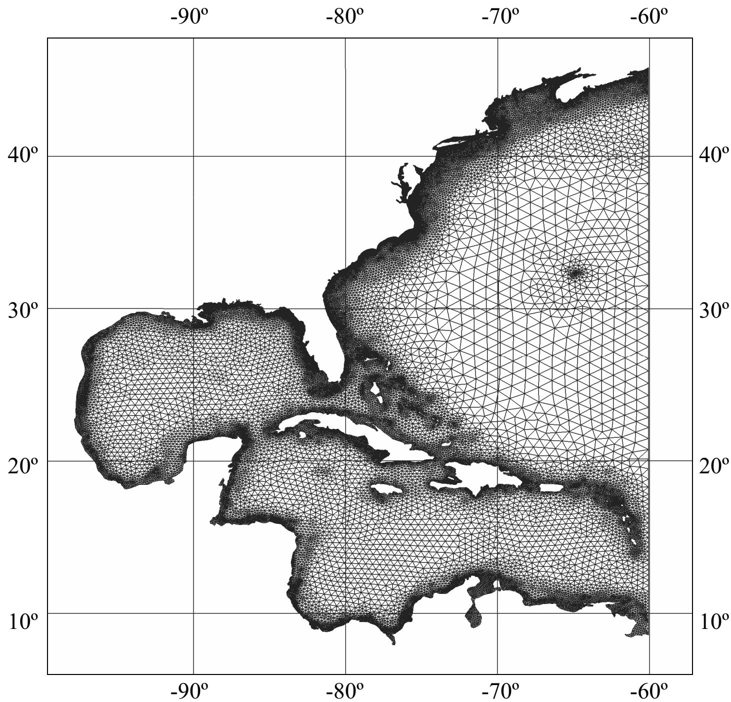

Figure 3. EC95 computational domain containing 31,435 nodes.

al. 1994). These same constituents are also specified for internal tidal potential forcing. The model uses a 30 s time step, while lateral eddy viscosity is not needed due to its coarse resolution. The τ_0 weighting parameter is spatially constant and set to 0.005.

With the successful completion of the EC95 tidal run, simulations with NARR meteorological forcing are initiated to compute nontidal water levels and depth-averaged currents at the boundaries of the DRB MEE. Tests listed in Table 1 are set up to examine stability conditions for meteorologically-forced runs using EC95. Initially the open ocean boundary condition is clamped to a constant elevation of 0 m. Wind and pressure forcing is ramped up over the run's first 15 days, a 1 s time step is set (much smaller than the 30 s time step used in the solely tidal run), and a lateral viscosity of 7 m^2/s is specified. However, model tests over a range of τ_0 values from 0.001 to 1.0 show high frequency oscillations for τ_0 less than 0.05 and instability for larger τ_0 values. These results indicate that this model setup is not a viable option for computing meteorologically-forced circulation over the EC95 domain.

Table 1. Meteorological simulations to examine stability using the EC95 domain.

Time Step (s)	Eddy Viscosity (m^2/s)	Weighting Parameter (τ_0)	Tide Ramp (day)	Wind, Ramp (day)	Pressure, Ramp (day)	Stable?
1	7	0.001 – 1.0	-	NARR, 15	NARR, 15	No
5, 30	0 – 5	0.005	12	NARR, 12	NARR, 12	No
5	5	0.005	25	NARR, 25	NARR, 25	No
1, 2.5	10	0.005	19	NARR, 19	NARR, 19	No
2.5	10	0.005	19	NARR, 5 (after tides)	NARR, 5 (after tides)	No
30	0	0.001	30	NARR, 7 (after tides)	NARR, 7 (after tides)	No
30	0	0.001	30	Filtered NARR, 7 (after tides)	Filtered NARR, 7 (after tides)	No
2.5	10	0.005	19	NARR, 19	Constant, 19	Yes
30	0	0.001	30	NARR, 7 (after tides)	Constant, 7 (after tides)	Yes
30	0	0.001	30	Filtered NARR, 7 (after tides)	Constant, 7 (after tides)	Yes
30	0	0.001	30	Filtered NARR + Observations, 7 (after tides)	Constant, 7 (after tides)	Yes
30	0	0.001	30	NARR, 7 (after tides)	Tapered, 7 (after tides)	Yes

Examination of the results show that the clamped boundary condition used in the EC95 meteorologically forced runs reflects surface waves off the open boundary, leading to model instability. In particular, it is noted that the open boundary is not far from the relatively shallow Windward Island chain, and the nonlinear response generated by the islands is not specified at the nearby clamped boundary. It is theorized that a combined tidally and meteorologically forced run could offer improved model stability due to the dissipation caused by tidal energy in shallow water regions, and due to the non-still boundary condition at the open ocean.

Therefore, testing is done to examine the viability of this approach. Tidal forcing including both boundary condition and internal body harmonic constants are taken from the Schwiderski global model. Meteorological forcing is imposed using linear interpolation of NARR wind and pressure fields. Initial model setup for these tests is based upon simultaneous ramping of tides and meteorology over a 12 day period. Time steps of both 30 s and 5 s are implemented, a range of eddy viscosity values (0 to 5 m^2/s) is tested, and τ_0 is set to 0.005. However, these tests all result in model instabilities. The model ramp is extended from 12 to 25 days, but this did not improve model stability (based on a run with a 5 s time step, eddy viscosity of 5 m^2/s, and τ_0 of 0.005). The time step is reduced (to 2.5 s and then to1 s), the lateral viscosity increased to 10 m^2/s, and ramp time increased to 19 days, but the model is still unstable. Ramping up the meteorological forcing over 5 days after tides spin up for 19 days also leads to instability for this model configuration. Similarly, a 7 day meteorological ramp after a 30 day spinup of tidal forcing with a 30 s time step, no lateral viscosity, and τ_0 of 0.001 is unstable. Considering that the 32 km resolution of the NARR has difficulty resolving the coastline, it is possible that sharp gradients in the meteorological forcing are generating spurious oscillations near the shore. Repeating the run above with smoothed forcing from the Gaussian filtered version of the NARR is also unstable. Final testing shows that disabling the advective terms for the runs above does not improve stability.

Therefore, all meteorologically forced runs using the EC95 domain are unstable when the elevation-specified (clamped) boundary condition is applied. This is regardless of bottom friction coefficient, lateral viscosity coefficient, time step, ramp length, whether tides and meteorology are ramped up together or separately, whether tides are applied or not, or if meteorology is smoothed by filtering.

ADCIRC is sensitive to generation and propagation of spurious oscillations because it is non-dissipative. Spurious oscillations which lead to model instability can be created when internally-generated long waves reflect off the clamped open ocean boundary. These waves can be due either to meteorological forcing (i.e. wind and atmospheric pressure) or nonlinear response generated by the physics in the governing equations (i.e. shallow water tidal constituents within coastal regions). It is not possible to know these wave conditions *a priori* and therefore accurate boundary conditions are not available. The nonlinear response generated in shallow water can be minimized at the open boundary by moving the boundary far from the coast, as with the basin scale domain. However, meteorologically forced response which is not incorporated into the boundary condition specification still can cause model instability.

In deep water, changes in water surface elevation due to meteorological forcing are predominantly from the inverted barometer effect (caused by low atmospheric pressure). Therefore, the EC95 model domain is tested by applying tides and wind with the atmospheric pressure set to a constant atmospheric background value. It should be noted this approach is used in daily water level predictions produced by ADCIRC on the EC95 domain (R. Luettich, personal comm.). Four model configurations are tested, all of which apply the elevation-specified (clamped) boundary condition and omit pressure field gradients. The first (time step of 2.5 s, 19 day ramp, 10 m^2/s eddy viscosity, τ_0 of 0.005) and second (time step of 30 s, 30 day tide ramp followed by 7 day wind ramp, 0 m^2/s eddy viscosity, τ_0 of 0.001) are both stable using the original NARR wind field despite how they differ in time step and dissipation parameters. The second run was repeated with the filtered NARR wind

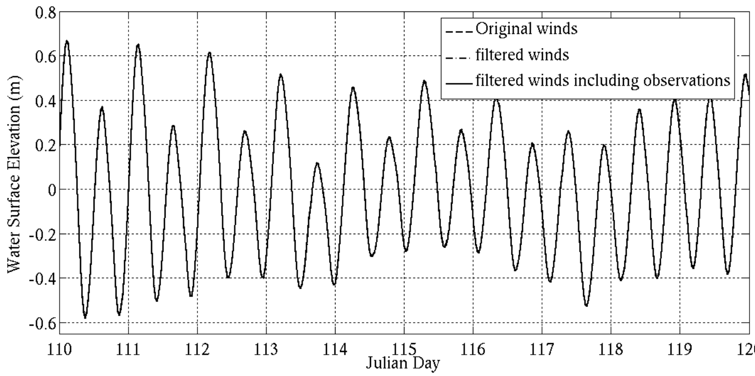

Figure 4. Water level time series at Ocean City, MD driven by original NARR winds, Gaussian filtered winds, and filtered winds with additional local observations.

fields and with the filtered NARR wind fields enhanced by local observations to determine if either improves meteorological forcing near Delaware Bay. However, Figure 4 shows that the results between all three forcings are virtually indistinguishable, indicating NARR wind forcing is not improved by Gaussian filtering or by interpolation of high resolution observations.

Limiting Atmospheric Pressure-Induced Water Level Response at the Open Ocean Boundary

Pressure forcing can contribute to a significant portion of the water surface elevation response because of the inverted barometer effect. However, the reflection of the surface pressure signal at the clamped open ocean boundary back into the domain leads not only to an incorrect response but also to non-physical spurious oscillations and model instability (as noted in the extensive testing above). In order to remove the existence of the inverted barometer pressure signal at the open ocean boundary, the pressure anomaly (difference from a background atmospheric pressure of 1013 mb) is tapered to zero at the open ocean boundary. This tapering is a simple linear interpolation of the pressure anomaly from 100 % of its NARR value west of 65° W to 0% of its NARR value at 61° W; the anomaly is set to zero between 61° and the open ocean boundary.

The goal of this strategy is to gain the pressure response at the coast and over Delaware Bay while maintaining model stability by removing surface waves at the boundary. This approach is tested with an efficient model setup successful in the tidal and wind forced tests: a 30 day ramp for tides followed by a 7 day ramp for meteorology, a 30 s time step, no lateral eddy viscosity, and a τ_0 of 0.001. This pressure-forced model run is stable and Figure 5 shows results along with the same model setup without pressure forcing and observations. The water level time series

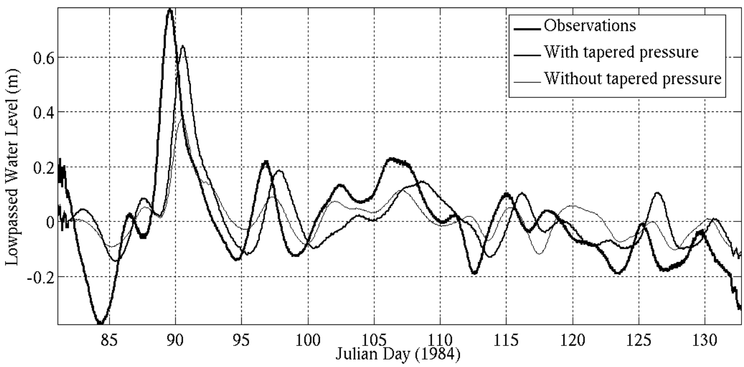

Figure 5. Low-pass filtered water level both with tapered pressure and without pressure forcing compared with observations at Atlantic City, NJ.

are 30 hour low-pass filtered to emphasize the non-tidal response. These results show that inclusion of the pressure forcing at the coast enables the model to track surges more closely, as seen for the event around Julian Day 90.

Testing with the EC95 domain shows that applying the inverted barometer pressure signal at a clamped (elevation-specified) open ocean boundary causes reflection of a surface wave back in to the domain in a non-physical way. The energy in the surface pressure response is aliased to higher frequencies, generating spurious oscillations (such as $2\Delta x$ waves) which commonly lead to model instability because of ADCIRC's highly non-dissipative behavior. Removing the surface pressure signal at the open boundary by tapering the atmospheric pressure anomaly to zero allows for atmospheric pressure forcing on the shelf while eliminating model instability. Inclusion of pressure forcing is advantageous because of its effect on the water surface over the shelf.

Model simulations using the tapered pressure forcing on the EC95 domain are stable and the quality of the results reasonable (Figure 5). However, it is not known if skill could be improved with a higher resolution grid. Therefore, a higher resolution version of the ADCIRC East Coast tidal database which was released in 2001 (EC2001) is also tested (Mukai et al. 2001). The resolution of the grid is noticeably finer than EC95, with 254,565 nodes (an eightfold increase) and spacing ranging from a maximum of about 20 km in the deep ocean to an average of around 2-3 km in Delaware Bay, reductions of a half to three quarters. The EC2001 grid also benefits from improved bathymetry and is known to provide an overall improved tidal response. Figure 6 shows the EC2001 computational grid.

First, the EC2001 grid is tested by applying tidal forcing at the open ocean boundary. These results show that the model only remains stable with the nonlinear advection terms disabled, regardless of other model parameters. This instability may be caused

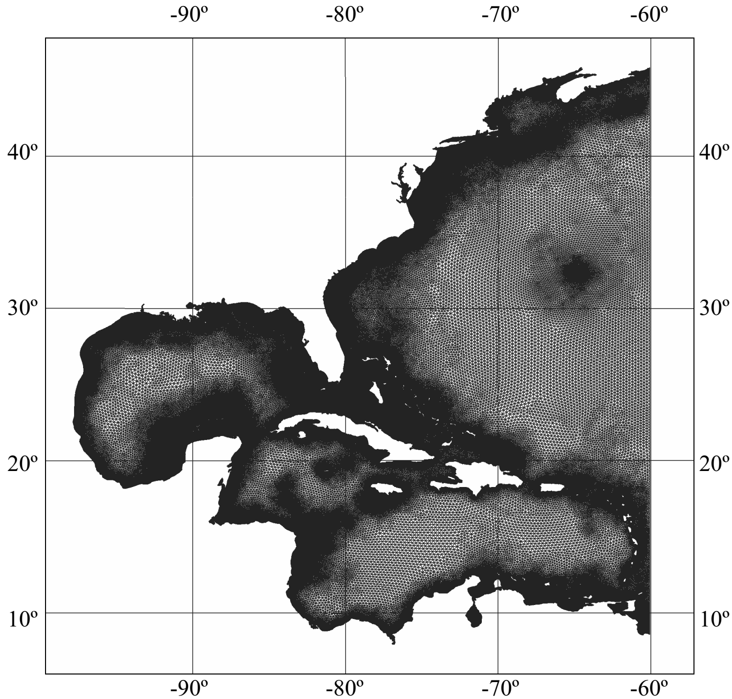

Figure 6. EC2001 computational domain containing 254,565 nodes.

by complex, nonlinearly generated response from the relatively shallow Windward Island chain which cannot be specified at the nearby clamped boundary. The tidal model run is only stable without application of the nonlinear advection terms; parameters were set at a 30 day ramp, a 2.5 s time step, a lateral eddy viscosity of 5 m^2/s, and a spatially varying τ_0 of 0.005 in deep water and 0.02 in shallow water. Testing a range of parameter settings with advection enabled did not provide model stability; these tests include variation in ramp length (4 and 30 days), time step (1.0, 2.5 , and 5.0 s), and lateral eddy viscosity (1 m^2/s and 5 m^2/s). It should be noted that disabling advective terms was also necessary in the development of the ADCIRC tidal database (Mukai et al. 2001), and model stability sensitivity to the advection terms is due to their explicit solution procedure. Additionally, strong spatial gradients in the flow field are not widely present in a basin-scale domain with coastal resolutions of 2 to 3 km and more, minimizing the impact of disabling advective processes in the model.

Synoptic hindcasts with EC2001 follow the set-ups used with EC95 in order to examine the effect of increased resolution of the meteorological forcing field and the

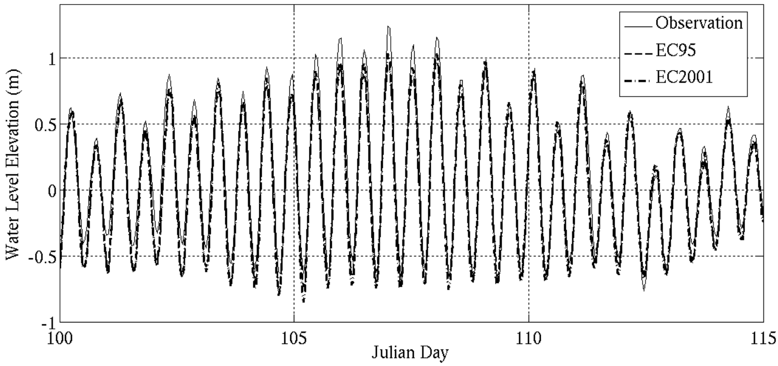

Figure 7. Synoptic water level time series from EC95 and EC2001 with tidal, wind, and tapered pressure forcing as compared to observations at Atlantic City, NJ.

hydrodynamics. EC2001 model simulations using tidal, wind, and unmodified atmospheric pressure forcing are unstable, as with EC95. Similarly, removal of the pressure forcing on the EC2001 domain leads to a stable model result for a tidal and wind-driven simulation (albeit still requiring disabling of the advection terms as with the tidally-forced EC2001 simulation).

Finally, the EC2001 domain is forced with a tapered pressure field along with wind and tidal forcing using the final model setup used for EC95. Removal of the inverted barometer effect at the open boundary by tapering the pressure anomaly to zero allows for incorporation of atmospheric pressure forcing on the shelf while eliminating the cause of the model instability. These results are compared to the results from the EC95 domain in Figure 7. It can be observed that the additional resolution in EC2001 does not noticeably modify the results. Therefore, the EC2001 grid does not provide a significant improvement for computation of water levels near Delaware Bay over the less costly EC95 grid.

Final Model Results

A stable and efficient model is developed for determining water level and current velocity at the boundary of the Delaware Bay models. Skill is examined by studying model results for both tidal and synoptic runs. In order to determine the model's ability to reproduce the tidal response, a harmonic analysis of modeled water level time series is performed to determine harmonic constants for a suite of tidal constituents. These results are compared to the harmonic constants produced by analysis of observed time series as published by NOAA's Center for Operational Oceanographic Products and Services. Tidal constituent data from field observations at two stations in the Delaware Bay region is used for comparison to tidal simulations on the EC95 domain. These stations are along the Atlantic Ocean coast and are

Table 2. Modeled and observed tidal constituent amplitude and phase (m, degrees).

Constituent	Atlantic City Observed	Atlantic City Modeled	Ocean City Observed	Ocean City Modeled
M_2	(0.594, 355.4)	(0.559, 353.6)	(0.501, 0.9)	(0.472, 357.6)
S_2	(0.116, 17.8)	(0.112, 13.8)	(0.097, 24.6)	(0.091, 15.6)
N_2	(0.141, 335.9)	(0.130, 339.4)	(0.117, 342.1)	(0.112, 341.9)
K_1	(0.110, 183.2)	(0.092, 174.7)	(0.088, 194.4)	(0.088, 177.3)
O_1	(0.075, 166.1)	(0.071, 181.6)	(0.085, 185.3)	(0.071, 191.6)

located at Atlantic City, NJ, and Ocean City, MD. The EC95 domain is run with tidal forcing for 79 days and a harmonic analysis is performed over the final 48 days. Five major tidal constituents included in model harmonic analysis are compared to observed harmonic constants in Table 2. These results show that the M_2 tide is dominant in this region but the additional constituents also contribute to the tidal response. The modeled tidal constituents are slightly under predicted in amplitude, but there is no more than a 4 cm difference for any one constituent. The modeled tidal phase shows a larger variation in accuracy, although the dominant M_2 constituent has less than 4 degrees of error. Finally, the model-based and observation-based tidal constituents are used to construct a time series for comparison in Figures 8 and 9. The seven most significant constituents (M_2, S_2, N_2, K_1, O_1, M_4, and M_6) are included in the time series. The only discernable difference in these time series is a slight model under prediction in tidal amplitude at the spring tide. Both analyses demonstrate a good comparison between the EC95 tidal model results and the observations.

The final synoptic model hindcast is used to examine the accuracy of the EC95 domain in providing boundary conditions to the Delaware Bay model domains. A water level-specified open ocean boundary condition is used to provide tidal forcing. Five tidal constituents are applied: M_2, S_2, N_2, O_1, and K_1. The hindcast is set to begin on 31 December 1983 so that Julian Day 1.0 1984 (1 January) will correspond to model run day 1.0 (which starts from 0.0). Nodal factors and equilibrium arguments are set for 31 December 1983. The NARR 10 m wind and mean sea level atmospheric pressure are linearly interpolated onto the ADCIRC computational grid to create 3 hour records for meteorological forcing. In order to prevent reflection of waves off of the clamped boundary, the atmospheric pressure anomaly is tapered to zero near the open ocean boundary as described previously. The fully nonlinear form of the model is used, and no lateral eddy viscosity is required because of the relatively coarse resolution of the model. The numerical weighting parameter in the GWCE is set to 0.001. The bottom friction coefficient is set to 0.003, but this increases nonlinearly below the break depth of 1.0 m (using hybrid friction parameter settings of γ_f=10.0 and φ_f=0.3333). Wetting of previously dry elements is allowed when the water depth exceeds 0.02 m and the estimated flow velocity exceeds 0.05 m/s. Version 45.11 of the ADCIRC model is used to generate the final results.

The final synoptic run is separated into two phases: a solely tidally forced period of almost a month that ramps up the tidal signal over 20 days, and a combined tidally and meteorologically forced run in which the meteorological forcing is ramped up

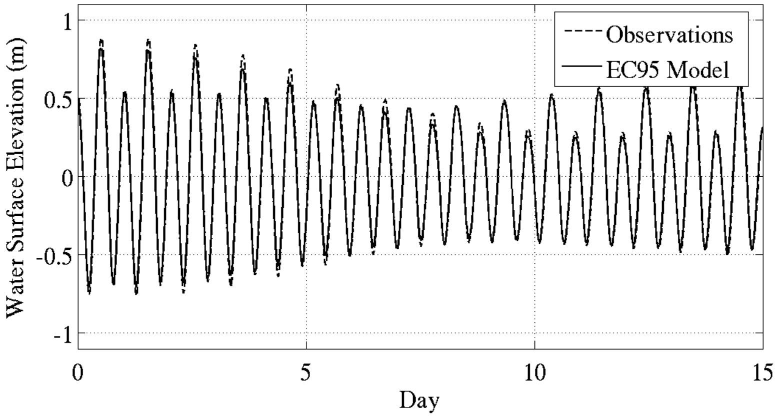

Figure 8. Reconstituted tidal signal at Atlantic City, NJ.

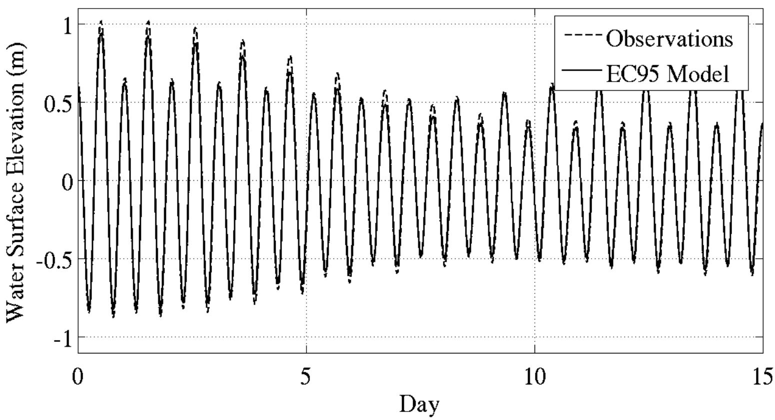

Figure 9. Reconstituted tidal signal at Ocean City, MD.

over 5 days. The solely tidally forced simulation starts on 31 December 1983 00Z and pauses at 00Z on 25 January 1984. Then the tidally and meteorologically forced synoptic run is continued from the end of the tidal run with a 5 day ramp applied to the meteorological forcing; hindcast output begins on 1 February 00Z. In order to keep the meteorological forcing files to a manageable size, the synoptic hindcast is broken into 3 month segments: 25 January 1984 00Z to 1 April 1984 00Z, 1 April 1984 00Z to 1 July 1984 00Z, and 1 July 1984 00Z to 1 October 1984 00Z. Records are made of water levels and depth-averaged velocities every 6 minutes around the mouth of Delaware Bay at the boundary of the DRB MEE. Output is recorded from

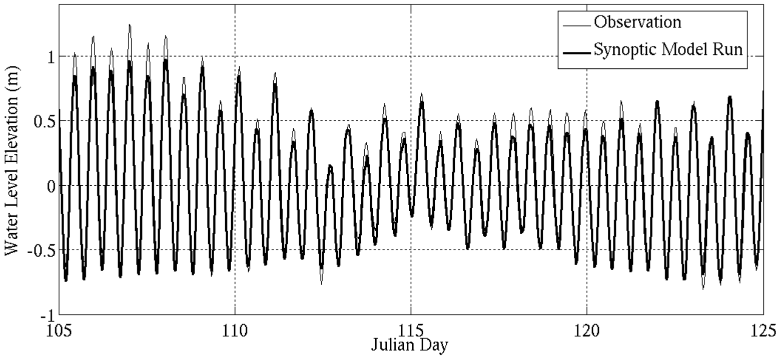

Figure 10. Synoptic model run output and observational data at Atlantic City, NJ.

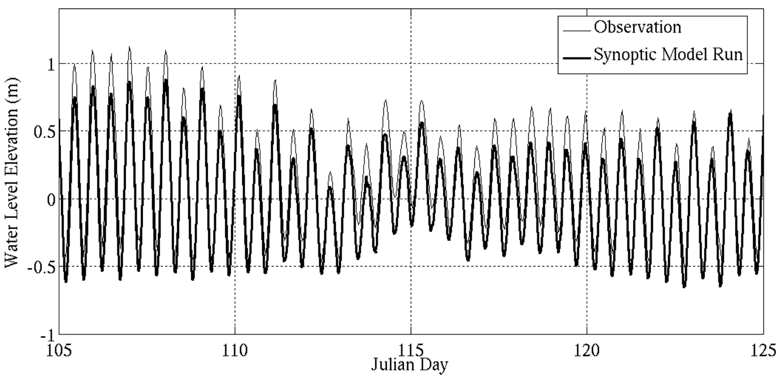

Figure 11. Synoptic model run output and observational data at Ocean City, MD.

1 February 1984 00Z to 1 October 1984 00Z and used to create input files for the estuarine-scale Delaware Bay models. The final synoptic run was executed on NOAA computing resources at the Earth System Research Laboratory's High Performance Computing System. Sixty four 32-bit Intel Xeon processors running at 2.2 GHz were used to complete a 3 month synoptic run with a 30 s time step in approximately 2.5 hours.

The final synoptic model run is compared to observational data in order to examine non-tidal model performance. Water level time series are compared against observations at Atlantic City, NJ and Ocean City, MD. The model output is plotted against the observations in Figures 10 and 11. These plots demonstrate a close match of the EC95 model to the observed water level time series around Delaware Bay.