is elevation-forced with harmonic data [obtained from application of the WNAT model domain (Hagen and Parrish 2004)] corresponding to seven principal tidal constituents \( K_1, O_1, M_2, S_2, N_2, K_2, Q_1 \); applied boundary forcings are ramped over a period of 20 days (Luettich et al. 1992); a time step of \( 3 \) s is used to ensure that the Courant number criterion is satisfied throughout the computational domain (Westerink et al. 1994a); 90 days of real time is simulated; the last 45 days of the simulated water surface elevations are harmonically analyzed [using the harmonic analysis utility contained within ADCIRC-2DDI (Luettich et al. 1992)] in order to determine the harmonic information relating to 23 tidal constituents (with frequencies ranging from fortnightly to eighth-diurnal speeds). The wetting and drying algorithm is employed, with the minimum bathymetric depth set to 0.01 m (i.e., computational nodes and the accompanying elements with water depths less than the prescribed minimum bathymetric depth are considered to be dry). The hybrid bottom friction formulation [see Eq. (5)] is used, specifying the hybrid bottom friction parameter values according to Bacopoulos (2005): \( C_{f,\text{lin}} = 0.0035 \); \( H_{\text{break}} = 10 \) m; \( \theta = 10 \); and \( \gamma = 1/3 \). Horizontal eddy viscosity [see
Eq. (4)] is set to 5.0 m²/s. The GWCE weighting parameter $\tau_0$ is set to 0.020 (Kolar et al. 1994b). Note that the model is set up for an astronomic tide-only simulation in that no other forcings (e.g., wind and river discharge) are present in the experiments. This ensures that the results and analyses following are based on historical (astronomic tides only) to model (astronomic tides only) comparisons.

Five tidal simulations are performed in order to investigate the effects of domain extent on the modeling and simulation of tidal circulation within the Loxahatchee River estuary (Table 1). (It is noted that advection is disabled for each of these five tidal simulations.) First, the limited mesh is applied to serve as a benchmark to which subsequent simulation results are compared. Then the limited_TF and extended meshes are applied in order to isolate the effects of appending tidal flats to the limited domain extent, and to observe the response due to incorporating the AICWW into the computational domain, respectively. Following, an alternative implementation of the limited mesh applies tidal elevation forcings on the northern AICWW boundary [Fig. 2(a)], where the corresponding harmonic forcing data are obtained from the simulation results associated with the application of the extended mesh. Finally, the limited_TF mesh is applied under the “alternative boundary-condition implementation” [Fig. 3(a)], herein referring to when tidal elevation forcings are applied on the northern AICWW boundary.

Three additional tidal simulations are then performed in order to examine the influence of advection on the modeling and simulation of tidal circulation within the Loxahatchee River estuary (Table 1). (It is noted that the advective terms are enabled in each of these three tidal simulations.) First, the limited mesh is applied to serve as a benchmark to which subsequent simulation results are compared. Next, the extended mesh is applied in order to explore the role of advection in the Loxahatchee River estuary and throughout the AICWW. Finally, the limited mesh is applied under the alternative boundary-condition implementation [Fig. 2(a)].

### Simulation Results and Discussion

It is advantageous to define the computational domain to encompass a large expanse of the continental shelf in addition to the local region of interest (Kolar et al. 1994a; Westerink et al. 1994b). In addition, an error analysis performed by Kojima (2005) demonstrates the efficacy of the WNAT model domain for tidal computations in the western North Atlantic Ocean. Thus, it is assumed that the tidal elevation forcings supplied by the WNAT model domain are sufficient to use toward forcing the open-ocean boundaries of the shelf-based model domains employed herein.

Two main simulation results are presented in this section: (1) quantitative analyses of computed water surface elevations for the five water-level gaging stations found within the Loxahatchee River estuary, with respect to the extent of the computational domain and the inclusion of advection in the numerical model; and (2) qualitative analyses of domain-wide computed velocity residuals for Jupiter Inlet and the entrance to the central embayment, with respect to the level of description of the AICWW and the enabling of the advective terms in the tidal simulations.

**Quantitative Analyses of Computed Water-Surface Elevations**

Assessing model performance in terms of water surface elevations involves a comparison of model output to historical data through use of the tidal resynthesis (Reid 1990)

$$T(t) = \sum_{n} H_n \cos(\omega_n t - g_n)$$

where $T(t)$=time-dependent resynthesized tidal signal; $H_n$ =amplitude of the $n$th tidal constituent; $\omega_n$=frequency of the $n$th tidal constituent; $g_n$=phase (relative to Greenwich mean time) of the $n$th tidal constituent; $N$=total number of tidal constituents applied in the tidal resynthesis (64 historical; 23 model). (It is noted that all tidal resyntheses performed herein are carried out over 14 days in order to cover a complete spring-neap tidal cycle. Further, all tidal resyntheses performed herein are resolved using...

<table>
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<tr>
<th>Mesh application</th>
<th>AICWW included</th>
<th>Tidal flats included</th>
<th>Boundary conditions</th>
<th>Advection included</th>
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Table 2. Absolute Average Phase Errors (°) Associated with the Five (Domain-Extent-Sensitivity) Runs Performed (Advection Disabled)

<table>
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<th>Mesh application</th>
<th>Water-level gaging station [labeled from most downstream (left) to most upstream (right) location]</th>
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<td>Extended</td>
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Table 3. Coefficients of Determination (%) [Eq. (7)] Associated with the Five (Domain-Extent-Sensitivity) Runs Performed (Advection Disabled)

<table>
<thead>
<tr>
<th>Mesh application</th>
<th>Water-level gaging station [labeled from most downstream (left) to most upstream (right) location]</th>
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aRefer to Fig. 1 for the locations of the five water-level gaging stations.
bUnder alternative boundary-condition implementation.

determination begins with a determination of the absolute average phase error (Tables 2 and 4), which is calculated by averaging the differences between the times of cyclical peaks and troughs of the historical and model tidal signals. [It is noted that for a semidiurnal (M2-dominated) tide with a period of 12.4 h, an absolute average phase error of 10° corresponds to a time discrepancy of 20 min and 40 s.] The model tidal signal is then adjusted for the absolute average phase error in order to determine the goodness of fit between the historical and (phase-corrected) model tidal signals, using the coefficient of determination (Tables 3 and 5) as a measure of accuracy (to provide the second error estimation)

\[ R^2 = 1 - \frac{\sum (\text{Hist}_n - \text{Mod}_n)^2}{\sum (\text{Hist}_n - \overline{\text{Hist}})^2} \]  

where Hist\(_n\) = historical tidal elevation at time \(n\); Mod\(_n\) = model tidal elevation at time \(n\); \(\overline{\text{Hist}}\) = average historical tidal elevation; \(N\) = total number of discrete points used in the error estimation.

We select these two error estimations for the following reasons: (1) the absolute average phase error isolates from the overall data fit information about the timing of the tides and (2) the (postphase correction) coefficient of determination isolates from the overall data fit information about the amplitudes of the tides.

Table 2 and 3 provide a means by which to quantitatively assess the phase and goodness-of-fit performance of the various 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 absolute average phase errors shown in Table 2 are less than 10° [equivalent to a time discrepancy of 20 min and 40 s for a semidiurnal (M2-dominated) tide with a period of 12.4 h], demonstrating that the timing of the tides is well simulated by the numerical model, regardless of the domain extent used. In addition, the majority of the coefficients of determination presented in Table 3 are above 92%; however, it is noteworthy that four of the five water-level gaging stations from the limited mesh application fall below 92%. Therefore, the first goal of our numerical experiment is to improve upon the limited mesh application.

Close examination of the first three rows of Tables 2 and 3 permits us to assess the level of improvement gained from the incorporation of the surrounding tidal flats (limited_TF) versus the inclusion of the AICWW (extended) in the computational domain. For example, phase performance is improved at four of the five water-level gaging stations when the surrounding tidal flats are included (see Table 2; limited_TF versus limited). In addition, goodness-of-fit performance is improved at all five water-level gaging stations when the surrounding tidal flats are included (see Table 3; limited_TF versus limited). It is also interesting (with the limited_TF mesh application) that a more significant improvement is achieved for the two most upstream water-level gaging stations (see Tables 2 and 3; Kitching Creek and River Mile 9.1), whereas a less significant improvement is achieved for the three most downstream water-level gaging stations (see Tables 2 and 3; Coast Guard Dock, Pompano Drive, and Boy Scout Dock).

While the addition of the surrounding tidal flats to the limited mesh serves to improve the simulation results, it is interesting that the limited mesh application is more greatly improved when the AICWW is incorporated into the computational domain (extended). For example, phase performance is improved at four of the five water-level gaging stations when the AICWW is included (see Table 2; extended versus limited). In addition, goodness-of-fit performance is improved at all five water-level gaging stations when the AICWW is included (see Table 3; extended versus limited).
It is also interesting (with the extended mesh application) that a more significant improvement is achieved for the three most downstream water-level gaging stations (see Tables 2 and 3; Coast Guard Dock, Pompano Drive, and Boy Scout Dock), whereas a less significant improvement is achieved for the two most upstream water-level gaging stations (see Tables 2 and 3; Kitching Creek and River Mile 9.1).

Intercomparing the simulation results presented in the first three rows of Tables 2 and 3 indicates that the effects of the surrounding tidal flats are significant along the upstream river reaches, whereas the AICWW substantially impacts the hydrodynamics occurring throughout the entirety of the Loxahatchee River estuary, especially near the inlet. It then behooves us to examine the facility of employing the alternative boundary-condition implementation in order to account for the hydrodynamic influence of the AICWW. Under the alternative boundary-condition implementation, the limited domain extent produces virtually the same simulation results as those produced by the extended domain extent (Tables 2 and 3; limited_ALT versus extended). To this end, the limited domain extent is deemed appropriate, however, only when the northern AICWW boundary [Fig. 2(a)] is forced with tidal elevations obtained from application of the extended mesh.

All data intercomparisons indicate that both the AICWW and the surrounding TFs are important to consider when simulating tidal behavior in the Loxahatchee River estuary (see Tables 2 and 3). Therefore, we are motivated to apply the limited TF mesh under the alternative boundary-condition implementation. In fact, it is observed that the limited_TF_ALT mesh application provides for the best solution. Phase performance is improved at four of the five water-level gaging stations when the surrounding tidal flats are included and the AICWW is accounted for in the alternative boundary-condition implementation (see Table 2; limited_TF_ALT versus limited); goodness-of-fit performance is improved at all five water-level gaging stations when the surrounding tidal flats are included and the AICWW is accounted for in the alternative boundary-condition implementation (see Table 3; limited_TF_ALT versus limited).

Defining the computational domain in terms of spatial extent serves to enhance the numerical model by revealing that both the AICWW and the surrounding tidal flats are major contributors toward (tidally induced) water-level changes in the Loxahatchee River estuary. It is expected in a shallow water system for tidal flow to be affected by advection, and thus, we are motivated to explore the contributing role of advection toward (tidally induced) water-level changes in the Loxahatchee River estuary. Tables 4 and 5 provide a means by which to quantitatively assess the phase and goodness-of-fit performance of the various computational meshes in terms of water surface elevations, with respect to the inclusion of advection in the numerical model. Intercomparison of the error estimations shown in Tables 2–5 demonstrates that advection provides an improved model skill (albeit only slightly) for the four most upstream stations of the Loxahatchee River estuary. While advection provides some benefit to the numerical model, the associated improvement may be considered negligible when compared to the effect of domain extent on the simulation results.

**Qualitative Analyses of Domain-Wide Computed Velocity Residuals**

The observed differences in simulated water surface elevations when the different domain extents are used (Tables 2 and 3) reveal that tidal behavior in the upstream river reaches is moderately influenced by local features (i.e., the surrounding tidal flats) while astronomic tides throughout the entirety of the Loxahatchee River estuary (namely in the central embayment and areas around Jupiter Inlet) are strongly influenced by remote effects (i.e., the AICWW). In addition, while we demonstrate that advection plays a minor role toward tidal fluctuations in terms of water surface elevations (Tables 2–5), it is worth examining the contribution of advection toward the generation of the tidal residual. To this end, Fig. 5 provides a means by which to qualitatively assess the performance of the various computational meshes on a velocity-residual basis, with respect to the hydrodynamic influence of the AICWW and the inclusion of advection in the numerical model.

### Table 4. Absolute Average Phase Errors (°) Associated with the Three (Advection-Sensitivity) Runs Performed (Advection Enabled)

<table>
<thead>
<tr>
<th>Mesh application</th>
<th>Water-level gaging station [labeled from most downstream (left) to most upstream (right) location]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coast Guard Dock</td>
</tr>
<tr>
<td>Limited</td>
<td>0.350</td>
</tr>
<tr>
<td>Extended</td>
<td>7.937</td>
</tr>
<tr>
<td>Limited_ALTb</td>
<td>6.555</td>
</tr>
</tbody>
</table>

*aRefer to Fig. 1 for the locations of the five water-level gaging stations.
bUnder alternative boundary-condition implementation.

### Table 5. Coefficients of Determination (%) [Eq. (7)] Associated with the Three (Advection-Sensitivity) Runs Performed (Advection Enabled)

<table>
<thead>
<tr>
<th>Mesh application</th>
<th>Water-level gaging station [labeled from most downstream (left) to most upstream (right) location]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coast Guard Dock</td>
</tr>
<tr>
<td>Limited</td>
<td>93.37</td>
</tr>
<tr>
<td>Extended</td>
<td>97.32</td>
</tr>
<tr>
<td>Limited_ALTb</td>
<td>97.17</td>
</tr>
</tbody>
</table>

*aRefer to Fig. 1 for the locations of the five water-level gaging stations.
bUnder alternative boundary-condition implementation.
which the computation of velocity residuals. Also, the 14-day period over wide velocity model output is resolved at a time step of 30 min, within the ADCIRC code provides for continuity within the GWCE formulation, thus preserving mass in the numerical simulation. The implementation of the GWCE using a continuous Galerkin approach are not extended mesh application for (or contradiction to) the trends observed in the water-level responses presented in Tables 2–5.](H20849)

We must remark that our tidal residuals are processed from model output (depth-integrated velocities) based on a GWCE formulation of the shallow water equations. While numerical solutions of the GWCE using a continuous Galerkin approach are not locally conservative, it has been demonstrated that with proper implementation of the GWCE (Kolar et al. 1994b) global mass balance error is near zero and local mass balance errors are confined to the forcing boundary (Dawson et al. 2006). The forcing boundaries of all model domains considered in this study are far removed from the tidal inlet to ensure that local mass balance errors are not affecting the numerical solution at the tidal inlet and within the estuary. In addition, treatment of wetting and drying within the ADCIRC code provides for continuity within the GWCE formulation, thus preserving mass in the numerical solution (Nielsen and Apelt 2003).

Qualitative analyses of velocity residuals involve an averaging of computed tidal velocities over an $M_2$ tidal period (Tee 1976; Pingree and Maddock 1977; Prandle 1978). The $M_2$ tidal period-averaged velocities are then averaged over a 14-day period to provide the velocity residual (Fig. 5). (It is noted that all domain-wide velocity model output is resolved at a time step of 30 min, providing a sufficient amount of data to use for the domain-wide computation of velocity residuals. Also, the 14-day period over which the $M_2$ tidal period-averaged velocities are averaged is between day 14 and day 28 in the numerical simulation.)

All of the velocity-residual vector plots shown in Fig. 5 indicate an ebb-dominated net flow pattern for Jupiter Inlet and the AICWW. (It is noted that all velocity residuals computed herein are strictly a result of tidal distortion caused by the nonlinear growth of higher harmonics and compounds of the principal astronomic tidal constituents. The asymmetry of the tidal velocity is responsible for a tidal residual, which is not to be interpreted as a net volume exchange.) The ebb dominance in the computed tidal residual is based on an averaging over the 14-day period from day 14 to day 28 in the numerical simulation. The tidal residual may change if calculated over a different 14-day period in the numerical simulation. On this basis, we are not claiming to have determined the true tidal residual. Instead, the 14-day averaging period is held consistent (from day 14 to day 28 in the numerical simulation) between all model data sets so that meaningful comparisons can be made.

It is evident that the incorporation of the AICWW into the computational domain has a measurable impact on the mean tidal circulation produced through Jupiter Inlet and the AICWW [Fig. 5(a) versus (b)]. The ebb dominance in the tidal residuals resulting from the nonlinear effects of the Loxahatchee River estuary [Fig. 5(a)] is enhanced by the hydrodynamic influence of the AICWW [Fig. 5(b)]. In fact, the difference between the domain-wide velocity-residual data sets resulting from the applications of the extended and limited meshes is computed [Fig. 5(c)] to further highlight the impact of the AICWW on tidal residuals for the Loxahatchee River estuary. In addition, the similarities in the velocity-residual vector plots shown in Figs. 5(b and d) further substantiate the facility of employing the alternative boundary-condition implementation, where the alternative boundary-condition implementation is shown to be sufficient toward accounting for the hydrodynamic influence of the AICWW.

Contrary to the influence of advection on the water surface elevations simulated by the numerical model (Tables 2–5), enabling the advective terms in the tidal simulations serves to greatly affect the mean tidal circulation generated within the Loxahatchee River estuary. The net flow pattern through Jupiter Inlet and the AICWW remains ebb-dominated (and of near equal magnitude) when advection is included in the numerical model [Fig. 5(e) versus (b)]. The relatively large residual velocities produced outside of Jupiter Inlet [Fig. 5(e)] arise from an offshore eddy, which is fed, to some extent, by the net tidal outflow through Jupiter Inlet. The difference between the domain-wide velocity-residual data sets resulting from the applications of the EXTENDED mesh, when advection is considered, and when advection is neglected, is computed [Fig. 5(f)] to further identify advection as a contributor toward the development of tidal residuals (Tee 1976). The observation of eddies offshore, through the inlet throat/embayment entrance, and within the AICWW [Fig. 5(f)] demonstrates the stronger rotational flows that are captured in the numerical model when advection is considered.

Conclusions

A depth-integrated numerical model, ADCIRC-2DDI, is applied to simulate two-dimensional tidal flows within the Loxahatchee River estuary, located in Southeastern Florida. Three different versions of an unstructured, finite-element mesh are employed in tidal simulations in order to assess the effects of incorporating the AICWW versus including the surrounding tidal flats in the computational domain. The model-building approach presented in this
paper places focus on more fully identifying the computational domain for the Loxahatchee River estuary, to result in the following findings: (1) the AICWW has the potential to provide a hydrodynamic interconnection between the coastal and estuarine systems found along the east coast of Florida and (2) a limited domain extent for estuarine and coastal models must consider the application of additional boundary forcings, when applicable (e.g., along the AICWW), in order to account for the hydrodynamics occurring outside of the model boundaries. While attention has been paid to the Loxahatchee River estuary, we conclude that as the AICWW is a continuous hydraulic channel along the entire east coast of Florida, the hydrodynamic influence of AICWW should be considered when modeling any single estuary along Florida’s east coast. Quantitative analyses of computed water surface elevations demonstrate the enhancements made to the numerical model when the surrounding tidal flats are considered; however, it is shown that the numerical model is more significantly improved when the AICWW is more fully described. On a phasing error and goodness-of-fit basis, extending the limited domain extent to incorporate a greater reach of the AICWW (125 km) and three additional inlets (Fort Pierce, St. Lucie, and Lake Worth) into the computational domain results in a substantial enhancement of the numerical model.

Qualitative analyses of domain-wide computed velocity residuals are presented to further highlight the impact of including the AICWW in the computational domain, and to examine the influence of advection on the mean tidal circulation generated within the Loxahatchee River estuary. The difference in the resulting net flow patterns, when the limited and extended domain extents are employed, indicates that the AICWW plays a major role over the long term movement and distribution of waterborne constituents within the Loxahatchee River estuary. The qualitative analyses of domain-wide computed velocity residuals performed in this study also suggest that advection plays a significant role over the long term transport characteristics of the Loxahatchee River estuary. The formation of rotational flow fields offshore and within Jupiter Inlet and the AICWW due to the inclusion of advection in the numerical model supports the findings of Nihoul and Ronday (1975) and Tee (1976), where these eddies result mainly from the transfer of vorticity from the tidal component to the mean circulation through advection-based nonlinear interactions.

Due to computational constraints, many estuarine and coastal models employ a limited domain extent, and thus, more attention is demanded on properly identifying the open-water boundaries of the respective models. It is shown (on a water-level and velocity-residual basis) that for the Loxahatchee River estuary, a limited domain model is adequate only when the northern AICWW boundary is elevation-forced with harmonic data generated by application of the extended domain model. Therefore, it is recommended that estuarine and coastal models of limited domain extent consider additional boundary forcings in order to account for the hydrodynamic influence provided by adjacent water bodies (e.g., the AICWW along Florida’s east coast). At present, tidal behavior in the AICWW is poorly understood and there exists little, if any, relevant tidal information to use in generating an AICWW boundary condition applicable for a localized model. Until a tidal database is developed for the AICWW, it remains necessary to generate the AICWW boundary condition from a larger scale hydrodynamic simulation.

We restate the fact that all simulation results presented in the paper have not been calibrated. Calibrating the numerical model prior to testing for domain extent and boundary-condition specification would fold in relevant features of the tidal physics, and would thus, invalidate the simulation results. By the methodology presented herein, one builds on an existing model to learn more about the tidal hydrodynamics of the domain while simultaneously incorporating additional physics into continuously improving versions of the model. Model calibration can then proceed with a physically based bottom friction characterization of the Loxahatchee River estuary using a Manning’s type parameterization. We propose that such a model-building strategy ultimately brings the most relevant physics into the numerical model.

Acknowledgments

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Notation

The following symbols are used in this paper:

\[ C_f = \text{bottom friction coefficient}; \]
\[ C_{fr} = \text{minimum friction factor that is approached in deep water when the hybrid bottom friction function reverts to the quadratic bottom friction function}; \]
\[ E_h = \text{horizontal eddy viscosity}; \]
\[ f = \text{Coriolis parameter}; \]
\[ g = \text{acceleration due to gravity}; \]
\[ g_n = \text{phase (relative to Greenwich mean time) of the } n^{th} \text{ tidal constituent}; \]
\[ H = \text{total height of water column}; \]
\[ H_{break} = \text{break depth to determine if the hybrid bottom friction function will behave as a quadratic bottom friction function or increase with depth similar to a Manning’s type bottom friction function}; \]
\[ H_t = \text{amplitude of the } n^{th} \text{ tidal constituent}; \]
\[ \text{Hist} = \text{average historical tidal elevation}; \]
\[ \text{Hist}_t = \text{historical tidal elevation at time } n; \]
\[ h = \text{bathymetric depth, relative to MSL}; \]
\[ M_l = \text{depth-integrated momentum dispersion, longitudinal direction}; \]
\[ M_t = \text{depth-integrated momentum dispersion, latitudinal direction}; \]
\[ \text{Mod} = \text{model tidal elevation at time } n; \]
\[ N = \text{total number of terms included in mathematical series}; \]
\[ p_s = \text{atmospheric pressure at the free surface}; \]
\[ R = \text{radius of the Earth}; \]
\[ R^2 = \text{coefficient of determination}; \]
\[ t = \text{time}; \]
\[ T(t) = \text{time-dependent resynthesized tidal signal}; \]
\[ U = \text{depth-integrated velocity in longitudinal direction}; \]
\[ V = \text{depth-integrated velocity in latitudinal direction}; \]
\[ \alpha = \text{Earth elasticity factor}; \]
\[ \gamma = \text{dimensionless parameter that describes how quickly the friction factor increases as water depth decreases}; \]
\[ \zeta = \text{free surface elevation, relative to MSL;} \]
\[ \eta = \text{Newtonian tide potential;} \]
\[ \theta = \text{dimensionless parameter that describes how rapidly the hybrid bottom friction function approaches its upper and lower limits;} \]
\[ \lambda = \text{degrees longitude;} \]
\[ \rho_0 = \text{reference density of water;} \]
\[ \tau_{0s} = \text{GWCE weighting parameter;} \]
\[ \tau_{sb} = \text{applied free surface stress in longitudinal direction;} \]
\[ \tau_{sb} = \text{applied free surface stress in latitudinal direction;} \]
\[ \tau_s = \text{bottom stress;} \]
\[ \phi = \text{degrees latitude;} \]
\[ \Omega = \text{angular speed of the Earth;} \]
\[ \omega_n = \text{frequency of the nth tidal constituent.} \]

References


