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Operational Evaluation of ADCIRC-2DDI as Applied to the Western North Atlantic Ocean

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14. ABSTRACT

The model forecast system comprising the finite element-based hydrodynamic model ADCIRC-2DDI, the Navy Operational Global Atmospheric Prediction System (NOGAPS), and the Grenoble tidal database (FES95.2.1) is evaluated in the Western North Atlantic Ocean under an operational test (OPTEST) defined by the Naval Oceanographic Office (NAVOCEANO). Using tidal forcing at the open boundary, model forecasts of water elevations are made with and without wind forcing and compared to observations available through the National Atmospheric and Oceanic Administration (NOAA). The model forecast system, configuration, and implementation are described at length with respect to the definition of the operational test, data processing, and evaluation criteria. Model predictions fall within the acceptable Navy standard of 20% RMS amplitude error and 60 minutes phase error for both the tides-only and wind- and tidally-driven forecasts.

15. SUBJECT TERMS

OPTEST	ADCIRC	tides	forecast
operational	real-time	surge	U.S. East Coast

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OPERATIONAL EVALUATION OF ADCIRC-2DDI AS APPLIED TO THE WESTERN NORTH ATLANTIC OCEAN

1. INTRODUCTION

The goal of the Naval Oceanographic Office (NAVOCEANO) Tide and Surge Prediction System (TSPS) effort is to predict surface elevations and currents due to astronomical tides and storm surge. The crux of TSPS is the Advanced Circulation model (ADCIRC) developed by collaboration among the Coastal and Hydraulics Laboratory (CHL), formerly the Coastal Engineering Research Center (CERC), the University of North Carolina, the University of Notre Dame, and the Naval Research Laboratory (NRL) (Luettich et al. 1992). The model is finite element-based, which permits high resolution in shallow coastal or high-gradient areas, a necessity for accurate simulation of coastal tidal dynamics and for providing tactically meaningful products, and relative coarse resolution in deep/ocean areas, which allows for more appropriate ocean boundary specification.

ADCIRC-2DDI is the two-dimensional, depth-integrated version of the finite element-based model that solves the shallow water equations in their full nonlinear form appropriate for shelves, coasts, and estuaries. Accuracy of the model is corroborated by years of successful tidal prediction well-documented in the literature (e.g., Westerink et al. 1992; Westerink et al. 1994b; Grenier et al. 1995; Blain and Rogers 1998). Recent applications range from wave-induced circulation (Cobb and Blain 2000), hurricane storm surge prediction (Blain et al. 1994), and estuarine dynamics (Hench and Luettich 2000; Blain et al. 1994; Luettich et al. 2002). A history of successful implementation of the ADCIRC model within operational forecast systems has also been established (Luettich et al. 1996; Blain and McManus 1998).

Detailed herein is application of the finite element model ADCIRC-2DDI in an operational context. Sea surface elevation and currents are predicted under wind and tidal forcing over coastal waters of the Western North Atlantic Ocean. The computed forecasts are then compared to available observations along the coast of the eastern seaboard of the United States. Before discussing the operational test (OPTEST) itself, considerable detail is provided on the model system, configuration, and implementation. The OPTEST and the criteria for its evaluation are then defined, along with specifics on the treatment of the observational data. Later sections

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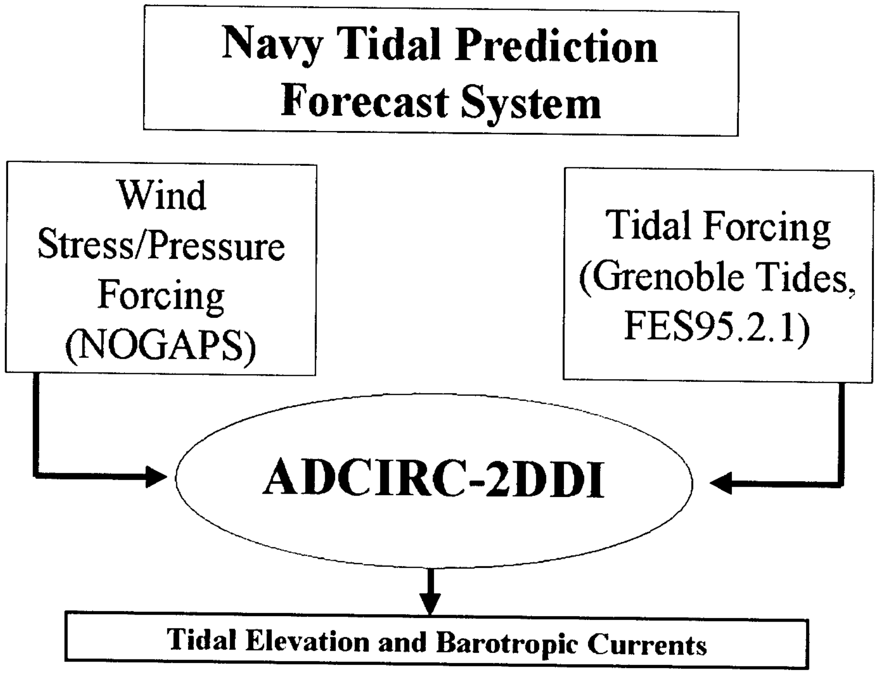

Fig. 1 — Model forecast system

detail comparisons between model predictions and observations. A summary assessing the capability of ADCIRC to perform in an operational or forecast framework is included.

2. MODEL FORECAST SYSTEM

The model forecast system (Fig. 1) comprises the hydrodynamic model, ADCIRC-2DDI, and models which provide forcing over the domain and at the open boundary. The Navy Operational Global Atmospheric Prediction System (NOGAPS) provides operational wind stress and atmospheric pressure forecasts over the model domain. In combination with tidal forcing extracted from the Grenoble tidal database (FES95.2.1) and applied at the open boundary of the computational domain, ADCIRC-2DDI predicts tidal elevation and barotropic currents as part of the Navy tidal prediction forecast system.

2.1 ADCIRC-2DDI

ADCIRC-2DDI is a finite element-based model; the depth-integrated version of a set of two- and three-dimensional fully nonlinear hydrodynamic codes. ADCIRC-2DDI solves the two-dimensional, depth-integrated shallow water equations, subject to the hydrostatic pressure and Boussinesq approximations. For the applications discussed here, the lateral mixing and baroclinic terms in the momentum conservation equations are neglected, leading to the following set of governing equations expressed in spherical coordinates in a primitive, non-conservative form, subject to bottom friction effects:

$$\frac{\partial \zeta}{\partial t} + \frac{1}{Rcos\phi}\frac{\partial\, UH}{\partial \lambda} + \frac{1}{R}\frac{\partial\, VH}{\partial \phi} - \frac{VH\, tan\phi}{R} = 0 \tag{1}$$

$$\frac{\partial U}{\partial t} + \frac{U}{Rcos\phi}\frac{\partial U}{\partial \lambda} + \frac{V}{R}\frac{\partial U}{\partial \phi} - \left(\frac{U\, tan\phi}{R} + f\right)V =$$

$$-\frac{1}{Rcos\phi}\frac{\partial}{\partial \lambda}\left[\frac{p_s}{\rho_o} + g\zeta - g(\eta + \Upsilon)\right] - \frac{\tau_{b\lambda}}{\rho_o H} + \frac{\tau_{s\lambda}}{\rho_o H} - \tau_* U \tag{2}$$

$$\frac{\partial V}{\partial t} + \frac{U}{Rcos\phi}\frac{\partial V}{\partial \lambda} + \frac{V}{R}\frac{\partial V}{\partial \phi} + \left(\frac{U\, tan\phi}{R} + f\right)U =$$

$$-\frac{1}{R}\frac{\partial}{\partial \phi}\left[\frac{p_s}{\rho_o} + g\zeta - g(\eta + \Upsilon)\right] - \frac{\tau_{b\phi}}{\rho_o H} + \frac{\tau_{s\phi}}{\rho_o H} - \tau_* V \tag{3}$$

where t is time, λ, ϕ are degrees longitude (east of Greenwich positive) and degrees latitude (north of the equator positive), ζ is free surface elevation (relative to the geoid), U, V are depth-integrated horizontal velocities, and H is the total water column thickness. Ω is the angular speed of the Earth (7.29212×10^{-5} rad/s), R the radius of the Earth, f $(= 2\Omega \sin\phi)$ is the Coriolis parameter determined by latitude, g is gravity, and $(\eta+\Upsilon)$ represents the Newtonian tidal potential, Earth tide, self attraction, and load tide term. $\tau_{s\lambda}$ and $\tau_{s\phi}$ are latitudinal and longitudinal surface stresses, and ρ_o is the reference density of water. Standard quadratic parameterizations for the bottom stresses $\tau_{b\lambda,\phi}$ are used:

$$\tau_{b\lambda} = C_f(U^2 + V^2)^{1/2}U \tag{4}$$

$$\tau_{b\phi} = C_f(U^2 + V^2)^{1/2}V, \tag{5}$$

where C_f is a dimensionless friction coefficient.

Finite element discretization of the primitive continuity equation (Eq. (1)) tends to produce spurious modes in the resulting solutions. Thus, a Generalized Wave Continuity Equation (GWCE) is used and can be obtained by reformulating Eqs. (1) through (3) (Lynch and Gray 1979; Lynch 1983; Kinnmark 1984). The GWCE is discretized in space using the finite element method. The time domain is treated using finite difference techniques. The GWCE and momentum equations (Eqs. (2) and (3)) are then solved for ζ, U, and V. Further details of the ADCIRC family of codes are presented by Luettich et al. (1992), Kolar et al. (1994a,b), and Westerink et al. (1994a).

ADCIRC has a successful history in tide and surge prediction, with applications to regions that include the Mediterranean, the U.S. East coast, the Gulf of Mexico, the North Sea, the

Yellow Sea-Sea of Japan region, the Red Sea, and the Arabian Gulf. Modeled dynamics have been driven by various combinations of forcings such as tides, waves, and wind. More recently, ADCIRC has been applied in a forecasting mode (Luettich et al. 1996; Blain and McManus 1998) and has proven to be a powerful tool in hindcast/forecast prediction of coastal ocean currents and sea surface elevations.

2.2 NOGAPS

NOGAPS is a global spectral numerical weather prediction model. NOGAPS assimilates available satellite observations as well as conventional observations in the solution of the primitive conservation equations under the hydrostatic approximation over the global domain, from the surface to 10 mb atmospheric pressure. Forecast predictions of vorticity, divergence, virtual potential temperature, specific humidity, and terrain pressure are used in deriving winds, heat fluxes, and surface pressures that serve as forcing for ocean and atmospheric models. Description of the NOGAPS design and development can be found in Barker (1992a, 1992b); Hogan and Rosmond (1991) and Goerss and Phoebus (1992) document details of its operational implementation.

The times of reanalysis for NOGAPS forecasts are at 0Z and 12Z, with intermediate forecasts every 6 hours. Model predictions of winds and wind stress are available at a resolution of 1 degree over the Western North Atlantic Ocean. Wind stresses are used as the source of wind forcing in this application.

2.3 Grenoble FES95.2.1

The Grenoble tidal database FES95.2.1 is derived from solutions of the global hydrodynamic model developed by LeProvost et al. (1994), which assimilates TOPEX/POSEIDON altimetry data using the representor approach. The associated tidal model includes 26 tidal components. High resolution concentrated over the major topographic features allows the model to capture local characteristics of tidal waves unresolved in conventional global hydrodynamic ocean tide models (Le Provost et al. 1995; Genco et al. 1994). Solutions from this tidal database are interpolated to the open boundaries of regional prediction systems for use as tidal open boundary forcing.

3. MODEL CONFIGURATION

The finite element model ADCIRC is applied to the Western North Atlantic (WNAT) domain (Westerink et al. 1994b) for operational testing. This domain covers the Gulf of Mexico, contiguous basins, and extends out into the deep Atlantic Ocean, and is chosen for operational testing because of the availability and accessibility of data in the region.

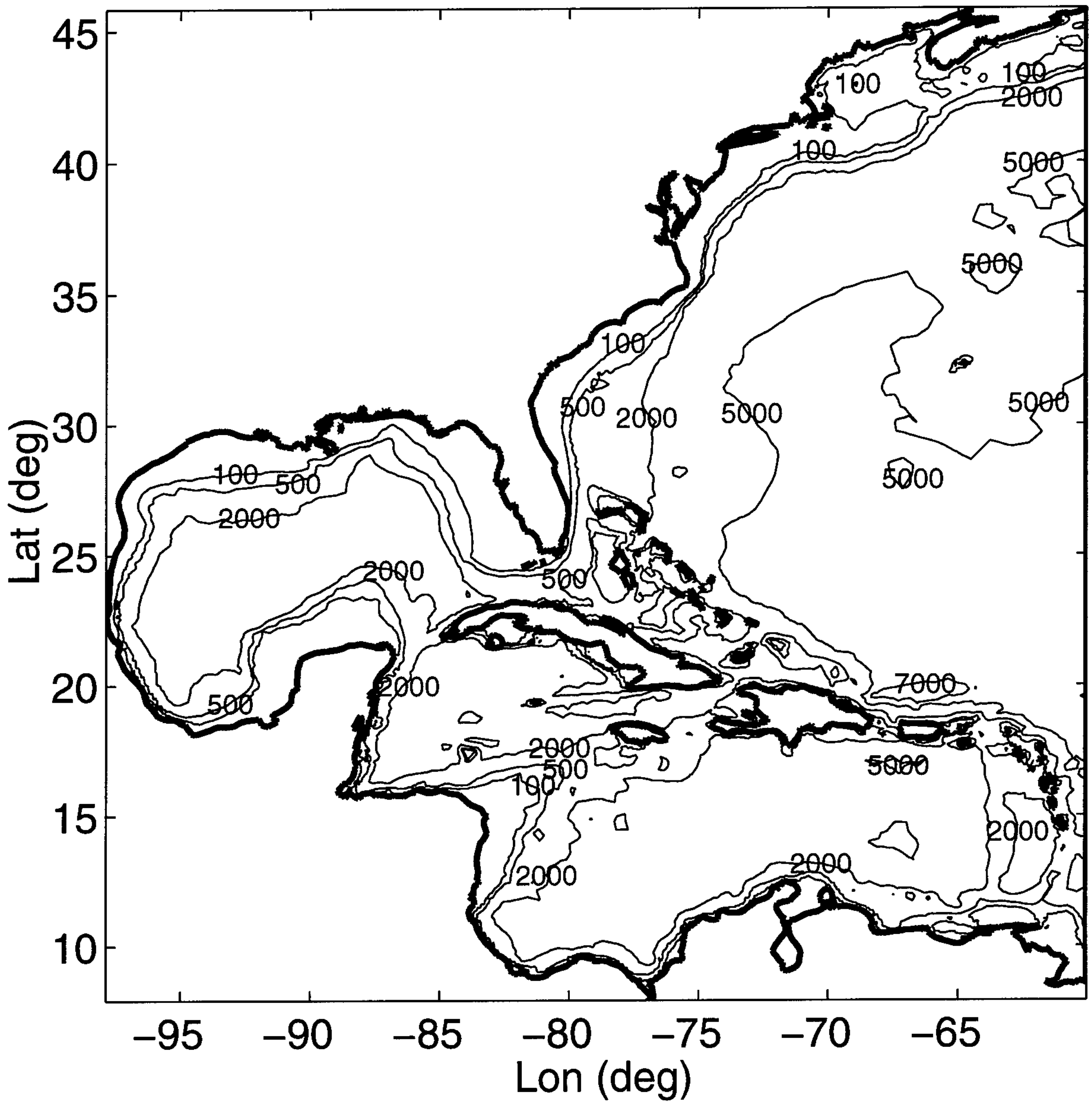

Fig. 2 — The Western North Atlantic grid, with bathymetry contours in meters

3.1 Western North Atlantic Domain

The domain of application spans the entire Western North Atlantic Ocean (Fig. 2), with the eastmost boundary at 60° W. The land boundary stretches from Nova Scotia in the north, down the eastern seaboard of the United States, including the Gulf of Mexico, Central America, encompassing the Caribbean Sea and the north coast of Venezuela just southeast of Trinidad and Tobago at the border between Venezuela and Guayana.

The Western North Atlantic domain is discretized using 36,185 nodes and 67,811 elements. The grid named *eastcoast* was originally obtained from the Army Corps of Engineers at Engineer Research Development Center, Waterways Experiment Station, Vicksburg, Mississippi, and forms the basis for tidal forecasting in the Western North Atlantic by NAVOCEANO. The *eastcoast* grid has been used in a number of tide and storm surge studies (Blain et al. 1994; Westerink et al. 1994b). Bathymetry and coastline information is obtained from the topographic database ETOPO5 from the National Center for Atmospheric Research and is supplemented by the National Oceanic and Atmospheric Administration (NOAA) Digital U.S. Coastal Hydrography sounding database. Resolution ranges from 5.6 km near shore to 44.5 km in the open ocean.

3.2 Forcing

Applied forcing includes direct astronomical forcing due to the tidal potential derived from six tidal harmonic constituents dominant in the Western North Atlantic Ocean (M_2, S_2, K_2, N_2, O_1, and K_1). The model is additionally forced by 10 tidal constituents of specified elevation at the open boundary (previous six plus Q_1, P_1, μ_2, and L_2). Values for the tidal amplitudes and phases at the open ocean boundary are extracted from FES95.2.1, a global tidal database produced by Le Provost et al. (1994).

Operational forcings in the form of surface wind stress and atmospheric pressure fields are obtained from NOGAPS (Hogan and Rosmond 1991). Resolution of the NOGAPS products is rather coarse at 1 degree. Higher resolution operational products, such as the Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) (Hodur 1997; Hodur and Doyle 1999), exist but often do not completely cover the domain of an ADCIRC application. No attempts have been made in the operational context to merge atmospheric products to use the COAMPS high-resolution forcing and retain complete coverage of the computational domain.

3.3 Implementation

Nonlinear bottom friction is implemented as defined by Eqs. (4) and (5), with the bottom friction coefficient set to a constant equal to 0.003 over the entire domain. Finite amplitude terms are excluded from the model equations (i.e., the depth is linearized by using the bathymetric depth, rather than the total depth, in all terms except the transient term in the continuity equation) and shoreline wetting and drying of elements is disabled. All advective terms in the GWCE and momentum equations are included in the dynamics.

ADCIRC model forcing (tidal potential, open boundary elevation, winds) is introduced gradually over a period of days according to a hyperbolic ramp function. Application of the forcing in this way avoids shocking the system, which can produce spurious modes in the computed solution. Definition of the length of the ramp period is dependent on the applied forcing and region of application. Before proceeding, it is important to assess sensitivity of the model prediction to the ramp length.

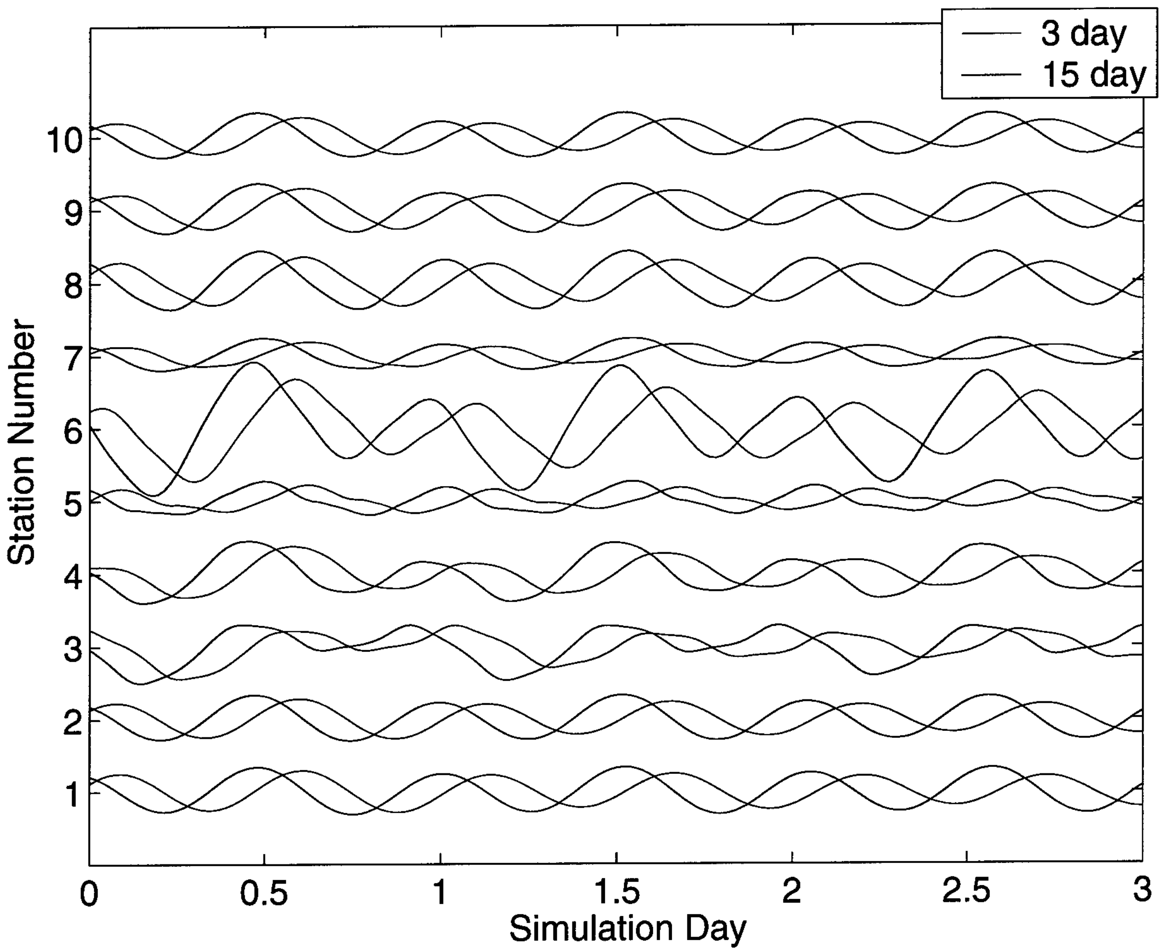

Fig. 3 — Time series of tidal elevations at 10 NOAA stations in the Western North Atlantic. Model solutions with 3-day (red) and 15-day (blue) ramping periods are shown.

Initial experiments with ramping periods of 3 and 15 days are conducted to demonstrate this sensitivity. A ramping period that is too long will yield the same solution as that with a ramping period of appropriate length, but will require more computational resources, extending the total simulation length unnecessarily. However, a solution whose ramping period is too short will show differences in the computed solution as compared with an appropriately spun-up solution. Comparison of the elevation time series solutions produced by these initial experiments shows that there is a non-negligible difference between elevation solutions over the first three days of simulation following 3-day and 15-day spin-up periods (Fig. 3). Clearly, a 3-day ramping period is too rapid to eliminate numerical artifacts in the solution. By experience, a 15-day ramping period is known to be appropriate and is used for all subsequent model forecasts.

4. OPERATIONAL TEST

4.1 Definition

Before its acceptance into a Navy operational setting, an operational forecast system must meet specific criteria defined through a process known as an operational test. The ADCIRC prediction system, as well as the overall effectiveness of ADCIRC in the prediction of ocean water levels in barotropic shallow and deep water environments, is evaluated here. Model predicted currents are not evaluated in this operational test, as there is little real-time littoral current data that can be used to validate model prediction given the resolution of the large Western North Atlantic domain. For ADCIRC, root mean square (RMS) percent error of predicted water levels versus NOAA observed water levels must be less than 20%. Phase error must not lead or lag on the average by any more than 60 minutes.

Model simulations are performed on the Western North Atlantic grid under tidal forcing with and without the inclusion of wind forcing. For the OPTEST, ADCIRC is run with wind forcing for 31 2-day simulations, from July 19 to August 17, 2000. Each of these forecasts is hot-started from an initial tidal 18-day simulation, using the conditions at the beginning of day 16 to start a 2-day forecast with a 30-second timestep. A second ADCIRC forecast is computed without wind forcing for the entire 31-day testing period to examine the effect of wind forcing on model forecast skill.

4.2 Data Description

Model predictions are compared to time series of mean lower-low water (MLLW) available through the NOAA website (http://www.co-ops.nos.noaa.gov). Ten stations (Sandy Hook, New Jersey; Atlantic City, New Jersey; Kiptopeke, Virginia; Windmill Point, Virginia; Sewells Point, Virginia; Chesapeake Bay, Virginia; Duck, North Carolina; Springmaid Pier, North Carolina; Fort Pulaski, North Carolina; and St. Augustine Beach, Florida) are chosen for operational validation based on location within the domain itself and location within shallow coastal waters (Fig. 4), as well as data quality. Elevation data are at 6 minute resolutions over the OPTEST period of July 19 to August 17, 2000.

4.3 Data Processing

These NOAA observation time series are preprocessed to remove spurious peaks in the data and to filter out high-frequency noise. The mean is removed from the lower-low tidal signal so that the data can be directly compared to the model forecasts, which are referenced to a mean sea level condition.

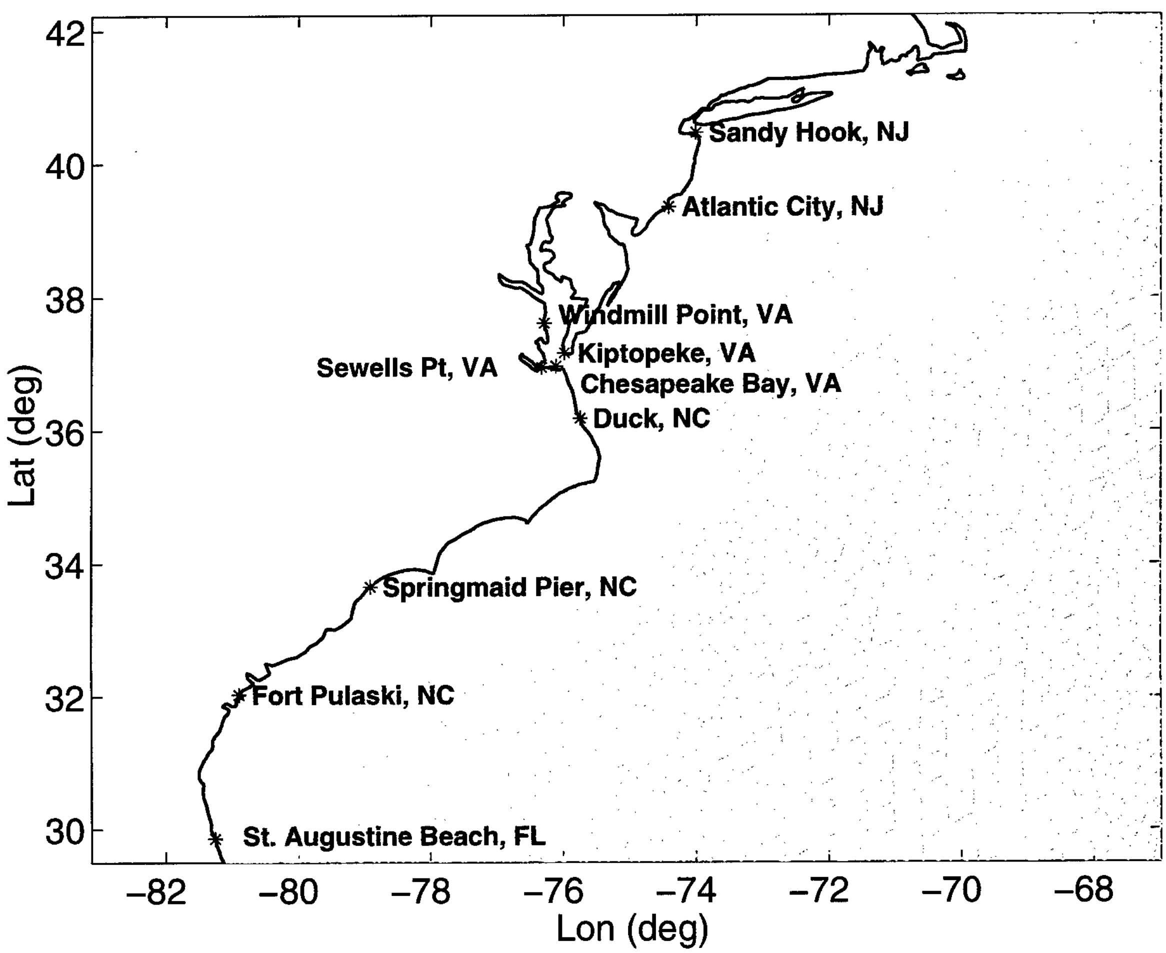

Fig. 4 — Location and position of NOAA stations with respect to the finite element grid

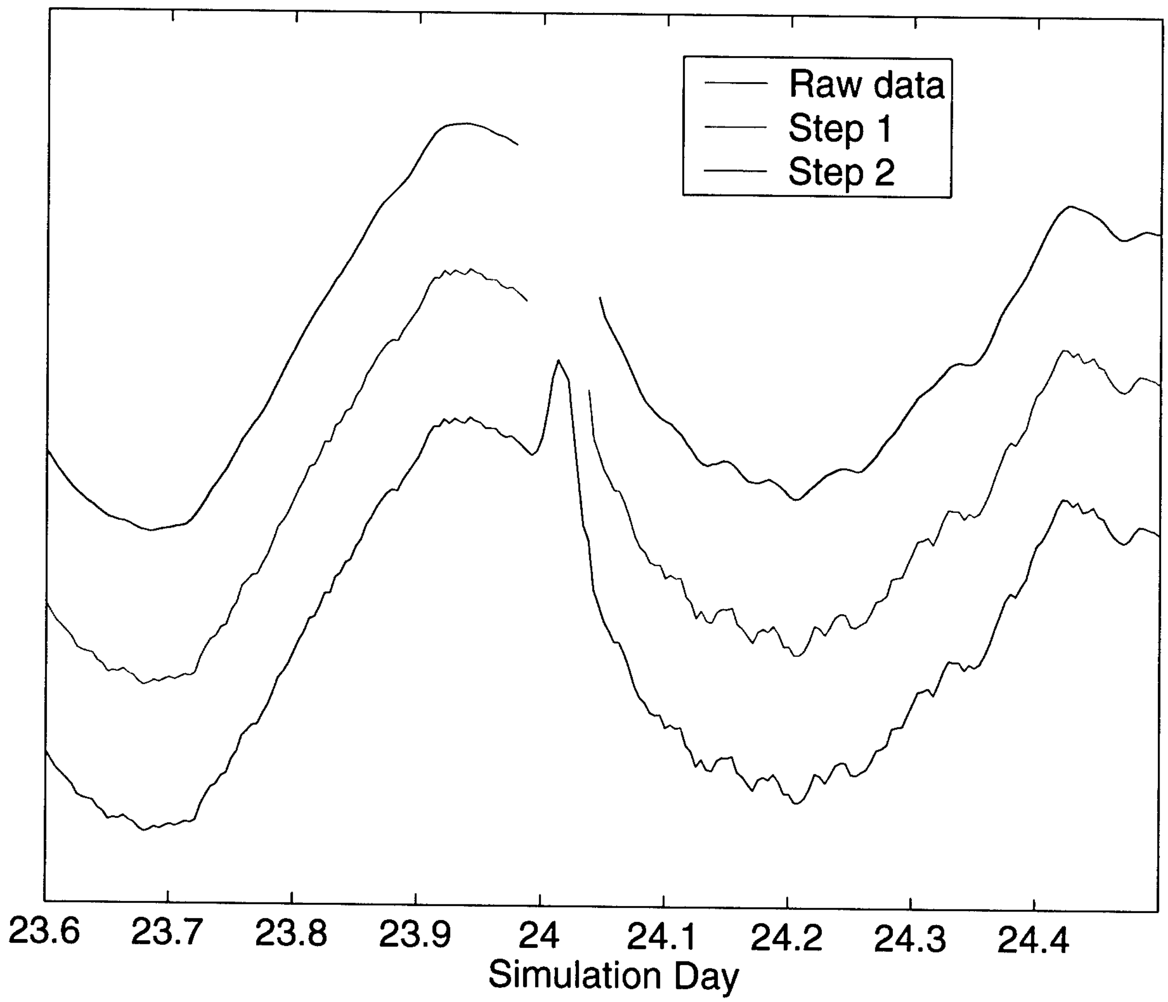

Fig. 5 — Elevation observations at St. Augustine Beach, Florida. Raw observations are shown in red, with data spikes removed (step 1) shown in green, and after filtering (step 2) shown in blue. Each is offset by 0.75 m for visibility in comparison.

4.3.1 Data Removal

At most stations, several spikes as large as 8 m are scattered throughout the data. Such spikes are usually the result of instrument error during data collection, and are identified visually. To avoid contamination of values near these peaks through filtering, these spurious values are eliminated from the dataset (Fig. 5, green). Less than 6 hours of data is removed from the combined data set of all 10 stations over 31 days, representing less than 0.09% of the data.

4.3.2 Filtering

Instrument noise can also contaminate time series of collected data with small amplitude but high frequency noise (Fig. 5, blue). To smooth this variation, the data are then filtered using a standard five point (half-hour) running mean filter. Successive elevation values are averaged over a half-hour window in time, repeated over all successive five points of time series elevation in the data set.

4.3.3 Removal of the Mean

A value for mean sea level is not explicitly defined by the model. Rather, ADCIRC model computed elevations represent a deviation from mean sea level. Thus, mean sea level must be removed from the observations for valid comparison. One must be careful in choosing the appropriate mean to remove from the data. Shorter term means might include short time-scale tidal or wind-induced variations; it might be inappropriate to remove them from the overall signal.

In order to ensure removal of the appropriate mean and assess the sensitivity of the data to the mean removal, the daily, 2-day, 7-day, and 30-day means are calculated by station for the elevation dataset. Daily, 2-, and 7-day means exhibit variability on the scale of 50 cm (Fig. 6) and suggest the occurrence of several wind events on the time scale of 7 to 9 days. Variability of the shorter scale means due to tidal and wind-induced conditions indicate that such means are not independent of time and therefore are not appropriately defined. Clearly, a 30-day mean that covers the entire OPTEST period is necessary for obtaining meaningful model-data comparisons. The 30-day mean is then removed from the filtered observational time series, which forms the basis for comparison to ADCIRC model forecast time series.

4.4 Evaluation Criteria

The OPTEST has been defined such that the RMS percent error of ADCIRC predicted water levels versus NOAA observed water levels must be less than 20%, with phase error less than 1 hour. Amplitude and phase errors in the model forecast compared to the observational data are calculated independently. Phase error is first calculated, and amplitude error is then calculated based on the phase-corrected model forecast as an RMS error. Additional error measures include the bias and the mean absolute error (MAE), which serve as supplemental means to assess model forecast skill. Details of the evaluation techniques can be found in the Appendix.

5. ANALYSES

Two sets of model-data comparisons are considered. ADCIRC-computed elevations are compared to NOAA observational data at 10 stations for forecasts that contain tidal forcing and include or exclude wind forcing. Four measures (phase error, RMS amplitude error, bias, and MAE) are computed for both forecast simulations and form the basis for evaluation of the operational model system. For the case forced by both tides and wind, statistical errors are calculated based on 48-hour tidal forecasts and corresponding successive 2-day blocks of the observational data between July 19 and August 17, 2000. To examine the sensitivity of the 2-day forecast

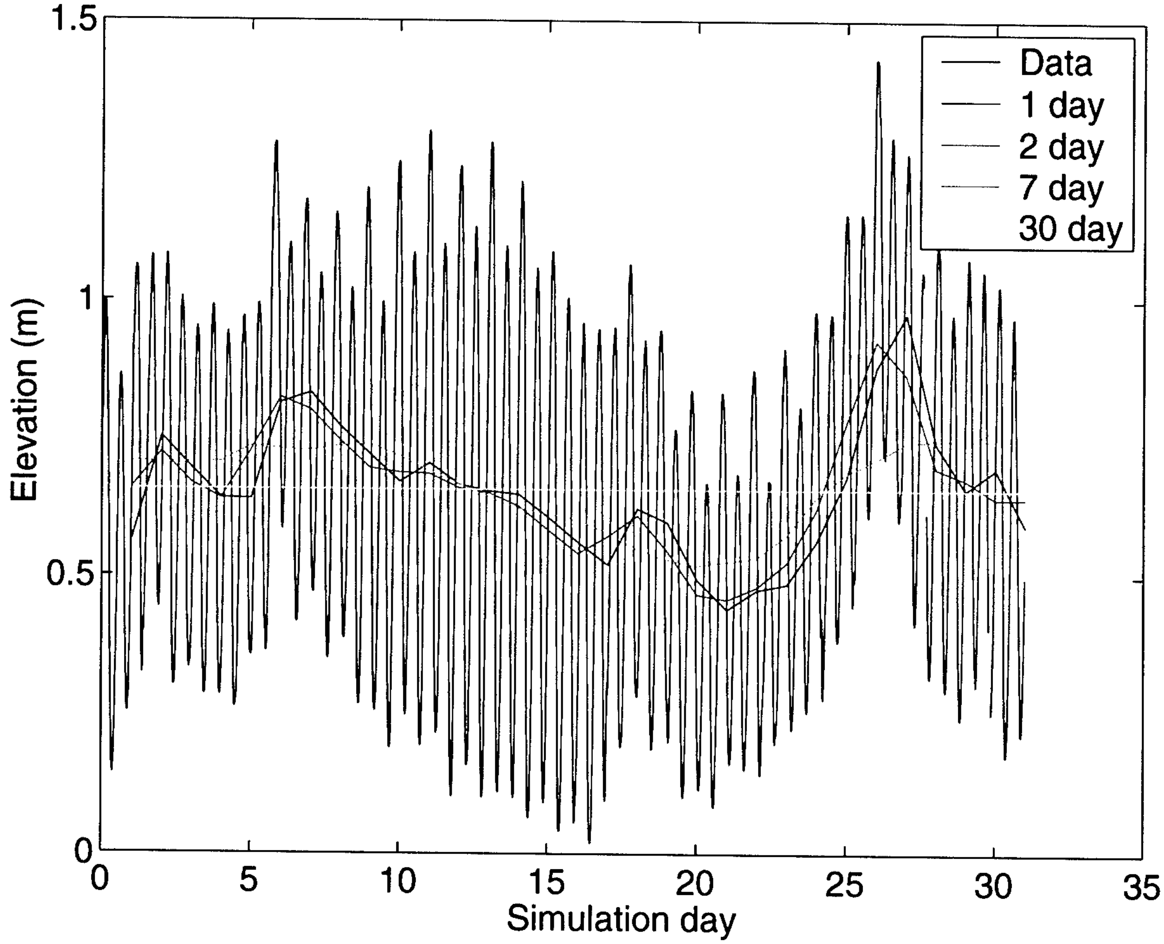

Fig. 6 — Daily, 2-, 7-, and 30-day means compared to filtered data from Chesapeake Bay, Virginia

Table 1 — Statistics for the Tide- and Wind-Forced Case (Day 1). *Original RMS reflects the RMS error before correction for the phase error. Phase RMS is calculated on the phase-shifted time series of elevation.*

Station Name	Station Number	Phase error (hrs)	origRMS (m)	phaRMS (m)	Bias (m)	MAE (m)
Sandy Hook, NJ	8531680	-0.20	0.1128	0.0886	0.0282	0.0786
Atlantic City, NJ	8534720	-0.09	0.1132	0.1049	0.0403	0.0964
Kiptopeke, VA	8632200	-0.20	0.1188	0.1091	0.0110	0.1001
Windmill Point, VA	8636580	-0.69	0.1175	0.1063	0.0259	0.0999
Sewell's Point, VA	8638610	0.01	0.1509	0.1449	0.0325	0.1307
Chesapeake Bay, VA	8638863	0.04	0.1351	0.1301	0.0194	0.1190
Duck, NC	8651370	-0.07	0.1209	0.1157	0.0214	0.1089
Springmaid Pier, NC	8661070	-0.12	0.1131	0.0995	0.0187	0.0883
Fort Pulaski, NC	8670870	-0.64	0.2604	0.1394	-0.0012	0.1186
St. Augustine Beach, FL	8720587	-0.20	0.1056	0.0895	-0.0168	0.0812
Average over stations	—	-0.22	0.1348	0.1128	0.0179	0.1022

to the NOGAPS wind forcing, the first and second day forecast error measures are computed separately to give day 1/day 2 statistics.

Without wind forcing, the ADCIRC forecast does not include any real-time variation. As such, a direct comparison between the 30-day observational time series and ADCIRC model time series at the 10 stations can be made directly. The following sections detail the computed statistics that are used to evaluate ADCIRC's performance compared to the observed data.

5.1 Tidal and Wind Forcing

The second 24 hours of the 48-hour forecasts could potentially contain slightly more error due to the uncertainty in the wind field forecasts used as model forcing. To isolate any effects of this uncertainty, comparisons to the observations are made separately for the first and second 24 hours of the 48-hour forecast. The errors for the daily forecasts are then averaged over the 31 days of the OPTEST to obtain an overall measure of error for each forecast period (day 1 or day 2). Tables 1 and 2 present the computed errors for amplitude and phase.

Day 1 and day 2 statistics compare very favorably with each other (Figs. 7 and 8), indicating that the solution does not degrade significantly in time when using the NOGAPS forecast wind stress. Mean phase errors indicate a lag of approximately 13 minutes, with values ranging from a lag of 39 minutes at Windmill Point, Virginia to a slight lead of about 2 minutes at Chesapeake Bay, Virginia (Fig. 8). Correction for the calculated phase error as detailed in the Appendix

Table 2 — Statistics for Tide- and Wind-Forced Case (Day 2). *Original RMS reflects RMS error before correction for the phase error. Phase RMS is calculated on the phase-shifted time series of elevation.*

Station Name	Station Number	Phase error (hrs)	origRMS (m)	phaRMS (m)	Bias (m)	MAE (m)
Sandy Hook, NJ	8531680	-0.20	0.1136	0.0905	0.0312	0.0806
Atlantic City, NJ	8534720	-0.09	0.1112	0.1030	0.0418	0.0944
Kiptopeke, VA	8632200	-0.21	0.1183	0.1091	0.0171	0.1003
Windmill Point, VA	8636580	-0.68	0.1175	0.1064	0.0324	0.1003
Sewell's Point, VA	8638610	-0.01	0.1497	0.1439	0.0390	0.1302
Chesapeake Bay, VA	8638863	0.03	0.1345	0.1297	0.0263	0.1188
Duck, NC	8651370	-0.07	0.1189	0.1138	0.0244	0.1072
Springmaid Pier, NC	8661070	-0.13	0.1189	0.1044	0.0217	0.0926
Fort Pulaski, NC	8670870	-0.64	0.2601	0.1384	0.0123	0.1184
St. Augustine Beach, FL	8720587	-0.20	0.1044	0.0910	0.0019	0.0822
Average over stations	—	-0.22	0.1347	0.1130	0.0248	0.1025

reduces mean amplitude RMS error from an average 13.5 cm to 11 cm. Values range from 9 cm at the northern and southernmost observation stations to 14.5 cm at Sewell's Point, Virginia (Fig. 7). Compared to the values of the average maxima of the elevation time series, these errors range from 4.1% to 12% error.

Day 1 predictions are generally unbiased with respect to amplitude, with an average bias of less than 2 cm, although the model tends to overpredict 1 to 3 cm in the northern part of the observational array, and underpredict slightly at the two southernmost stations. Day 2 statistics show a more pronounced overprediction at all stations of about 2.5 cm, indicating perhaps slightly larger applied wind stresses on day 2.

One source of error is apparent upon examination of the time series of filtered observations (Fig. 6). The presence of a large wind event over the Chesapeake Bay region is indicated in the elevation time series at Kiptopeke, Windmill Point, Sewell's Point, and Chesapeake Bay, Virginia, as well as Duck, North Carolina, which show a marked increase of 20 to 30 cm/s in the daily mean (Fig. 9) between days 25 and 29 (August 11 to 15, 2000). The spatial and temporal scales of the disturbance relative to the daily mean elevations suggest that a rather large wind event passed through the Chesapeake region during these last few days of observations. The scale of the NOGAPS model used as wind forcing for ADCIRC model forecasts cannot capture local wind effects, of which this feature is representative.

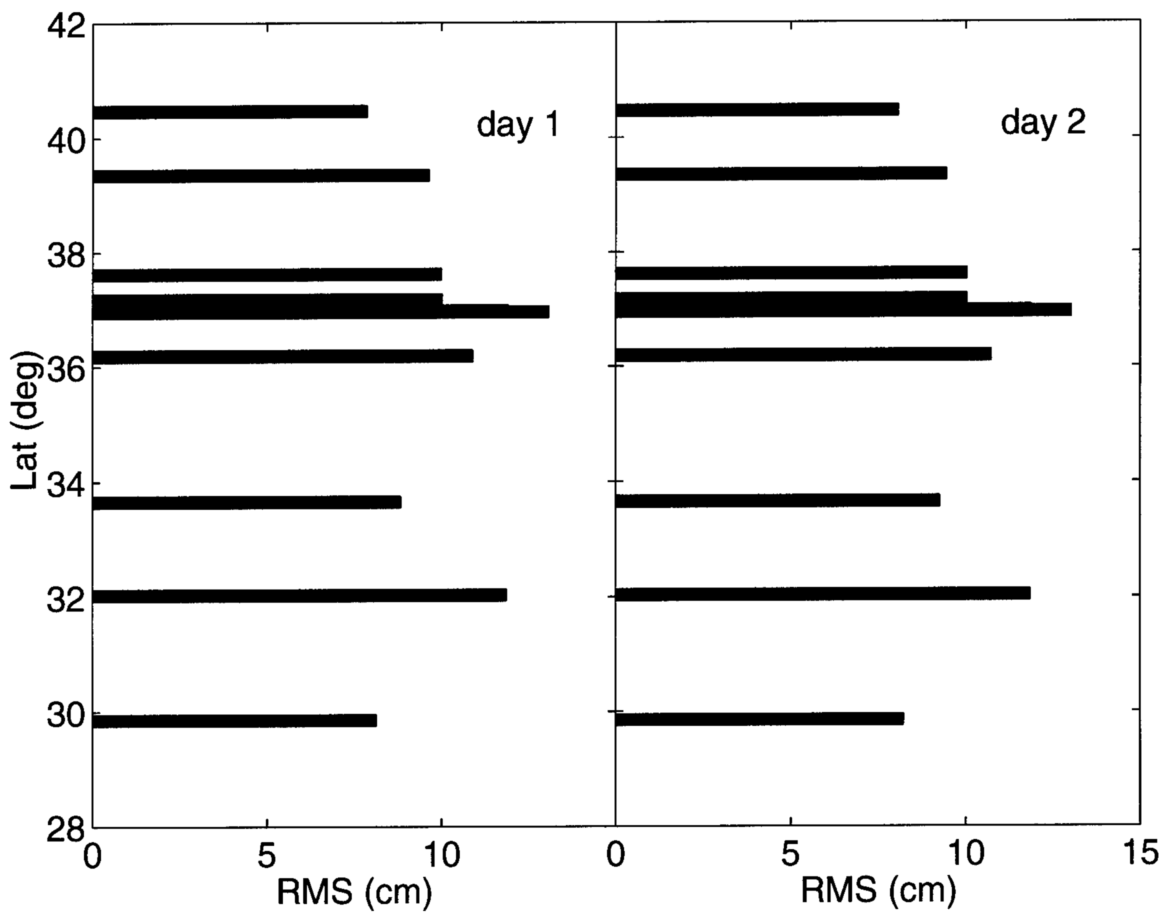

Fig. 7 — RMS elevation errors (in cm) for day 1 (red) and day 2 (blue)

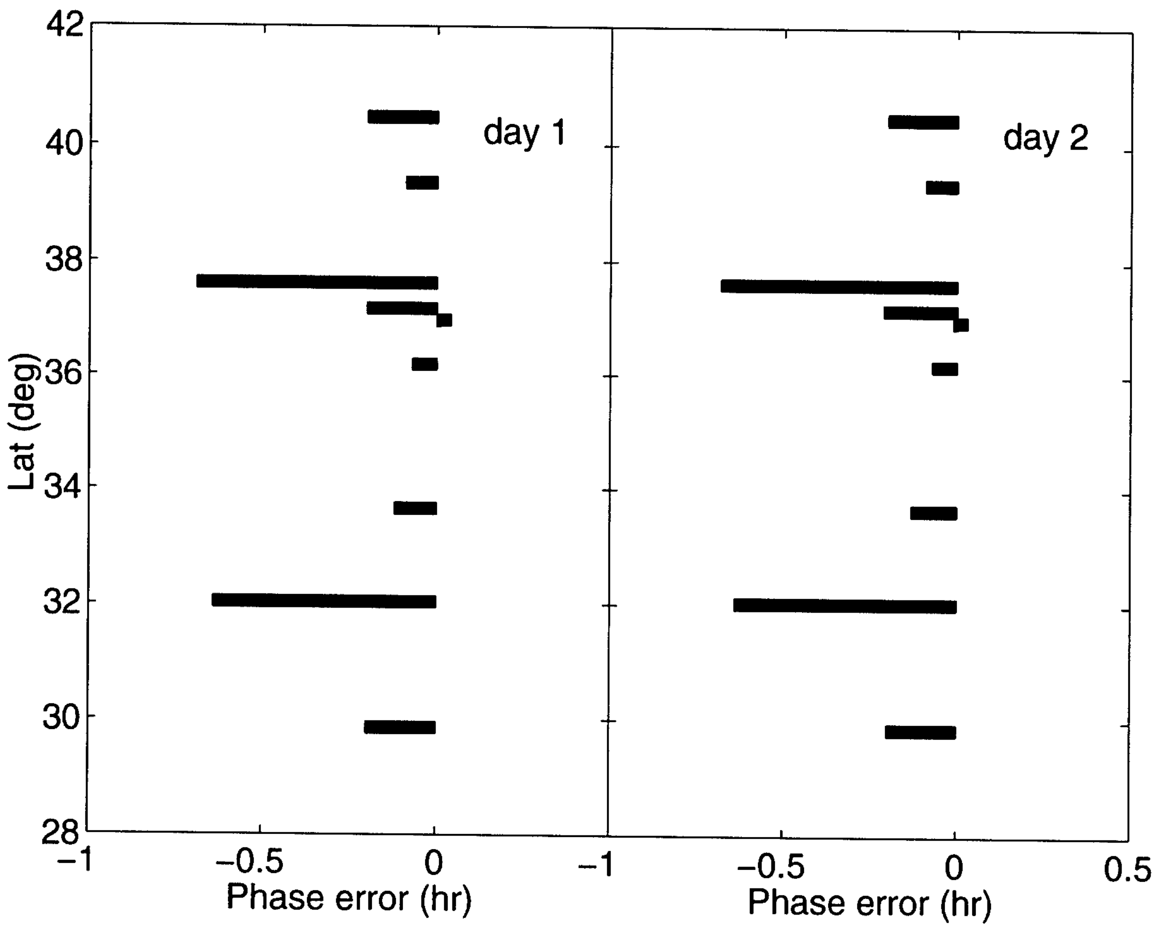

Fig. 8 — Phase errors (in hours) for day 1 (red) and day 2 (blue)

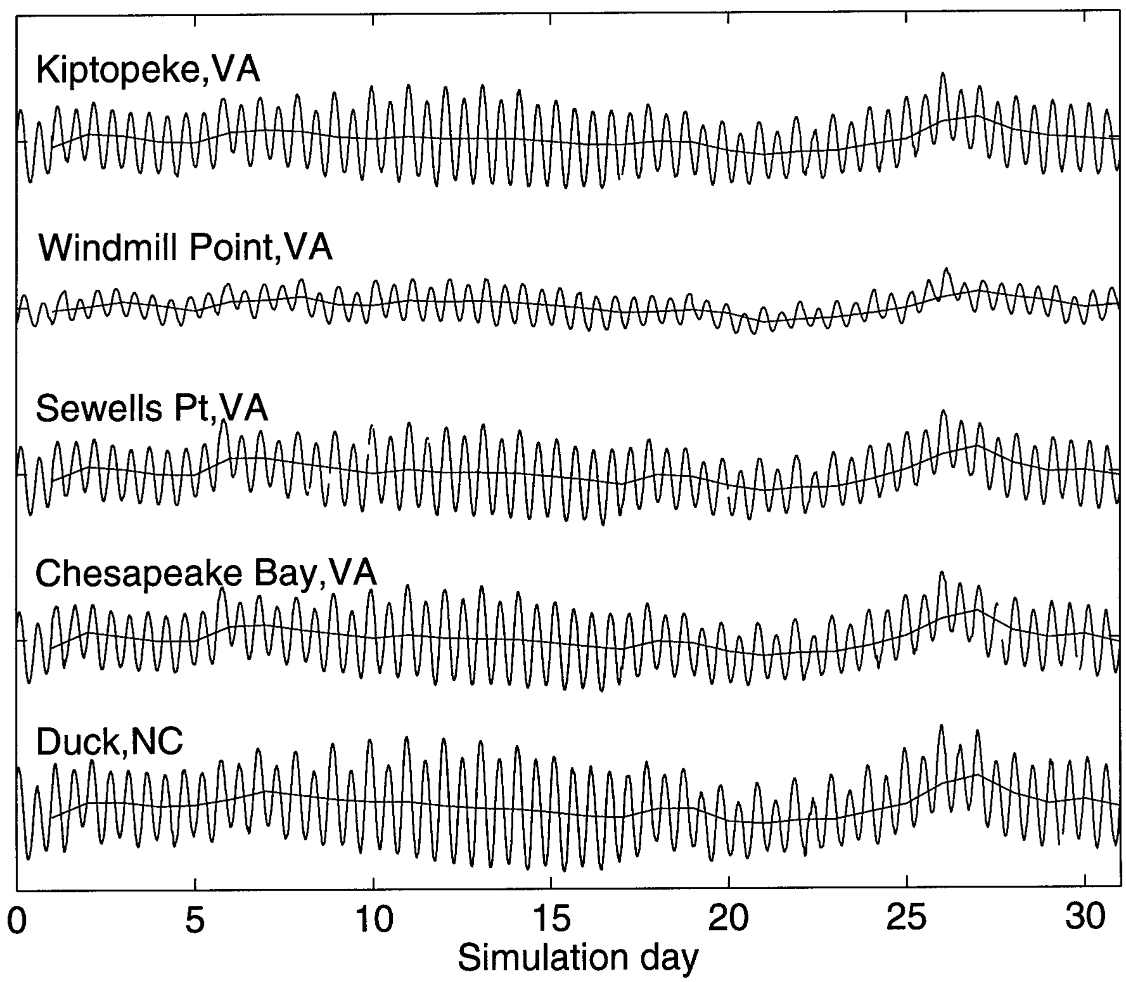

Fig. 9 — Elevation time series (blue) and daily means (red) for selected observation stations affected by a possible wind event

Table 3 — Statistics for the Tide-Only Forcing Case. *Original RMS reflects the RMS error before correction for the phase error. Phase RMS is calculated on the phase-shifted time series of elevation.*

Station Name	Station Number	Phase (hrs)	origRMS (m)	phaRMS (m)	Bias (m)	MAE (m)
Sandy Hook, NJ	8531680	-0.17	0.1159	0.1084	0.0037	0.0826
Atlantic City, NJ	8534720	-0.03	0.1240	0.1236	0.0062	0.0926
Kiptopeke, VA	8632200	-0.20	0.1241	0.1202	-0.0041	0.0946
Windmill Point, VA	8636580	-0.70	0.1052	0.0971	0.0018	0.0786
Sewell's Point, VA	8638610	0.00	0.1501	0.1501	-0.0009	0.1186
Chesapeake Bay, VA	8638863	0.03	0.1442	0.1441	0.0022	0.1139
Duck, NC	8651370	-0.03	0.1427	0.1425	0.0056	0.1081
Springmaid Pier, NC	8661070	-0.07	0.1109	0.1094	0.0032	0.0921
Fort Pulaski, NC	8670870	-0.60	0.2670	0.1492	-0.0044	0.1248
St. Augustine Beach, FL	8720587	-0.13	0.0995	0.0931	0.0038	0.0766
Average over stations	—	-0.19	0.1384	0.1238	0.0017	0.0982

5.2 Tidal Forcing Alone

Model simulations without wind forcing do not include unknown time variations due to wind setup. Thus, only a single simulation over the entire 31-day operational evaluation period of July 19 through August 17, 2000 is necessary. This single simulation takes advantage of the fact that, under tidal forcing alone, the second 24 hours of a 48-hour model forecast is identical to the 24-hour forecast made for the next day. Model validation statistics are calculated in the same manner as for tidal- and wind-forced forecasts, but comparisons are made over the entire 31-day time series at once. Results are shown in Table 3.

Phase errors without wind forcing are slightly less than those of the wind- and tidally-forced forecasts, with an average 11.4 minutes compared to 13.2 minutes lag. As a result, the effect of phase shifting in RMS error is less marked (1.5 cm on average), and amplitude RMS errors are slightly higher than in the wind-forced simulations (Fig. 10). Comparison of the bias statistic for both sets of simulations highlights the effect of wind on the solution. Because the signal is purely tidal in the case excluding wind forcing, bias in the phase-shifted solution is on the order of millimeters. Bias for the forecasts including wind forcing are an order of magnitude greater, indicating a tendency towards overprediction. Improved RMS errors suggest the importance of wind forcing and surge in the dynamics in the coastal region.

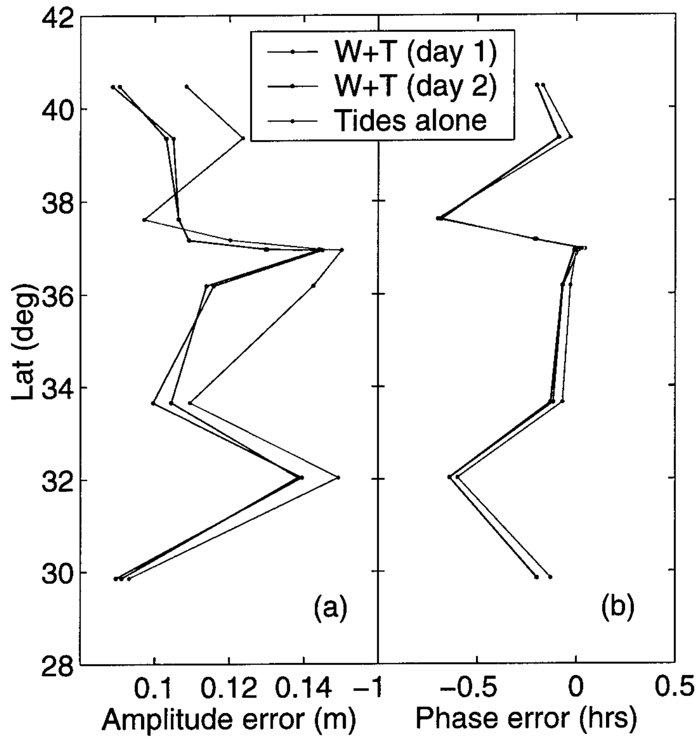

Fig. 10 — Amplitude (a) and phase errors (b) for forecasts forced by tides and wind (day 1 shown in red, day 2 shown in blue) and tides alone (green)

6. CONCLUSIONS

The finite element model ADCIRC-2DDI has been applied over the Western North Atlantic Ocean in an operational context, or OPTEST, as defined by the Naval Oceanographic Office. Both tides and wind-forced and tide-forced only simulations provide forecasts of sea surface height which fall within the acceptable Navy standard of 20% amplitude error and 1 hour phase error. Mean RMS tidal amplitude errors for the tidal- and wind-driven and the tidally-forced forecasts are 11.3 and 12.4 cm, which translate to 11.4% and 12.5% error over an average 1 m amplitude signal, and phase errors are 13.2 and 11.4 minutes, respectively. With very close proximity of several of the observation locations to the land boundary of the grid (less than 100 m at Fort Pulaski and Springmaid Pier, North Carolina), relatively small errors such as these represent even greater success.

Comparisons between the forecasts with and without the inclusion of wind forcing show the importance of applied wind forcing to the simulation. Phase error increases slightly with the inclusion of surge effects into the dynamics. Although the inclusion of wind also causes a small increase in amplitude bias towards overprediction in the region, amplitude RMS errors improve significantly. A wind event appears in the Chesapeake Bay area near the end of operational testing period (August 11 to 15, 2000), a feature not resolved by the applied NOGAPS surface wind stress and atmospheric pressure fields.

Proper care must be taken to ensure proper implementation of the forecast model and the validity of model-data comparisons. The ramping period of the ADCIRC model predictions must be chosen in a way that minimizes numerical noise due to the introduction of model forcings. In addition, observational data must be properly processed for meaningful model-data comparison. Spikes and bad data due to instrument error must be removed from the dataset, the data must be filtered to remove high-frequency noise, and finally, an appropriate mean must be removed from the data to ensure a valid comparison. Given these steps to ensure data quality, it has been shown that the ADCIRC model forecast system effectively predicts elevations in an operational setting as measured by comparison to NOAA observed elevations along the U.S. East Coast, under the forcing of NOGAPS wind stress and Grenoble (FES95.2.1) open boundary forcing.

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Appendix

CALCULATION OF STATISTICS

Traditionally, tidal elevation time series comparisons are made by finding the peaks and troughs in the two datasets and comparing the time of occurrence and magnitude of these points to compute phase and amplitude errors. However, this straightforward method can incorrectly pinpoint high and low tide, where highly nonlinear dynamics or instrument error may produce double peaks or troughs. Instrument error can also produce missing data or spurious values not completely smoothed by filtering, further complicating the identification of the true peaks and troughs.

For this application, phase and amplitude errors are calculated independently by searching for the phase lag that maximizes correlation between the two time series. Amplitude error is then calculated on the phase-shifted time series that is optimal in time. By using the entire time series to calculate phase shift and amplitude error, the presence of multiple peaks and troughs do not affect statistics as significantly. In addition, using this method, even very sparse observational data can be compared with model computations, whereas the more direct peaks and troughs method would fail. Step-by-step descriptions of these calculations are outlined below.

Phase Error

The phase error is calculated by first interpolating the ADCIRC time series from 6-minute to 2-minute time intervals to achieve greater precision in determining phase error. This interpolated time series is then shifted both backward and forward in time (with respect to the "center") in increments of 2 minutes, from -4.0 to 4.0 hours (Fig. A1), effectively creating a "bundle" of model predictions, each shifted in time by a small amount.

Correlation between the phase-shifted time series and observational time series is calculated for each curve in the "bundle" of phase-shifted predictions, and maximized over the "bundle." The phase shift that results in the correlation closest to unity is reported in hours in the statistics tables. Mathematically, this can be expressed as the Δt that minimizes the following expression:

$$\frac{\sum \; (\eta_p(\Delta t) - |\eta_p(\Delta t)|) \; (\eta_o(\Delta t) - |\eta_o(\Delta t)|)}{| \sum \; (\eta_p(\Delta t) - |\eta_p(\Delta t)|) \; (\eta_o(\Delta t) - |\eta_o(\Delta t)|) \; |} \tag{A1}$$

where $\eta_p(\Delta t)$ and $\eta_o(\Delta t)$ are the predicted and observed elevations at phase shift Δt.

This method of calculation for the optimal phase shift allows even very sparse data to be compared to the observations, as it is the trend of the observations that is compared to that of the model forecast, not individual peaks and troughs. In practice, however, model-data comparisons are only made in the case where at least 50% of the data are available for comparison.

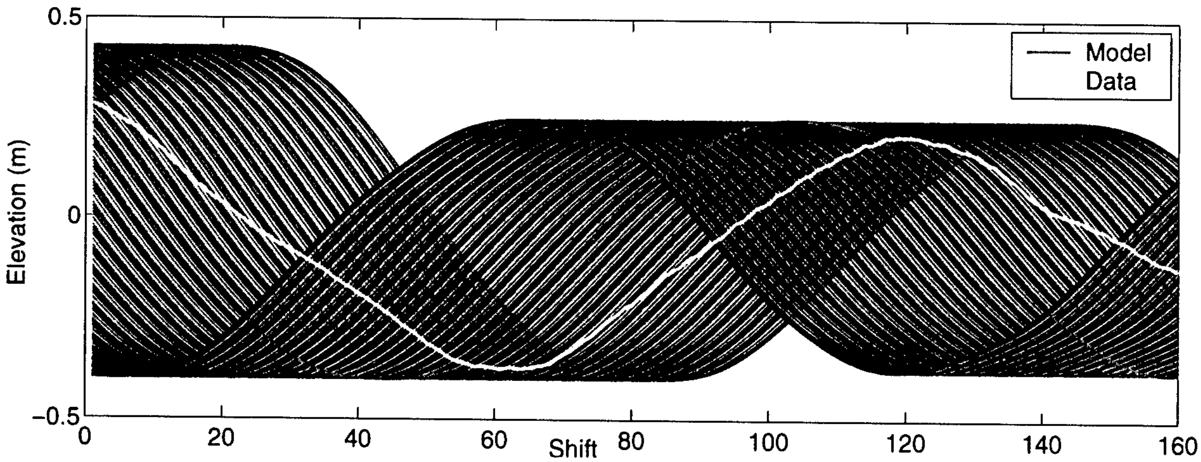

Fig. A1 — Model elevation forecast (cyan, foreground) and observations (yellow, foreground) over a 12-hour block. The model forecast is shifted backward and forward in time in 2-minute increments. The "bundle" of phase-shifted time series is shown in the background.

Amplitude Error Measures (RMS, Bias, MAE)

The amplitude error is evaluated by calculating the RMS error

$$rms = \sqrt{\frac{\sum(\eta_p - \eta_o)^2}{N}} \tag{A2}$$

between the original and phase-shifted time series. This RMS error is not based on heights of tidal peaks and troughs, but rather, it is calculated for the entire time series. It can be shown that this method produces phase and RMS errors in good agreement with a more laborious peak and trough method where correct identification of maxima and minima are difficult to identify through automated methods and may have to be corrected by hand.

Bias considers the sign of the difference between the time series and is calculated as the mean bias of the phase-shifted ADCIRC time series with respect to observational data.

$$phabias = \frac{\sum(\eta_p - \eta_o)}{N} \tag{A3}$$

Mean absolute error (MAE) is calculated by station as the mean absolute difference between the phase-shifted ADCIRC time series with respect to observational data.

$$phamae = \frac{\sum|\eta_p - \eta_o|}{N} \tag{A4}$$