NOAA Technical Report NOS CS 28

THREE-DIMENSIONAL HYDRODYNAMIC MODEL DEVELOPMENTS FOR A DELAWARE RIVER AND BAY NOWCAST/FORECAST SYSTEM

Silver Spring, Maryland
January 2011

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Coast Survey Development Laboratory

Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
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THREE-DIMENSIONAL HYDRODYNAMIC MODEL DEVELOPMENTS FOR A DELAWARE RIVER AND BAY NOWCAST/FORECAST SYSTEM

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January 2011

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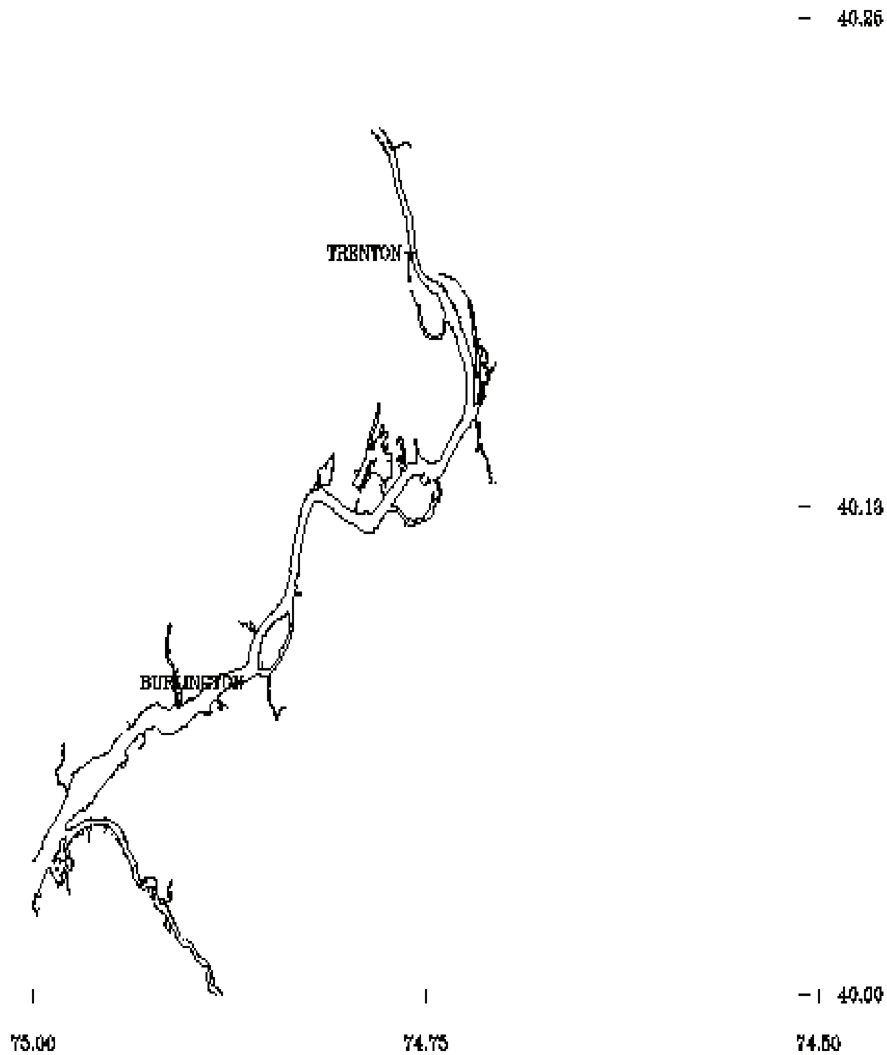
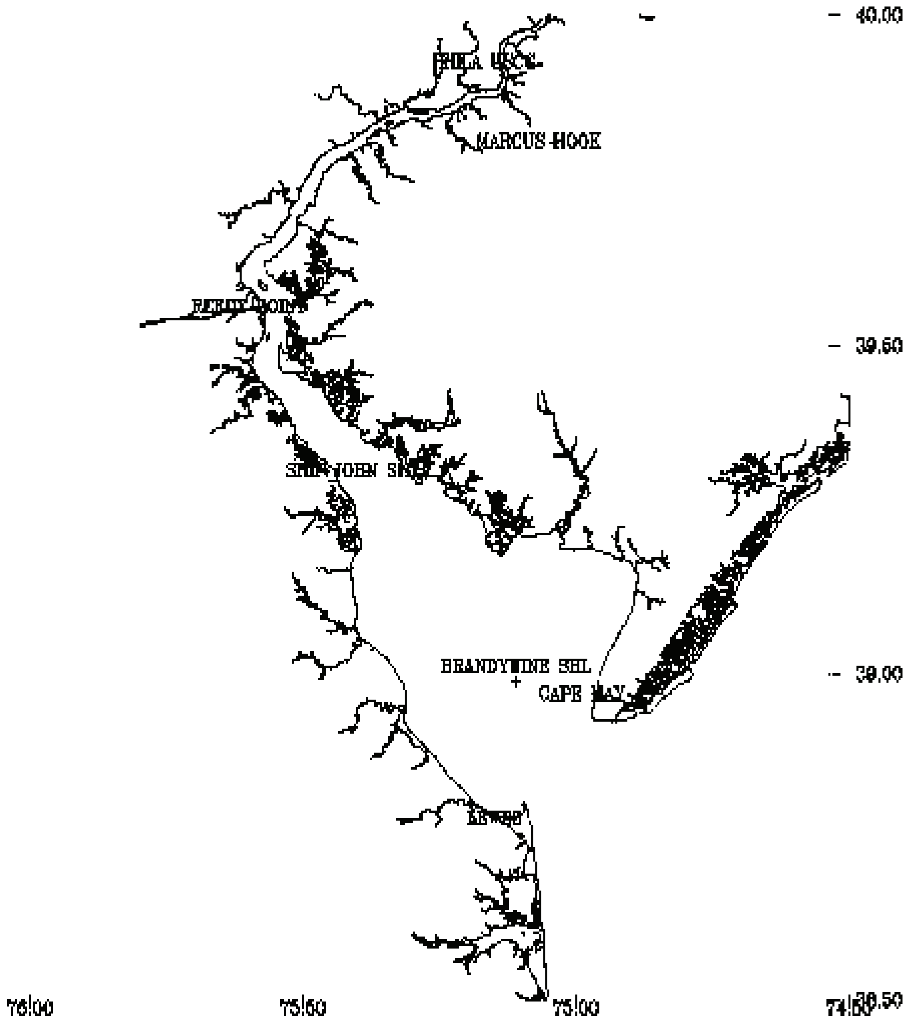
ABSTRACT

The National Ocean Service (NOS) installed a Physical Oceanographic Real Time System (PORTS) during 2003 to provide water surface elevation, currents at prediction depth (4.7m below MLLW) as well as near-surface and near-bottom temperature and salinity, and meteorological information. To complement the PORTS, a new next generation nowcast/forecast system has been developed. This next generation nowcast/forecast system domain extends from the head of tide at Trenton, NJ out to the continental shelf break and is run on the National Center for Environmental Prediction (NCEP) supercomputers based on a recently developed High Performance Computing Coastal Ocean Modeling Framework (HPC-COMF; Zhang et al., 2010) to allow four times daily six-hour nowcasts and 48 hour forecasts. In conjunction with this effort, a Model Evaluation Environment (MEE) as described by Patchen (2008) was constructed for the Delaware River and Bay based on the NOS 1984-1985 Circulation Data Survey (Klavans et al., 1986). As a first step the MEE results are used to guide the development of the Delaware River and Bay Nowcast/Forecast System. First, we describe and present the results from the MEE. Based on the MEE results, the Princeton Ocean Model (POM) and the Regional Ocean Modeling System (ROMS) were selected for further application in the Delaware River and Bay and both used the same medium resolution grid. Next, POM and ROMS common medium resolution grid revised simulation results are presented, respectively, in an effort to improve upon the MEE results. To further improve results in the river sections, a new higher resolution grid using the DELFT3D-RFGRID software was constructed. To take advantage of the parallel computing opportunities at National Centers for Environmental Prediction (NCEP), ROMS was selected as the hydrodynamic model in Delaware Bay Operational Forecast System (DBOFS). ROMS high resolution grid results are presented for the two 15-day simulations as well as for an extended seven month hindcast and contrasted with the medium resolution results. The ROMS high resolution grid was used to investigate the sensitivity of the tidal response to bottom roughness coefficients and offshore tidal constituents in eighteen tidal simulations during April 1984. Upon further improvement of the model tidal dynamics as a result of the sensitivity analysis, a 13-month tidal simulation as well as a 13-month hindcast were performed and are discussed. Next, the construction of the semi-operational nowcast/forecast system at NCEP is presented. Finally, conclusions are drawn and recommendations for formal skill assessment and transition to operations are advanced.



Base Map 1. Upper Delaware River Principal City Locations.



Base Map 2. Lower Delaware River and Bay Principal City Locations.

1. INTRODUCTION

The National Ocean Service (NOS), Center for Operational Products and Services (CO-OPS), installed a Physical Oceanographic Real Time System (PORTS) during 2003 to provide water surface elevation, currents at PORTS prediction depth (4.7m below MLLW) as well as near-surface and near-bottom temperature and salinity, and meteorological information at the locations shown in Figure 1.1 and the PORTS screen capture in Figure 1.2. To complement the PORTS, a new next generation nowcast/forecast system has been developed. This next generation nowcast/forecast system domain extends from the head of tide at Trenton, NJ out to the continental shelf break and is run on the National Center for Environmental Prediction (NCEP) supercomputers based on a recently developed High Performance Computing Coastal Ocean Modeling Framework (HPC-COMF; Zhang et al., 2010) to allow four times daily six-hour nowcasts and 48 hour forecasts. The approach used in the previous generation forecast systems, based on the original Coastal Ocean Modeling Framework (COMF; Gross et al., 2006) as discussed by Aikman et al. (2008), was to contain as little of the shelf as possible to still allow an appropriate response at the estuarine entrance to afford computation of hourly nowcasts and 30 hour forecasts (four times per day) on CO-OPS workstations.

While the majority of the previous generation forecast systems used the Princeton Ocean Model (POM), in conjunction with this effort, a Model Evaluation Environment (MEE) as described by Patchen (2008) was constructed for the Delaware River and Bay based on the NOS 1984-1985 Circulation Data Survey (Klavans et al., 1986) to compare both structured and unstructured grid models. The purpose of the MEE was to provide for a consistent comparison of hydrodynamic models using the same geometrical, forcing, and validation data, which would assist the model selection for the next generation Delaware River and Bay Operational Forecast System (DBOFS). The MEE also provides additional validation data particularly for currents and density that is not available within the PORTS. Therefore as a first step, the MEE results were used to further guide the DBOFS development.

In Chapter 2, we describe and present the results from the MEE. Based on the MEE results, the Princeton Ocean Model (POM) and the Regional Ocean Modeling System (ROMS) were selected for further application in Delaware River and Bay and both used the same medium resolution grid. In Chapters 3 and 4, POM and ROMS medium resolution grid simulation results are presented, respectively, in an effort to improve upon the MEE results. To further improve results in the river sections, a new higher resolution grid using the DELFT3D-RFGRID software was constructed. To take advantage of the parallel computing opportunities at NCEP, ROMS was finally selected as the hydrodynamic model in DBOFS. In Chapter 5, ROMS high resolution grid results are presented for the two 15-day simulations as well as for an extended seven month hindcast and contrasted with the medium resolution results in Chapter 4. In Chapter 6, the ROMS high resolution grid was used to investigate the sensitivity of the tidal response to bottom roughness coefficients and offshore tidal constituents in eighteen tidal simulations during April 1984. Upon further improvement of the model tidal dynamics as a result of the sensitivity analysis, a 13-month tidal simulation as well as a 13-month hindcast were performed and are discussed. In Chapter 7, the construction of the semi-operational nowcast/forecast system at NCEP is presented. In Chapter 8, conclusions are drawn and recommendations for formal skill assessment and transition to operations are advanced.

Figure 1.1. Delaware River and Bay PORTS. Note cu=current meter, wl=water level, wind=wind, at=air temperature, wt=water temperature, baro=barometric pressure, and ag=air gap.

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          Delaware River and Bay PORTS, NOAA/NOS 2010-03-03 09:34 EST

----------------------------Water Levels (above MLLW)---------------------------
Newbold                   3.1 ft, Falling Burlington               2.5 ft, Falling
Tacony-Palmyra Brdg       1.9 ft, Falling Philadelphia             1.5 ft, Falling
Marcus Hook               0.7 ft, Falling Delaware City            2.7 ft, Rising
Reedy Point               *** ft,         Ship John Shoal          5.3 ft, Rising
Brandywine Shoal Lt       6.6 ft, Rising  Cape May                 6.8 ft, Rising
Lewes                     6.1 ft, Rising
--------------------------------------Winds-------------------------------------
                           Spd Dir Gusts                            Spd Dir Gusts
Newbold                    9 kn ENE    18  Burlington             *** kn ***    ***
Delaware City             19 kn NNE    24  Ship John Shoal         20 kn NNE    23
Brandywine Shoal Lt       24 kn NNE    27  Cape May               *** kn ***    ***
Lewes                     20 kn NNE    25
----------------------------Air and Water Temperature---------------------------
                           Air   Water                              Air   Water
Newbold                   36 °F   40 °F   Burlington               37 °F   39 °F
Tacony-Palmyra Brdg       37 °F   38 °F   Philadelphia             37 °F   39 °F
Marcus Hook               37 °F   40 °F   Delaware City            37 °F   37 °F
Reedy Point              *** °F  *** °F   Ship John Shoal          37 °F   37 °F
Brandywine Shoal Lt       37 °F   37 °F   Cape May                 37 °F   40 °F
Lewes                     37 °F   38 °F
-------------------------------Barometric Pressure------------------------------
Newbold                 1001 mb Falling   Burlington             1001 mb Falling
Tacony-Palmyra Brdg     1001 mb Falling   Philadelphia           1001 mb Falling
Marcus Hook             1001 mb Steady    Delaware City          1001 mb Rising
Reedy Point              *** mb           Ship John Shoal        1000 mb Rising
Brandywine Shoal Lt      999 mb Rising    Cape May                999 mb Rising
Lewes                    999 mb Rising
----------------------------Salinity/Specific Gravity---------------------------
Station                   Salin.   S.G.   Station                  Salin.   S.G.
Burlington               0.0 psu    1.0   Ship John Shoal        13.5 psu   1.01
Brandywine Shoal Lt     14.1 psu   1.01
-----------------Air Gap/Bridge Clearance (above water surface)-----------------
Reedy Point Bridge       *** ft,
------------------Currents (F)lood, (S)lack, (E)bb, towards °T------------------
                           Spd          Dir                            Spd          Dir
Philadelphia            1.6 kn (E), 201.0°T Reedy Point              *** kn ( ),   ***°T
Brown Shoal             1.7 kn (F), 346.0°T


*** Data not displayed as a result of missing data or quality control monitoring. For more
 information, go to https://corms.nos.noaa.gov/instrument_status.html, or call CORMS
 at 301-713-2540.
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Figure 1.2. Text-based Delaware River and Bay PORTS screen capture, March 3, 2010 9:34 EST.

2. MODEL EVALUATION ENVIRONMENT EXPERIMENT

The purpose of the Model Evaluation Environment (MEE) is to provide for a consistent comparison of hydrodynamic models using the same geometrical, forcing, and validation data (Patchen, 2008). In the context of the DBOFS, the MEE provides additional validation data particularly for currents and density that is not available within the PORTS and therefore further supports its development. Here, we first describe and present the results from the MEE. For additional information refer to Feyen and Yang (2008), Myers (2008), Zhang and Wei (2008), and Lanerolle (2008).

2.1. Data Restoration and Analysis Efforts

The initial effort was to organize, recover, and process the historical water level, CT and current, and CTD data that were collected during the NOS circulation survey of 1984-1985 (Klavens et al., 1986). For further details on this effort refer to Loeper (2006) and Richardson and Schmalz (2006). Harmonic analysis results for water levels at the stations shown in Table 2.1 were obtained from CO-OPS. Station locations are shown in Figure 2.1 for the upper Delaware River and in Figure 2.2 for the lower Delaware River and Bay, respectively.

Table 2.1. Tidal Elevation Harmonic Analysis Inventory

Station No.	Lat	Lon	Description
8539993	40.188	-74.755	Trenton, NJ
8540433	39.812	-75.041	Marcus Hook, PA
8534883	39.295	-74.748	Tuckahoe River, NJ
8536110	38.968	-74.960	Cape May Canal, NJ
8537121	39.305	-75.375	Ship John Shoal, NJ
8538886	40.012	-75.043	Tacony Bridge, NJ
8534720	39.355	-74.418	Atlantic City, NJ
8539094	40.080	-74.873	Burlington, NJ
8545240	39.933	-75.142	Phila USCG, PA
8548989	40.137	-74.752	Newbold, PA
8545530	39.953	-75.138	Phila Pier 11, PA
8551762	39.582	-75.588	Delaware City, DE
8551910	39.558	-75.573	Reedy Pt, DE
8555889	38.987	-75.113	Brandywine Shoal, DE
8557380	38.782	-75.120	Lewes, DE
8558690	38.610	-75.070	Indian River, DE
8570283	38.328	-75.092	Ocean City Inlet, MD
8570280	38.327	-75.083	Ocean City Pier, MD
8573927	39.527	-75.810	Chesapeake City, MD

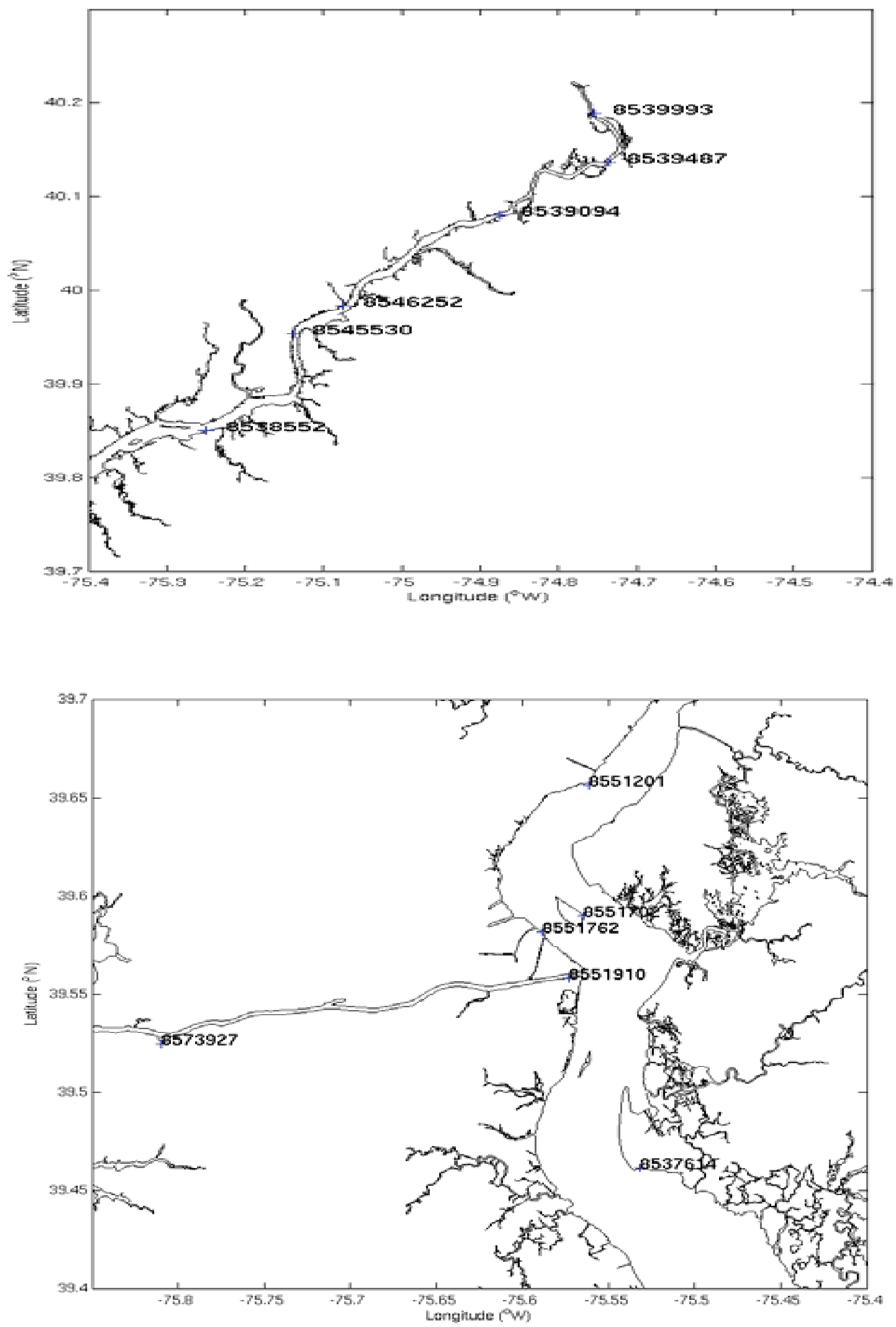


Figure 2.1. Upper Delaware River NOS Water Level Stations Locations.

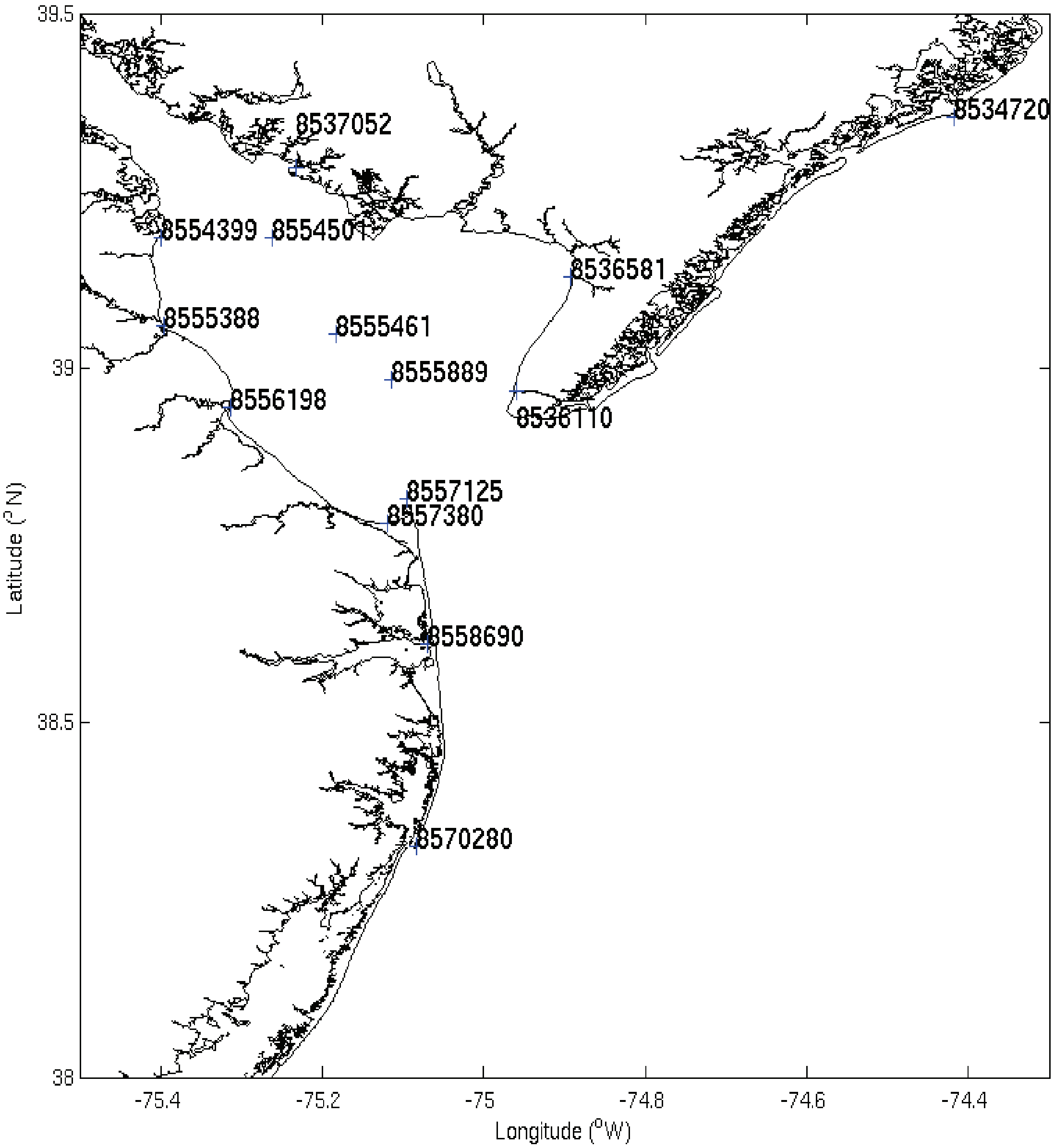


Figure 2.2. Lower Delaware River and Bay NOS Water Level Station Locations.

In addition to the CTD work, the following two programs and script were developed and tested: 1) del_ctd.filt.f (filtering program to remove S and T spikes and limit current directions), 2) harm29.f (program to develop control and data files for the NOS 29 day harmonic analysis program), and 3) harm29.sh (29 day harmonic analysis script, which performs the 29 harmonic analysis of all current stations with at least 29 days of data). All 29 day harmonic analyses of the current data at the locations shown in Table 2.2 and shown in Figures 2.3 and 2.4 were performed using the techniques described in Richardson and Schmalz (2006).

2.2 Grid Development

Here we focus on the development of the structured grids for POM and ROMS. To plan the grid development process, the following nautical charts were reviewed:

12274 Head of Chesapeake Bay
12277 Chesapeake and Delaware Canal
12304 Delaware Bay
12311 Delaware River: Smyrna River to Wilmington
12312 Delaware River: Wilmington to Philadelphia
12313 Delaware River: Philadelphia and Camden Water Fronts
12314 Delaware River: Philadelphia to Trenton

Of interest was to note the location of significant freshwater inflows and the configuration of the river above Philadelphia. Attention was also paid to the Schuylkill River inflow and the Chesapeake and Delaware (C&D) canal. After a review of the charts, 10 separate grid sections were identified as listed in Table 2.3. MATLAB was used with the SEAGRID grid generation (USGS Woods Hole Science Center, 2007) package to develop grids separately for each of the 10 sections. Two sections proved to be particularly difficult to generate grids for, due to 90 degree channel bends. A separate program was developed to link the grids by just using the downstream most grid coordinates at the junction of each of the two grids. The resulting grid was not orthogonal and proved not to be satisfactory due to the severity of the non-orthogonality.

Next the grid generation software employed in the generation of the Houston Ship Channel grid was reviewed (Schmalz, 2000a). Under this approach the downstream most grid is developed and then the coordinates at the top of the grid are specified as the bottom coordinates of the next upstream grid. This method proved to be successful in linking all 10 grids, but several grid spacings were very small, particularly along the lateral boundaries for the grid sections containing the 90 degree channel bend. As a result, the first 5 downstream grids were linked using the above approach and then a 6th grid was constructed to replace the next 5 upstream grid sections. The resulting grid is shown in the vicinity of the Philadelphia waterfront in Figure 2.5. Lanerolle (2008) has developed a grid fill procedure to create dummy grid cells within a complete rectangular shape to allow the present versions of POM and ROMS to run over these grid sections. This procedure was used to fill in the high resolution ROMS grid discussed in Chapter 5.

Table 2.2. Tidal Current 29-day Harmonic Analysis Inventory

Station	Above Bottom (ft)	Number of Sets	MLLW Depth(ft)
1	5, 63	1	75
2	5, 22, 47	2, 4, 2	60
3	5, 15	2, 3	33
4	6	2	21
5	5, 15	2, 3	30
11	10	1	60
12	50, 90	1, 1	116
16	10, 25, 35	2, 2, 3	59
17	10, 50, 75	2, 3, 1	100
18	6	1	20
19	5, 26	1, 1	43
21	5	1	20
22	5, 20	2, 3	34
23	8, 26	2, 2	38
23X	5, 26	1, 1	35
24	7	3	20
25	5	1	18
30	27	1	43
32	5	1	20
33	5, 36	1, 3	48
33X	15	1	30
41	14	1	28
42	17	1	33
43	19	1	34
47	28	2	43
49	18	1	30
51	5, 8, 28	1, 2, 3	45
52	14	1	34
57	10	1	59
58	16, 21	1, 1	36
59	35	1	50
60	30	1	45
61	13	1	28
134	10	1	25
151	25	1	40
152	25	1	40
154	5, 25	1, 3	40
155	7	1	22

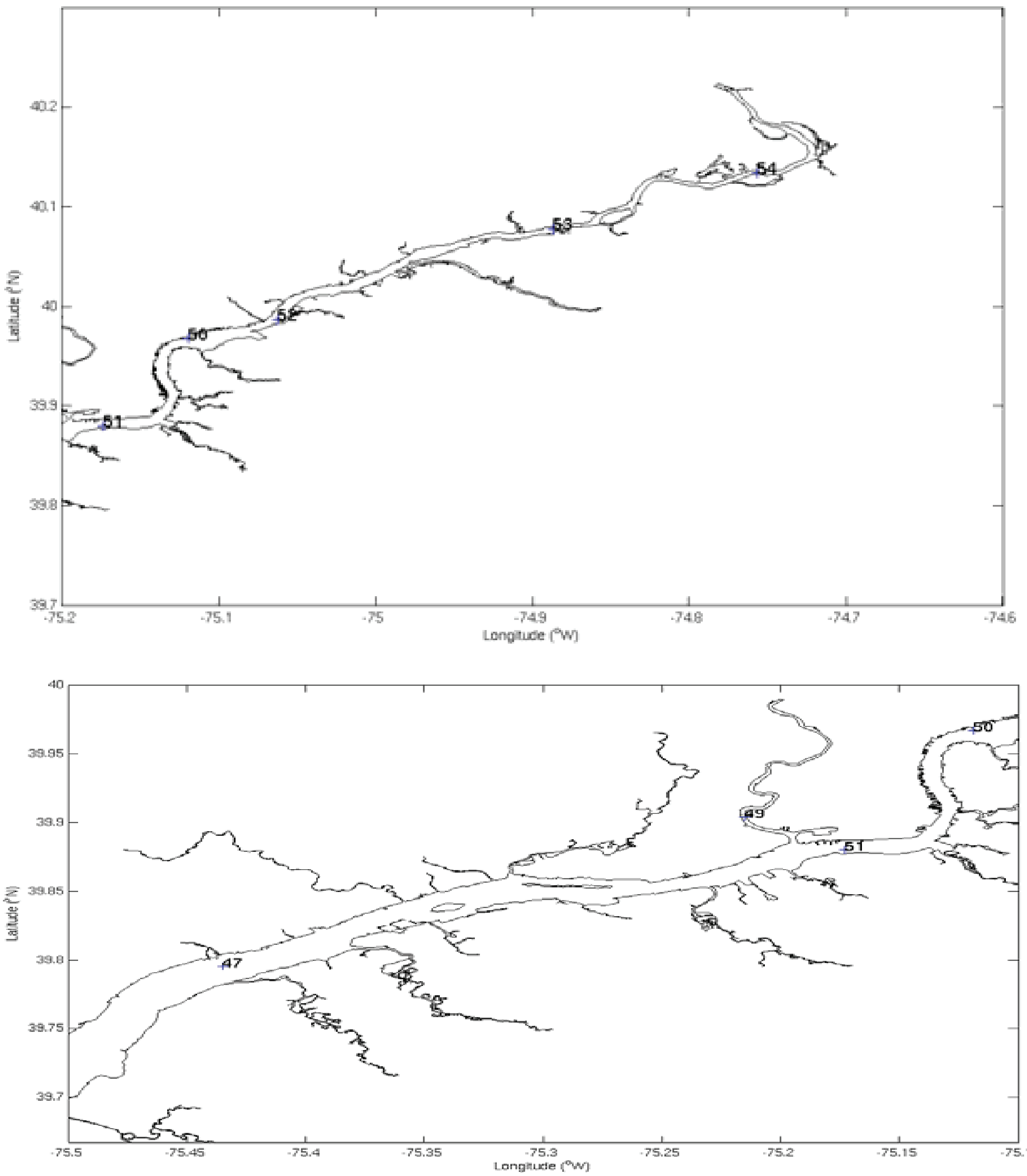


Figure 2.3. Upper Delaware River NOS Current, CT, and CTD Stations Locations.

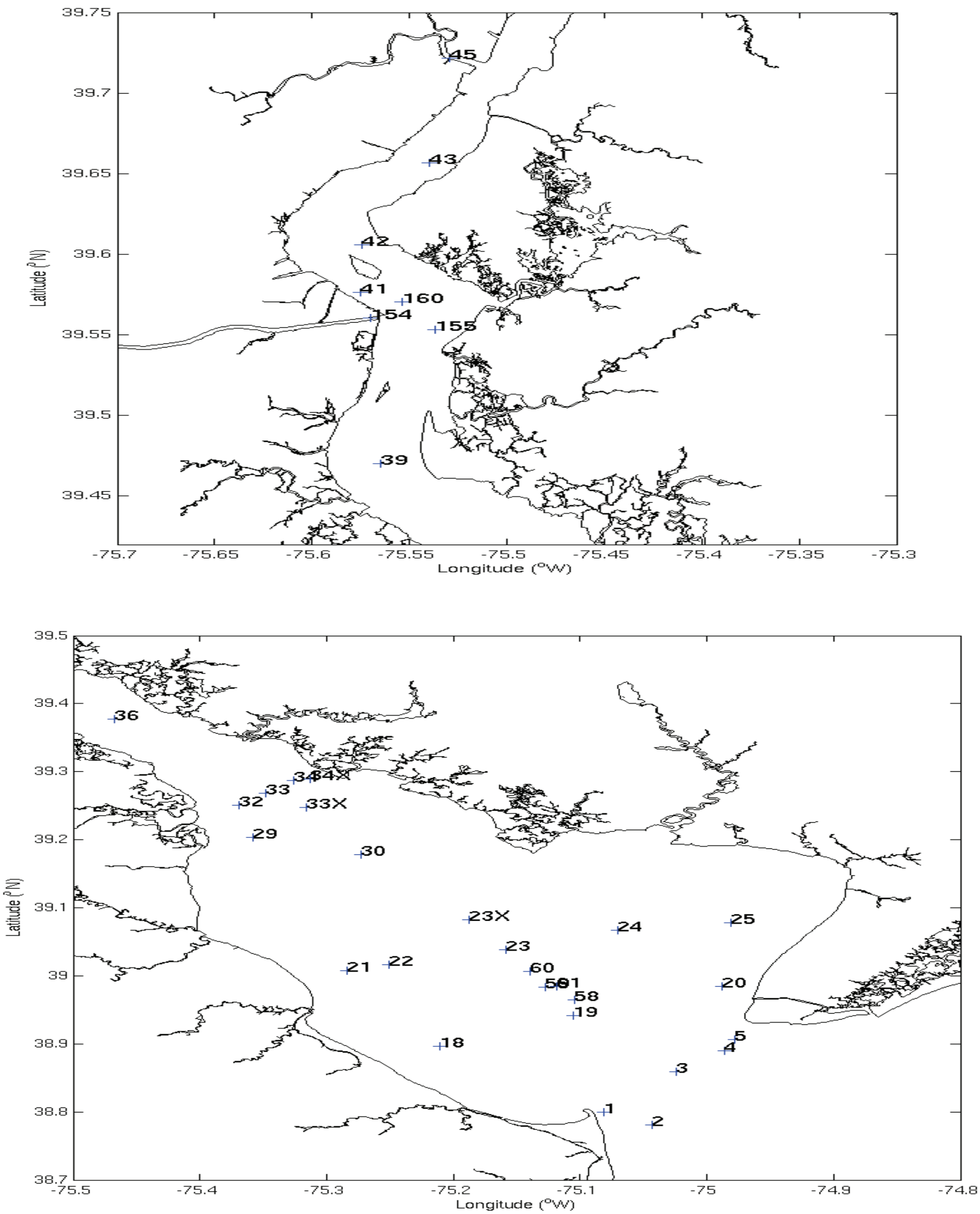


Figure 2.4. Lower Delaware River and Bay NOS Current, CT, and CTD Station Locations.

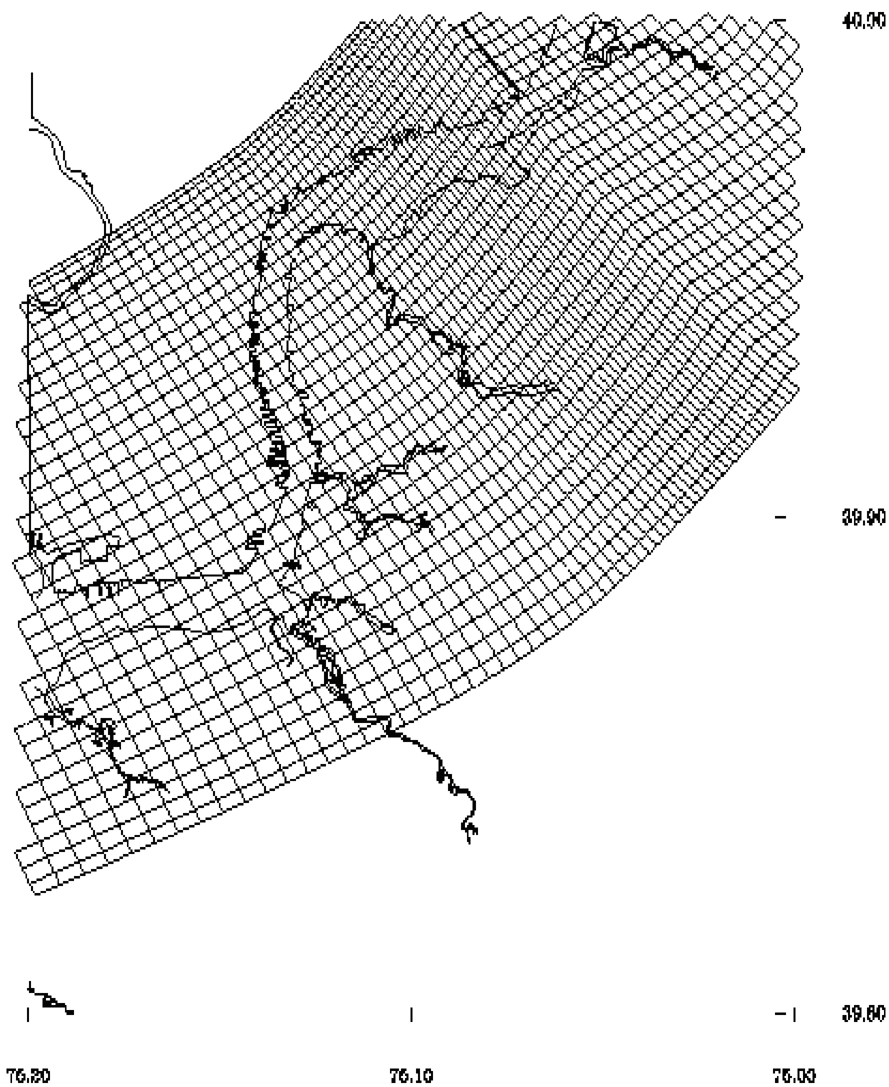


Figure 2.5. Grid Section 5 with the 90 degree channel bend and the Grid Section 6 lower portion.

As an alternative, a one piece grid was constructed for POM and ROMS using the SEAGRID package (USGS Woods Hole Science Center, 2007). Since the highest grid resolutions are on the order of 50 m, a fine resolution bathymetry and shoreline were obtained from the Cartographic and Geospatial Technical Program within the Coast Survey Development Laboratory. The computational grid for POM and ROMS is shown for the upper Delaware River in Figure 2.10 and for the Delaware Bay in Figure 2.11. The POM application employed 15 sigma coordinate levels in the vertical with uniform spacings below the surface level while ROMS used 10 generalized s coordinate levels.

2.3 Model Input Requirements

In addition to the computational grid, the models require accurate initial conditions of salinity and temperature; specification of conditions at the open-ocean lateral boundaries; river discharges; conditions at the Chesapeake side of the C&D Canal; and surface forcing, i.e., winds and heat fluxes. Initial salinity and temperature conditions were developed from the NOS circulation survey. Salinity and temperature at the lateral boundaries were determined from NOAA's World Ocean Atlas 2001 (NODC, www.nodc.noaa.gov), which provides monthly varying climatological values. Synoptic meteorological conditions were derived by blending NOAA's reanalysis wind product (NCEP, www.ncep.noaa.gov/mmb/rrean/index.html) on a 32 km grid with meteorological observations at NOAA buoys, C-Man stations and airports. River discharge data, including water temperature were obtained from the USGS. To determine water levels and currents at the open-ocean lateral boundaries the ADCIRC model for the Western Atlantic Ocean on the East Coast 1995 grid (Mukai et al., 2001) was used imposing the blended NCEP reanalysis wind product with available meteorological observations, and specifying the verified tidal constituents as developed by Myers (2007; personal communication) along the open-ocean boundary at 60^{o} W.

2.4. Model Evaluation Results

The following models were evaluated based on the four experiments as described in Patchen (2008):

1. Regional Ocean Modeling System (ROMS) as described in Shchepetkin and McWilliams (2005) and Haidvogel et al. (2008). On the Internet at: http://www.myroms.org
2. Princeton Ocean Model (POM) as described in Blumberg and Mellor (1987) and Blumberg and Herring (1987).
   On the Internet at: http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom
3. Finite Volume Coastal Ocean Model (FVCOM) as described in Chen et al. (2003, 2006). On the Internet at: http://fvcom.smast.umassd.edu/FVCOM/index.html
4. Semi-Implicit Eulerian-Lagrangian Finite Element Model (SELFE) as described in Zhang and Baptista (2008). On the Internet at: http://www.ccalmr.ogi.edu/corie/modeling

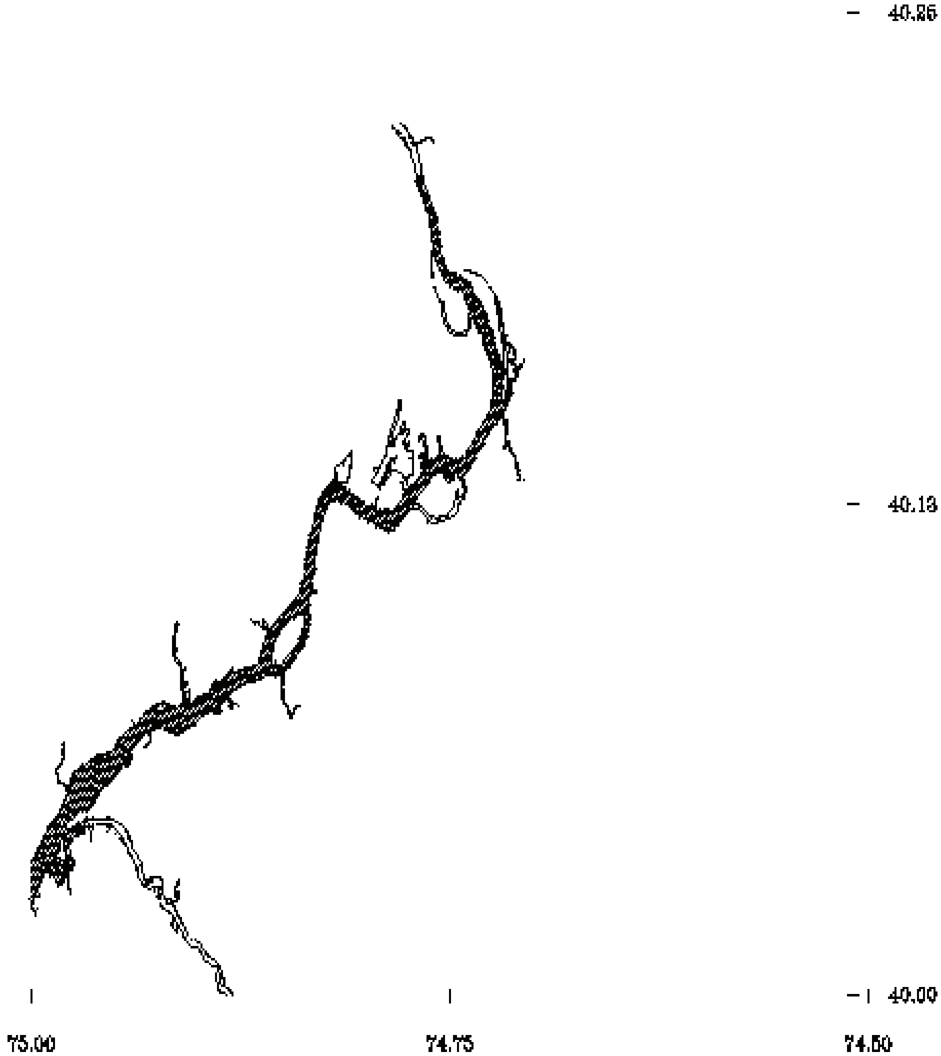


Figure 2.6. Upper Delaware River ROMS grid.

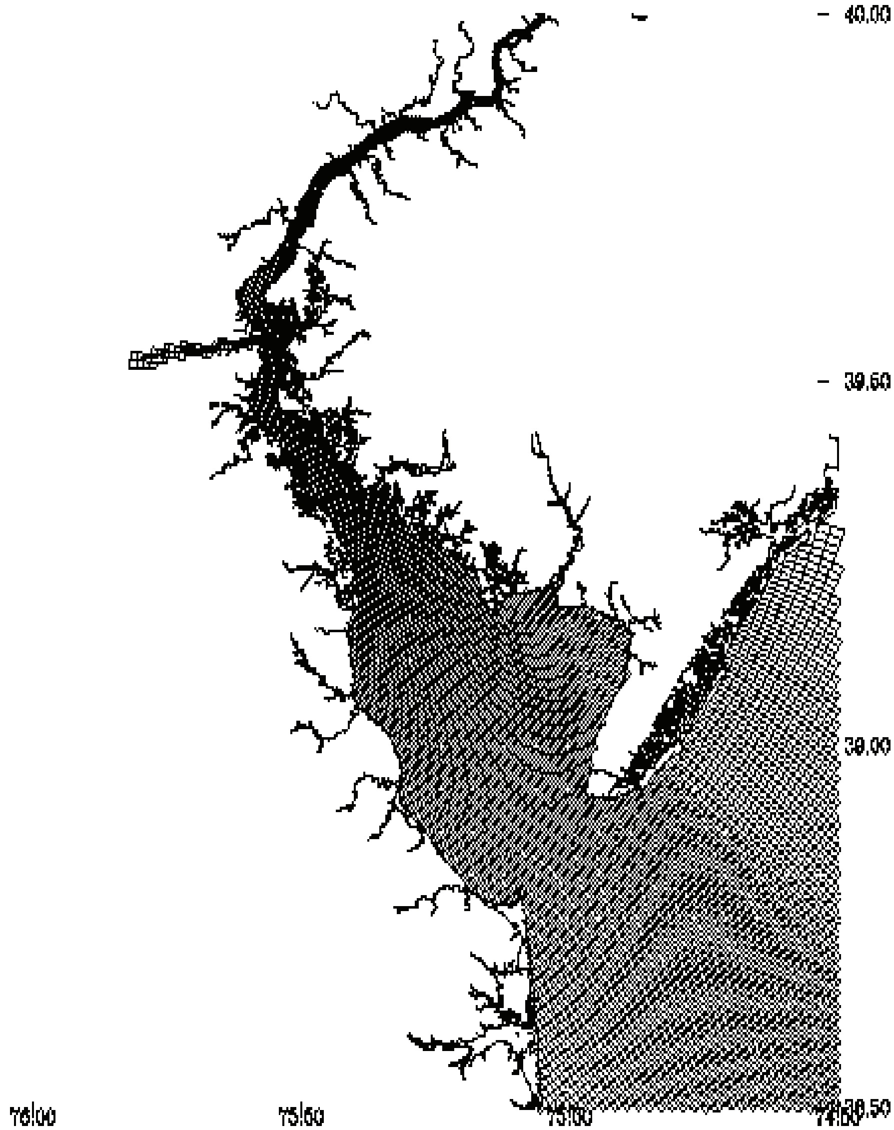


Figure 2.7. Lower Delaware River and Bay ROMS grid.

The reader is referred to Patchen (2008) for discussion of the Experiment 1 Tidal Simulation, Experiment 2 Density Front Locations, and Experiment 3 High River Runoff. Here we focus on the final experiment, which is a synoptic hindcast during the 1984-1985 NOS circulation survey from March 21 – September 7, 1984 During this period, three strong spring freshets occur, which are followed by decreased river discharges into the Fall; a late Spring meteorological event occurs on March 31, 1984. Using the NOS standardized skill assessment software (Zhang et al., 2006), the two structured grid models ROMS and POM are contrasted with the two unstructured grid models FVCOM and SELFE. Water level skill assessment results are given in Table 2.3 and indicate that none of the models performed well in the river section above Philadelphia, PA. It should be noted for each model, model datum was considered equal to MSL. All the models used a spatially uniform bottom roughness. In terms of a reference level of 15 cm the Central Frequency criteria of 90 percent (refer to NOS, 1999 and Hess et al., 2003) is not met at any of the water level stations by any of the models, with the results above Philadelphia, PA being particularly problematical. Skill assessment results for currents are given in Table 2.4 and are nearly the same for ROMS and POM with FVCOM showing better results than SELFE. FVCOM results overall appear to be the best for currents. Salinity skill assessment results are shown in Table 2.5. POM results appear to be better than ROMS in the frontal zone, however as with currents FVCOM appears to represent the salinity structure the best in this area. In the river sections, FVCOM salinity is near 2 PSU due to a boundary condition specification issue. Temperature skill assessment results are given in Table 2.6. Although POM and ROMS used different heat flux specifications, they were similar in skill. Results for FVCOM and SELFE were similar but were in general not as good as those obtained by POM and ROMS.

Table 2.3. MEE Water Level Skill Assessment Results.

Station	RMSE (cm)				CF(15 cm)			
	ROMS	POM	FVCOM	SELFE	ROMS	POM	FVCOM	SELFE
Atlantic City, NJ	11.5	11.5	10.8	10.8	80.7	80.9	83.5	83.6
Ocean City Pier, MD	13.1	13.6	13.4	13.4	72.9	71.7	72.2	72.2
Lewes, DE	11.9	13.3	10.7	12.3	80.7	75.8	85.0	84.5
Reedy Pt, DE	29.1	24.4	13.5	20.8	35.6	48.5	77.7	67.7
Philadelphia, PA	36.9	36.3	21.3	36.9	39.7	39.1	50.5	43.2
Cape May, NJ	12.1	13.0	11.3	13.5	82.5	79.6	81.7	73.4
Brandywine Shl, DB	11.7	12.7	10.3	13.8	85.4	81.8	85.4	73.4
Chesapeake City, MD	18.2	13.5	13.2	19.2	60.2	75.1	75.7	51.8
Trenton, NJ	58.9	50.2	47.4	57.6	21.3	28.7	17.9	24.5

Table 2.4. MEE Current Skill Assessment Results.

Station No.	Depth (m) Total	Obs	RMSE (cm/s) ROMS	POM	FVCOM	SELFE	CF(26cm/s) ROMS	POM	FVCOM	SELFE
1	22.9	3.7	25.4	24.5	19.4	24.4	66.6	67.9	81.9	71.0
17	30.5	7.6	11.9	8.8	12.2	9.8	97.5	99.2	96.1	99.4
23	11.6	3.7	15.1	15.7	23.7	21.4	91.3	89.9	73.7	78.9
33	14.6	3.7	29.0	26.1	15.4	31.8	57.7	64.3	90.8	46.9
39	12.8	4.3	23.0	40.8	17.7	34.4	72.8	36.4	82.4	49.8
42	10.1	4.9	36.8	28.6	18.9	27.3	51.4	61.5	84.0	61.7
47	13.1	4.6	37.7	36.9	19.2	29.8	36.9	32.6	82.1	49.6
50	15.2	7.3	33.5	29.7	28.2	32.5	47.7	50.2	63.4	47.6
51	13.7	5.2	33.6	33.7	21.9	34.1	44.2	40.1	76.6	45.2
52	10.4	6.1	22.5	21.6	19.8	23.2	74.5	77.4	80.5	74.9
54	11.0	4.6	11.3	9.4	8.3	9.1	98.0	99.4	100.0	99.6

Table 2.5. MEE Salinity Skill Assessment Results

Station No.	Depth (m) Total	Obs	RMSE (PSU) ROMS	POM	FVCOM	SELFE	CF(3.5 PSU) ROMS	POM	FVCOM	SELFE
1	22.9	3.7	4.1	4.0	1.5	11.4	48.0	54.3	97.3	0.0
17	30.5	7.6	1.5	1.5	1.5	2.0	100.0	100.0	100.0	94.2
23	11.6	3.7	6.3	5.5	3.2	10.8	4.3	40.7	73.8	0.9
33	14.6	3.7	11.5	9.2	4.8	11.3	1.7	22.5	48.4	2.5
39	12.8	4.3	6.1	3.2	1.8	3.5	43.2	67.5	96.6	61.6
42	10.1	4.9	4.2	0.3	2.5	0.4	60.3	100.0	100.0	100.0
47	13.1	4.6	0.0	0.0	1.7	0.0	100.0	100.0	100.0	100.0
50	15.2	7.3	0.0	0.0	2.2	0.0	100.0	100.0	100.0	100.0
51	13.7	5.2	0.0	0.0	1.6	0.0	100.0	100.0	100.0	100.0
52	10.4	6.1	0.0	0.0	2.3	0.0	100.0	100.0	100.0	100.0
54	11.0	4.6	0.0	0.1	1.2	0.1	100.0	100.0	100.0	100.0

Table 2.6. MEE Water Temperature Skill Assessment Results

Station No.	Depth (m) Total	Obs	RMSE (PSU) ROMS	POM	FVCOM	SELFE	CF(3.5 PSU) ROMS	POM	FVCOM	SELFE
1	22.9	3.7	2.5	2.3	1.7	3.5	78.0	83.9	94.5	53.4
17	30.5	7.6	2.0	2.6	1.6	4.4	89.8	76.4	92.3	47.2
23	11.6	3.7	3.3	3.4	2.2	6.0	67.7	54.1	84.2	16.7
33	14.6	3.7	1.5	2.2	1.6	5.3	97.8	84.6	92.0	20.8
39	12.8	4.3	0.4	0.9	6.8	6.6	100.0	100.0	0.0	0.0
42	10.1	4.9	0.7	2.2	5.7	4.7	100.0	91.3	6.8	21.3
50	15.2	7.3	1.1	0.8	2.0	1.5	100.0	100.0	84.6	100.0
51	13.7	5.2	3.0	4.7	3.0	2.8	64.3	61.5	63.6	58.9
52	10.4	6.1	1.1	0.9	2.0	1.5	100.0	100.0	84.9	100.0
54	11.0	4.6	1.7	1.7	1.8	1.7	100.0	99.2	97.8	98.3

2.5 Summary and Additional Considerations

To further study these results, values of bottom friction used in previous studies were reviewed. In the Long Island Sound Study, which employed 7 vertical levels to represent maximum depths order 70m, z_0=2 cm with CDmin=0.0025 was used (Schmalz, 1994. In Galveston Bay, the maximum water depths were only 20m and with 5 vertical levels, and z_0=1.5 mm with CDmin=0.0025 was used (Schmalz, 2000a; 2000b). Whitney and Garvine (2006) in simulating the interaction of the Delaware Estuary plume with the Delaware Coastal Current used POM with z_0=3 mm and CBCMIN=0.0050 (double the usual value). The high CBCMIN value would serve to increase the friction in the offshore regions to insure stability, while the lower z_0 value order 3 mm would improve the tidal response up river.

In reviewing the nautical charts, the depths within the present grid represent the channel up to Burlington, PA. From Burlington, PA to Newbold, PA the depths should be modified to insure the correct channel depth. However from Newbold, PA to Trenton, NJ, the navigation channel depths are only order 24 ft and they appear to be somewhat erratically represented in the present depth field. In addition, above Burlington, PA the grid cell widths may need some modification to insure that they represent the channel widths. It appears that some fine tuning in grid cell width and depths may need to be made above Burlington, PA to improve the tidal response at Trenton, NJ.

Based on the assessment of the MEE results, additional improvement in the water level and current response in the river section above Philadelphia, PA is needed by all of the models to meet the NOS skill requirements (NOS, 1999; Hess et al., 2003). The three-dimensional unstructured model results from FVCOM and SELFE were not clearly superior to the structured three-dimensional models POM and ROMS predictions, despite the extremely complex sinuous nature of the river shoreline, and therefore additional work with POM and ROMS was conducted. The approach was to work with the POM and seek improvements, due to the fact that it had been used in the original nowcast/forecast systems in New York Harbor, Galveston Bay, and in the Great Lakes.

3. POM MEDIUM GRID RESOLUTION HINDCASTS

Two fifteen day periods were selected for further consideration. The first period, 27 March – 10 April, 2004 contained a coastal surge event as well as a high flow event of 121,000 cfs. The second period, 10-24 September, 1984 was dominated by extremely low flow of order 3000 cfs at Trenton, NJ and represented a period of potential salinity intrusion. There also was very little storm activity along the coast and hence the period was dominated by astronomic tides and allowed for an assessment of the tidal response.

3.1 Hindcast Setup Procedures

To move toward a more standard nowcast/forecast system setup, the NOS operational Galveston Bay Nowcast/Forecast System was emulated but slightly modified using the approach developed during the Long Island Sound Study (LISS). In LISS, a second section of the grid generation program was used to provide the initial density structure, the SST field at 15 to 30 day intervals, and the salinity and temperature boundary conditions for rivers and the ocean boundary (Schmalz, 1994). In the present NOS Galveston Bay operational nowcast/forecast, a ten-step set-up program is used to provide the forcing for each 24 hour nowcast, and for the 30 hour forecast (Schmalz and Richardson, 2002). Within this program, the density structure is updated at the beginning of each nowcast based on the observed PORTS readings with the sea-surface temperature, salinity and temperature boundary conditions persisted over the nowcast/forecast period. Rather than employ this approach, the LISS approach for handling the initial and boundary conditions was used and then steps 6, 7, and 8 in the ten-step nowcast/forecast procedure were eliminated. The remaining steps are used to specify the simulation period (Step 1), generate harmonically reconstructed water surface elevation (Step 2) and currents (Step 3), place the observed data in the appropriate format for the graphics programs (Step 4), produce the subtidal water level signals at Chesapeake City, MD and Cape May, NJ (Step 5), generate the average daily inflows for the 12 rivers (Step 9), and use Barnes (1973) interpolation from meteorological data at 10 stations (including 2 offshore NBDC buoys) to provide the wind and sea-level atmospheric pressure fields. The subtidal water level signal at Cape May, NJ was applied to the entire ocean open boundary. Within the present operational NOS nowcast/forecast systems, the approach of applying a coastal water level measured or forecast subtidal water level to the entire open boundary has been used. In the present case with the open boundary extending to the shelf break this may not be valid. An alternative approach would be to reduce the extent of the grid on the shelf to perhaps the 20 to 50 m contour as used by Celebioglu and Piasecki (2006).

3.2 Baseline Simulation

Using the above methods, POM was used to simulate the period 27 March – 5 April, 1984 as an initial 10-day reference period. The medium resolution grid (also used in the ROMS medium grid simulations in Chapter 4) is shown in Figures 3.1 and 3.2 along with the locations of the NOS CTD/Current stations used in the model-data comparisons and the major surface meteorological stations used to develop the interpolated meteorological fields. Wind speed and direction and atmospheric pressure were produced using Barnes (1973) interpolation at three hour intervals with

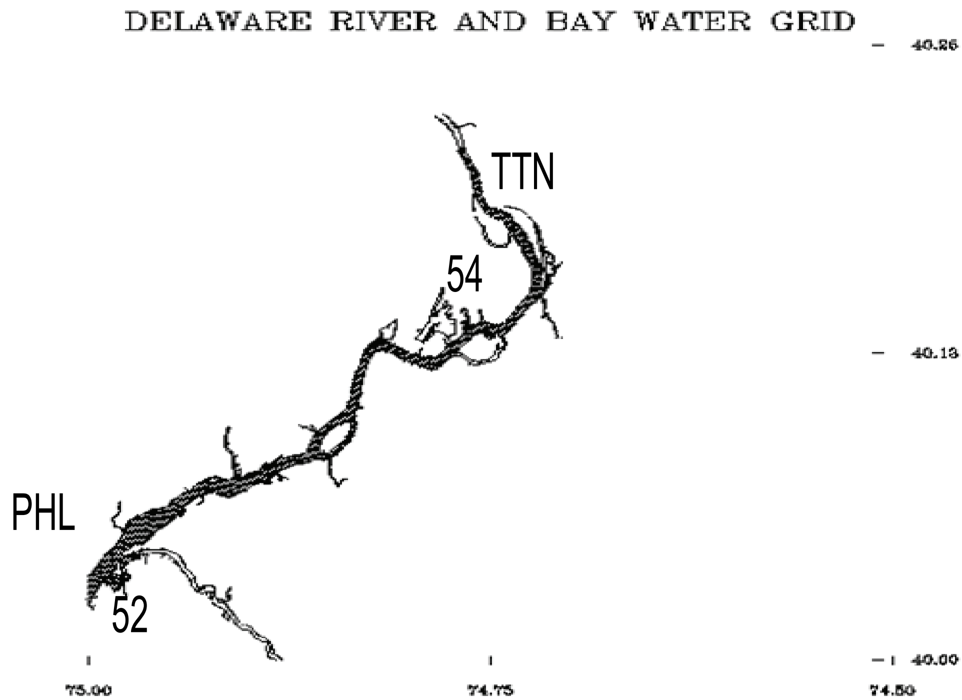


Figure 3.1. Upper River POM and ROMS grid. Note CTD/Current stations are numbered with Met Stations in text.

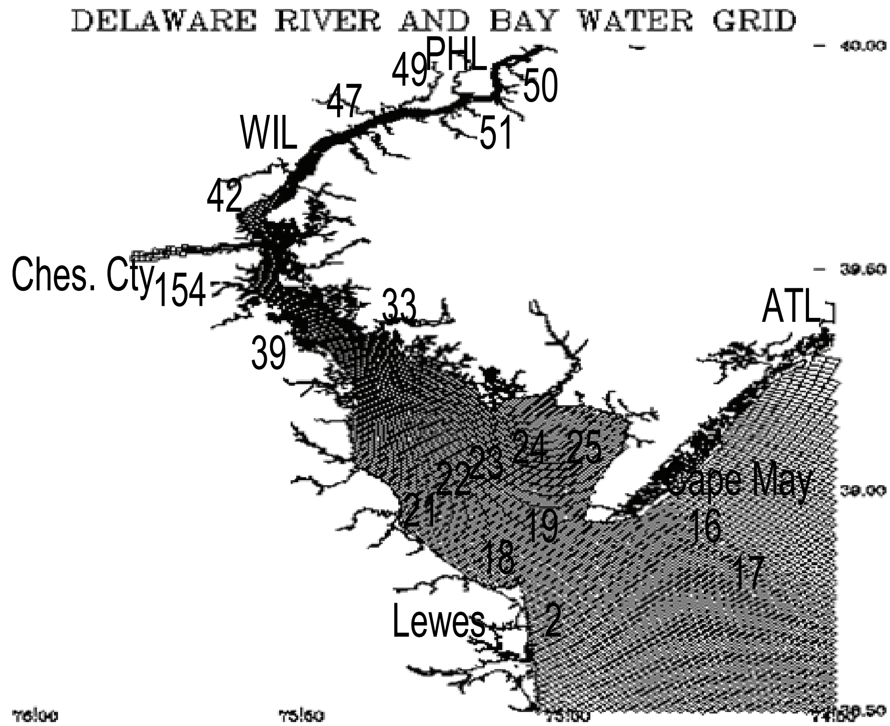


Figure 3.2. Lower River and Bay POM and ROMS grid. Note Current/CTD stations are numbered, while major cities and Met Stations are in text. Note NBDC buoy 44009 is located near the bottom left corner of the map, while NDBC buoy 44012 is further to the northeast.

wind speed and direction RMS errors order 2 m/s and 25 ^{o}T, respectively, and sea level atmosphere pressure RMS errors order 1.5 mb. In the MEE the subtidal water level at the head of the C&D canal was considered zero. Here, the subtidal water level signal at the Chesapeake Bay end of the C&D canal was based on Chesapeake City, MD as determined via a linear regression (bias=0.003, gain=0.784) from the Baltimore, MD subtidal water level over the four month period July-October, 1984. Monthly RMSEs were order 5 cm and storm periods were well produced.

Within the NOS operational nowcast/forecast systems water levels are specified with respect to the MLLW datum at each PORTS station. Within the Galveston Bay Nowcast/Forecast System the model datum is taken as MTL and at each station the tidal epoch adjustment from MTL to MLLW is added to the model prediction. Within the Delaware River and Bay system, two datums are used. Along the coast and within the Bay proper MSL is taken as the model datum, while above Philadelphia, PA mean river level (MRL) is assumed equal to NAVD-1988 and is taken as the model datum. Simulated water levels are compared with observations in Table 3.1 with RMSEs increasing from 14 cm at the Capes to 23 cm at Philadelphia, PA with a maximum near the head of tide at Trenton, NJ of 47 cm as shown in Figure 3.3. It should be noted that if one uses MSL as the datum throughout, the RMSE at Trenton, NJ increases to 53 cm. In this and all subsequent tables, the relative error corresponds to the Wilmott et al. (1985) dimensionless (0-1) relative error, with zero representing perfect agreement. Note for the time series plots (Figures 3.3-3.7) the indicator of agreement (IND AGMT) equal to one minus the relative error is given.

Table 3.1. Water Surface Elevation-MLLW (m) Baseline High Flow Hindcast: March 27 - April 5, 1984.

Station	RMS Error (cm)	Relative Error (-)	Model Mean (cm)	Observed Mean (cm)
Lewes, DE	14	0.02	91	86
Cape May, NJ	14	0.01	98	93
Indian River, DE	23	0.07	68	63
Phila. Pier 11, PA	23	0.04	135	133
Trenton, NJ	47	0.09	180	191

Current speed and direction are compared against observations in Tables 3.2 and 3.3, respectively. The current strength is under-predicted at Station 33 and within the river sections. Current directions are reasonably represented within the Bay and river sections, where the currents are rectilinear. At continental shelf stations16 and 17 the currents are rotary in nature and the model directions exhibit larger discrepancies from the observations. The simulated salinity at the corresponding model sigma level (K=1, 15 with 1 representing the near surface) are compared with observations in Table 3.4. One notes as shown in Figure 3.4 at Station 33 in the region of large horizontal gradients, the RMSE of order 6.5 PSU with a large discrepancy in model and observed means. The model temperature response is contrasted with observations in Table 3.5. With the SST specification, the RMSEs are within order 2 ^{o}C.

Table 3.2. Current Speed (cm/s) Baseline High Flow Hindcast:
March 27 - April 5, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (cm/s)	Relative Error (-)	Model Mean (cm/s)	Observed Mean (cm/s)
16 at 11	13.65	0.46	9.98	15.33
17 at 3	13.45	0.55	13.56	13.34
23 at 8	14.57	0.11	42.71	40.54
33 at 11	25.74	0.22	43.58	58.17
50 at 8	29.87	0.36	39.73	61.78
52 at 4	21.54	0.34	30.97	47.17

Table 3.3. Current Direction (^{o}T) Baseline High Flow Hindcast:
March 27 - April 5, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (^{o}T)	Relative Error (-)	Model Mean (^{o}T)	Observed Mean (^{o}T)
16 at 11	89.75	0.85	186.29	228.85
17 at 3	136.62	0.83	174.72	215.01
23 at 8	26.40	0.02	243.53	254.61
33 at 11	35.83	0.04	226.99	226.66
50 at 8	30.15	0.03	167.41	176.83
52 at 4	26.56	0.02	148.05	148.01

Table 3.4. Salinity (PSU) Baseline High Flow Hindcast:
March 27 - April 5, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (PSU)	Relative Error (-)	Model Mean (PSU)	Observed Mean (PSU)
16 at 3	0.95	0.73	31.66	32.58
16 at 8	0.67	0.71	31.66	32.19
16 at 11	0.83	0.70	31.63	32.28
17 at 3	1.12	0.92	32.71	33.78
23 at 8	1.23	0.57	25.81	25.58
33 at 11	6.48	0.67	20.01	13.14

Table 3.5. Temperature (^{o}C) Baseline High Flow Hindcast:
March 27 - April 5, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (^{o}C)	Relative Error (-)	Model Mean (^{o}C)	Observed Mean (^{o}C)
16 at 3	2.07	0.84	6.78	5.01
16 at 8	2.05	0.82	6.80	5.06
16 at 11	1.99	0.79	6.83	5.17
17 at 3	1.98	0.87	7.40	5.51
23 at 8	0.65	0.55	6.43	6.43
33 at 11	0.73	0.57	5.69	6.71

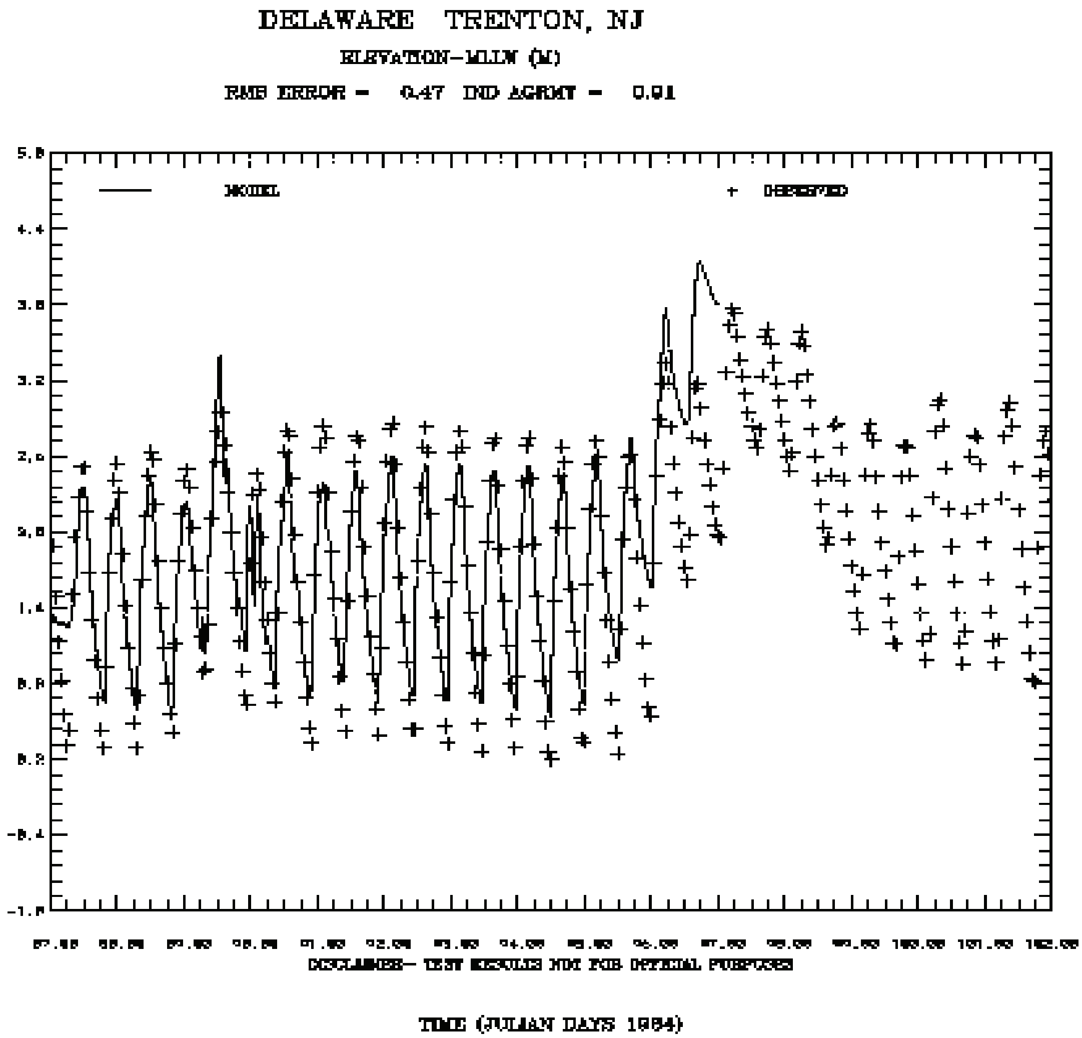


Figure 3.3. Baseline High Flow Hindcast (27 March – 5 April, 1984) Water Surface Elevation at Trenton, NJ. Note observations are at one hour intervals over the entire 15 day period, 27 March – 10 April, 1984.

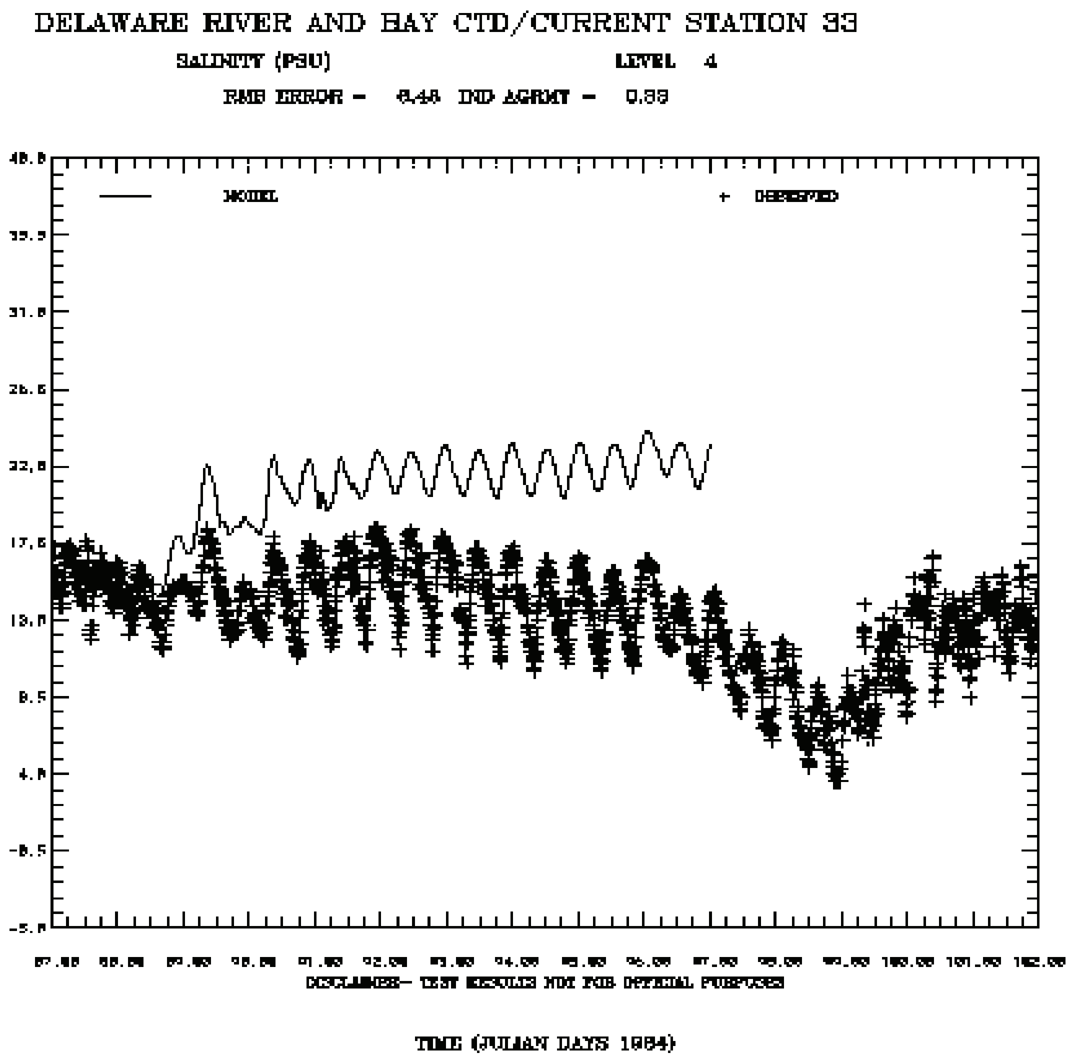


Figure 3.4. Baseline High Flow Hindcast (27 March – 5 April, 1984) Salinity at Station 33. Note observations are at 10 minute intervals over the entire 15 day period 27 March – 10 April, 1984.

3.3 Revised Geometry High Flow Simulation

To seek further improvement a revised geometry was employed. The C&D canal width was adjusted to its actual channel width of 121.9 m. It was straightened and made one grid cell wide. USACOE project channel depths were specified for the navigation channels from the Bay to Philadelphia, PA from Philadelphia, PA to Newbold, PA and from Newbold, PA to Trenton, NJ. In addition, several upriver marsh areas were specified at depths of order 1 m. A spatially varying bottom roughness was incorporated, such that over the continental shelf $z_0 = 1$ cm, from the Capes to the river mouth z_0 linearly decreases to 0.3 cm, from the river mouth to below the Tacony Bridge, NJ it remains at 0.3 cm, and from there to the head of tide it linearly increases to 1.3 cm.

Simulated water levels over the 27 March – 10 April, 1984 are contrasted with observations in Table 3.6. RMSEs are slightly reduced by 1 cm at Cape May, NJ and at Philadelphia, PA and are substantially reduced by 10 cm at Trenton, NJ as shown in Figure 3.5. In Tables 3.7 and 3.8, the current speed and direction comparisons are given. One notes the improved current speed response at Station 33 with current directions remaining nearly the same. In Table 3.9, the salinity response at Station 33 in the region of large horizontal salinity gradients is substantially improved with the RMSE reduced by order 4 PSU and with a much closer agreement to the observed mean (see Figure 3.6). In Table 3.10, the temperature response is very similar to that of the baseline hindcast.

Table 3.6. Water Surface Elevation-MLLW (m) Revised Geometry High Flow Hindcast: March 27 - April 10, 1984.

Station	RMS Error (cm)	Relative Error (-)	Model Mean (cm)	Observed Mean (cm)
Lewes, DE	13	0.02	86	86
Cape May, NJ	13	0.01	93	93
Indian River, DE	22	0.08	62	63
Ocean City Pier, MD	13	0.04	73	70
Phila Pier 11, PA	22	0.03	145	133
Trenton, NJ	37	0.04	204	191

Table 3.7. Current Speed (cm/s) Revised Geometry High Flow Hindcast: March 27 - April 10, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (cm/s)	Relative Error (-)	Model Mean (cm/s)	Observed Mean (cm/s)
16 at 11	12.76	0.48	9.82	15.33
17 at 3	12.73	0.59	14.06	13.34
23 at 8	15.28	0.14	42.40	40.54
33 at 11	19.46	0.12	52.19	58.17
50 at 8	27.83	0.38	46.72	61.78
52 at 4	17.99	0.26	38.65	47.17

Table 3.8. Current Direction (^oT) Revised High Flow Hindcast:
March 27 - April 10, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (^oT)	Relative Error (-)	Model Mean (^oT)	Observed Mean (^oT)
16 at 11	86.25	0.78	194.21	228.85
17 at 3	137.58	0.83	178.02	215.01
23 at 8	31.54	0.03	239.16	254.61
33 at 11	29.10	0.02	219.72	226.66
50 at 8	36.06	0.04	170.13	176.83
52 at 4	30.48	0.03	153.85	148.01

Table 3.9. Salinity (PSU) Revised Geometry High Flow Hindcast:
March 27 - April 10, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (PSU)	Relative Error (-)	Model Mean (PSU)	Observed Mean (PSU)
16 at 3	1.05	0.65	31.62	32.58
16 at 8	0.69	0.60	31.60	32.19
16 at 11	0.78	0.59	31.58	32.28
17 at 3	1.01	0.89	32.79	33.78
23 at 8	1.49	0.45	25.33	25.58
33 at 11	2.72	0.17	12.61	13.14

Table 3.10. Temperature (^oC) Revised Geometry High Flow Hindcast:
March 27 - April 10, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (^oC)	Relative Error (-)	Model Mean (^oC)	Observed Mean (^oC)
16 at 3	1.86	0.69	6.81	5.01
16 at 8	1.82	0.67	6.82	5.06
16 at 11	1.74	0.65	6.83	5.17
17 at 3	2.02	0.85	7.51	5.51
23 at 8	0.73	0.99	6.43	6.43
33 at 11	1.40	0.51	5.71	6.71

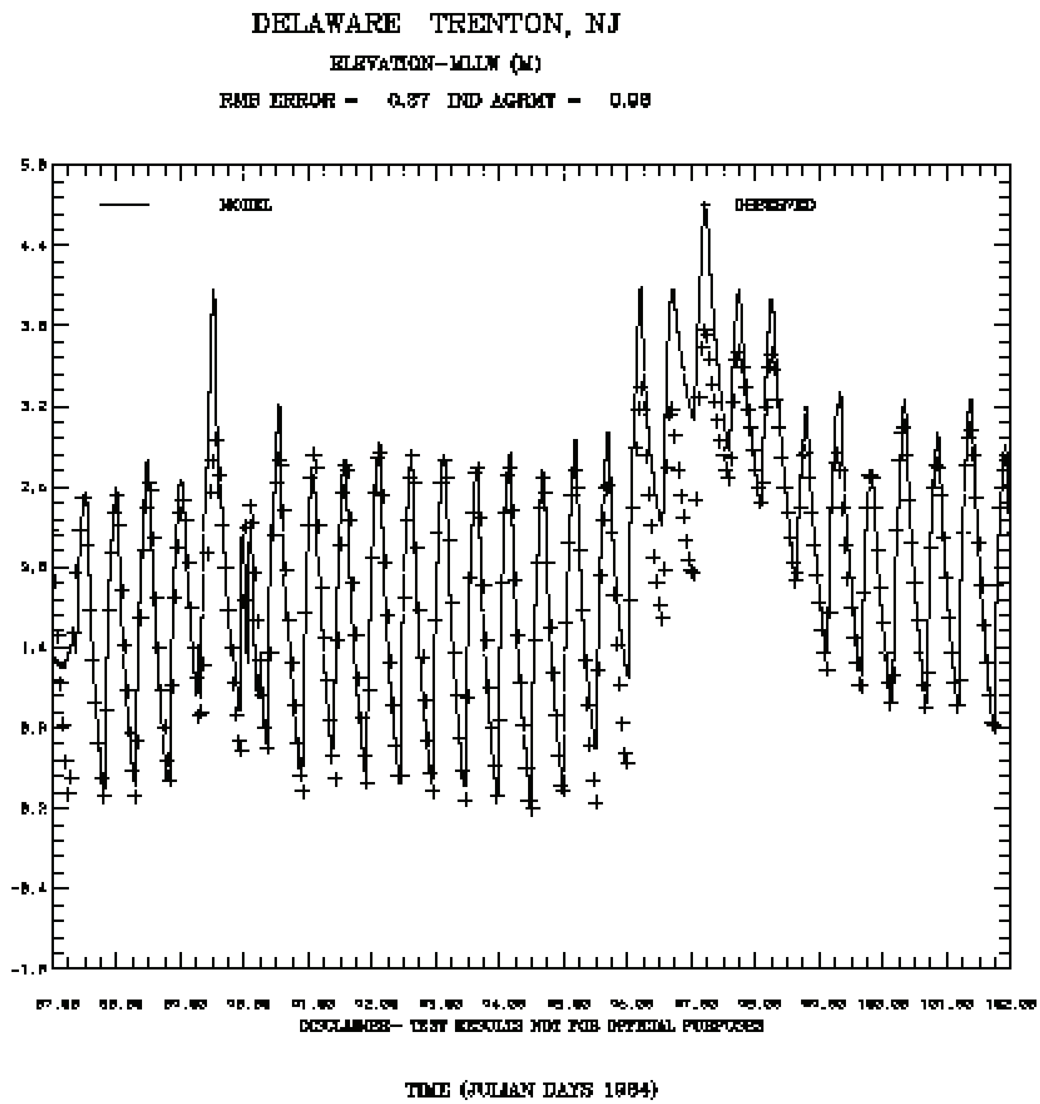


Figure 3.5. Revised Geometry High Flow Hindcast (27 March – 10 April, 1984) Water Surface Elevation at Trenton, NJ. Note observations are at one hour intervals.

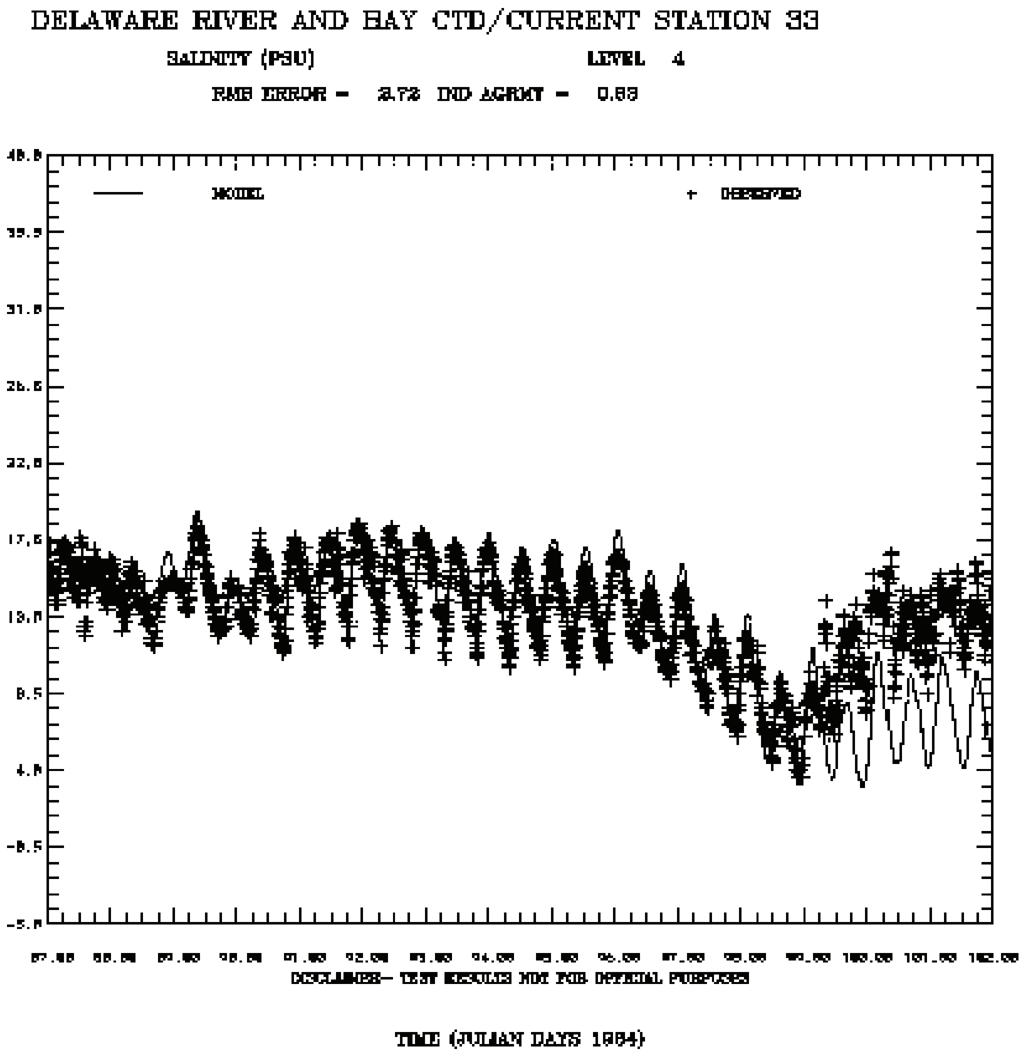


Figure 3.6. Revised Geometry High Flow Hindcast (27 March – 10 April, 1984) Salinity at Station 33. Note observations are at 10 minute intervals.

3.4 Revised Geometry Low Flow Simulation

To examine the effect of the revised geometry under low flow conditions, the 10-24 September, 1984 period was simulated. Wind speed and direction and atmospheric pressure as produced by the Barnes (1973) interpolation at three hour intervals are compared with hourly observations and are of the same order RMSE as for the high flow period. Note mean wind speeds are lower than during the high flow period and are quite gentle. Simulated water levels are contrasted with observations in Table 3.11. RMSEs are generally of the same order as obtained under high flow conditions particularly at Trenton, NJ as shown in Figure 3.7. However, one notes at the Capes and at Philadelphia, PA an increase of order 6 cm in RMSE. These results may be improved by reducing the grid extent onto the shelf, thereby specifying the subtidal water level signal nearer the measurement location. However, in so doing one loses the ability to predict the Delaware coastal current.

In Tables 3.12 and 3.13, the current speed and direction comparisons are given. One notes at Station 33 the current speed responses are very similar to those obtained for the high flow hindcast. Note the current speeds are slightly under-predicted at the upriver stations (33, 51 and 154). Current direction errors are comparable under both high and low flow conditions. In Table 3.14, the salinity response is compared with observations. One notes a very favorable comparison, particularly at Station 33 in the region of large horizontal salinity gradients and the model successfully represents the salinity intrusion under low flow conditions. As shown in Table 3.15, the temperature response also compares very well to the observations.

Table 3.11. Water Surface Elevation-MLLW (m) Revised Geometry Low Flow Hindcast: September 10-24, 1984.

Station	RMS Error (cm)	Relative Error (-)	Model Mean (cm)	Observed Mean (cm)
Lewes, DE	17	0.04	62	70
Cape May, NJ	21	0.04	73	79
Indian River, DE	17	0.07	39	47
Ocean City Pier, MD	17	0.06	51	61
Phila. Pier 11, PA	27	0.05	104	107
Chesapeake City, MD	12	0.03	111	111
Trenton, NJ	37	0.05	122	133

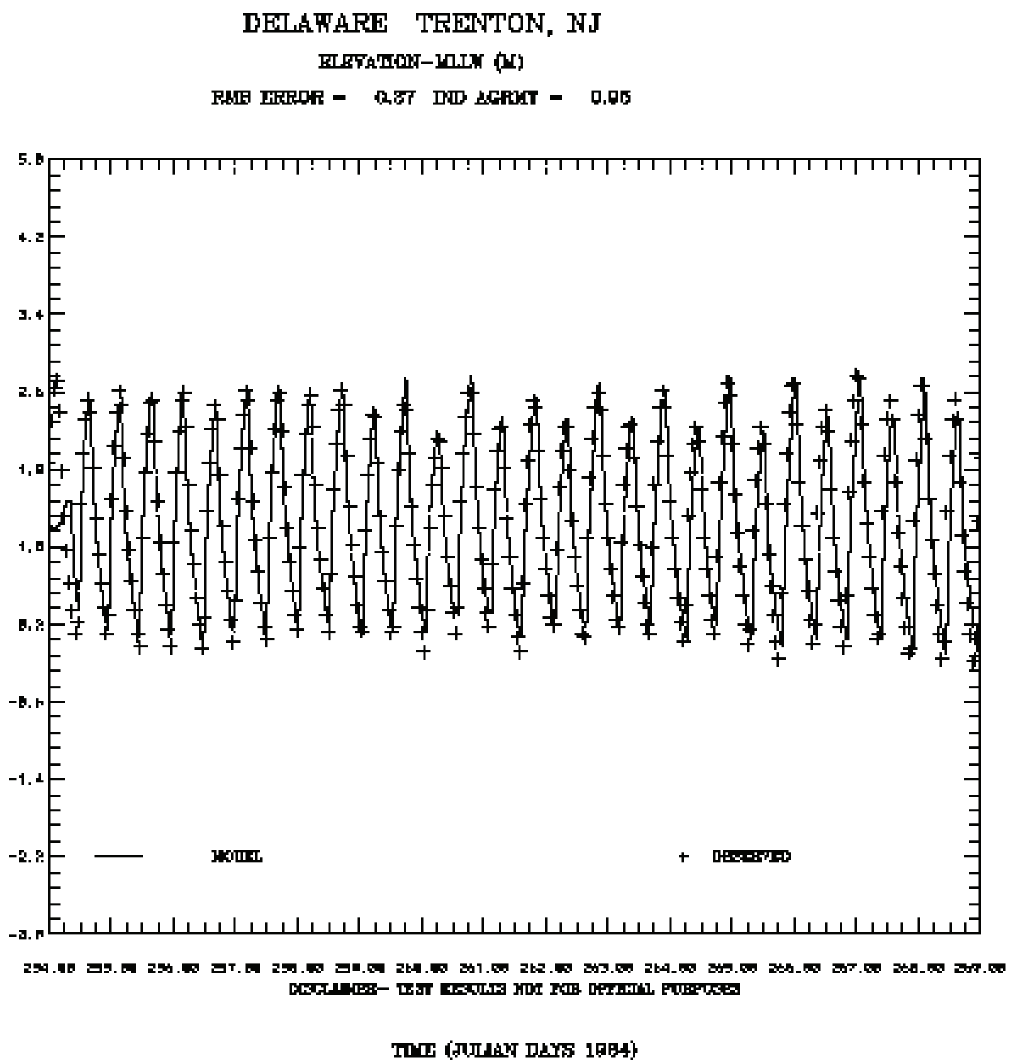


Figure 3.7. Revised Geometry Low Flow Hindcast (10 – 24 September, 1984) Water Surface Elevation at Trenton, NJ. Note observations are at one hour intervals.

Table 3.12. Current Speed (cm/s) Revised Geometry Low Flow Hindcast: September 10-24, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (cm/s)	Relative Error (-)	Model Mean (cm/s)	Observed Mean (cm/s)
2 at 7	22.64	0.29	42.16	39.01
16 at 11	7.55	0.53	7.44	9.89
17 at 15	12.59	0.54	9.66	17.71
18 at 2	11.47	0.24	25.97	25.18
19 at 2	15.92	0.31	31.55	28.27
19 at 8	22.65	0.27	44.74	45.45
22 at 6	16.52	0.20	32.52	41.69
23 at 2	20.50	0.47	32.84	17.34
24 at 2	14.23	0.31	30.66	27.69
25 at 2	10.90	0.22	23.04	29.22
33 at 2	16.06	0.33	22.06	29.28
15 at 9	27.15	0.36	43.12	61.46
154 at 2	27.18	0.57	10.26	31.47

Table 3.13. Current Direction (^{o}T) Revised Geometry Low Flow Hindcast: September 10-24, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (^{o}T)	Relative Error (-)	Model Mean (^{o}T)	Observed Mean (^{o}T)
2 at 7	46.54	0.08	231.70	212.66
16 at 11	59.06	0.30	159.53	217.85
17 at 15	69.50	0.31	196.75	230.55
18 at 2	17.12	0.01	220.75	238.79
19 at 2	29.24	0.02	232.75	257.01
19 at 8	39.79	0.05	234.96	247.18
22 at 6	17.88	0.01	231.26	231.98
23 at 2	6.56	0.00	240.77	269.80
24 at 2	39.07	0.05	234.91	245.13
25 at 2	120.56	0.86	117.22	184.53
33 at 2	48.11	0.07	225.88	226.26
15 at 9	39.65	0.04	186.91	194.25
154 at 2	99.01	0.33	209.43	187.41

Table 3.14. Salinity (PSU) Revised Geometry Low Flow Hindcast: September 10-24, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (PSU)	Relative Error (-)	Model Mean (PSU)	Observed Mean (PSU)
2 at 7	0.40	0.58	29.99	30.08
16 at 3	1.38	0.93	31.08	29.68
16 at 11	0.29	0.78	31.01	31.15
19 at 2	0.41	0.14	28.58	28.67
22 at 6	1.33	0.28	26.28	27.34
23 at 2	0.64	0.45	27.22	27.44
24 at 2	1.11	0.39	26.05	26.21
33 at 2	2.06	0.51	18.01	18.81
154 at 2	0.83	0.71	6.83	6.59

Table 3.15. Temperature (^{o}C) Revised Geometry Low Flow Hindcast: September 10-24, 1984. DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (^{o}C)	Relative Error (-)	Model Mean (^{o}C)	Observed Mean (^{o}C)
2 at 7	0.60	0.81	20.60	21.04
16 at 3	1.19	0.57	19.36	20.87
16 at 11	0.75	0.49	20.48	20.93
19 at 2	0.29	0.60	20.93	20.67
19 at 8	0.34	0.62	20.93	20.62
22 at 6	0.52	0.67	21.22	20.75
23 at 2	0.56	0.80	21.12	21.20
24 at 2	0.61	0.57	21.10	20.63
33 at 2	0.48	0.70	22.85	22.40

3.5 Summary and Additional Considerations

The revised geometry of the C&D canal, channel depth modifications, and the incorporation of a spatially varying bottom roughness, led to improved water level, current, salinity, and temperature response for both the high flow and low flow fifteen day periods. Further modification of the bottom roughness zones both in value and extent is warranted. The investigation of the bottom friction zones used by Walters (1992a; 1992b) and later employed by DiLorenzo et al. (1994) and Kim and Johnson (1998) would be worth consideration. In fact, Walters notes that it was only through the use of spatially varying bottom friction zones, that the correct astronomical tidal response could be achieved. Note in considering the Delaware Coastal Current, Whitney and Garvine (2006) employed a constant bottom roughness, $z_0 = 0.3$ cm. Ramsey et al. (1996) used six different bottom roughness Manning's n coefficients for the main channel and side embayments.

As noted by Johnson et al. (1988) and Galperin and Mellor (1990a; 1990b) a major issue is the representation of the river sections above Philadelphia, PA. Parker (1984; 1991) has studied the frictional effects in the river sections with a one-dimensional model. Within the present grid structure, order 4 grid cells are employed within the upper river sections with only 2 grid cells representing the river at Trenton, NJ. To specify the river inflow of the Delaware River at Trenton, NJ, the USGS station above the tide is used to specify the average daily discharge, which is split equally over two grid cells in POM and ROMS medium resolution grid. For the ROMS high resolution grid in Chapter 5 the flows are distributed as 0.3, 0.4, and 0.3 over the three grid cells. The USGS gage and forecast point is located on the left hand side bank looking downstream immediately above the Calhoun Bridge. The rapids seen on the navigation chart are called the "Trenton Falls" and the tide begins below them. Most of the diurnal fluctuations are from directed releases from the New York City reservoirs in the headwater areas in the Catskill Mountains of New York. In the USGS gage remarks section, it is noted that water is diverted just above the gage for Morrisville, PA and Trenton, NJ for water supply. They note that diurnal fluctuations at medium and low flow are caused by power plants on tributary streams. There are several large hydro-power stations on the Lackawaxen and Mongaup Rivers that release as needed. 99.99+% of the time the gage is not influenced by the tides. At two high tides during the April 2005 floods there may have been some influence (Nickelsburg, 2006). As a result, during high flow conditions, the average daily flow specification may need to be revised to hourly flow values.

A transition from POM to ROMS, as discussed in subsequent chapters, was made to see if comparable improvement in results with respect to the MEE could be achieved. It is desirable to implement ROMS to enable more efficient parallel computation using MPI within the National Centers for Environmental Prediction (NCEP) environment, since POM was not implemented within the MPI framework.

4. ROMS MEDIUM GRID RESOLUTION HINDCASTS

ROMS was employed to simulate the same high and low flow simulations of POM in Chapter 3. The same treatment of the subtidal water level boundary conditions and model datum were invoked. Within the Delaware River and Bay system, two datums are used. Along the coast and within the Bay proper MSL is taken as the model datum, while above Philadelphia, PA mean river level (MRL) is assumed equal to NAVD-1988 and is taken as the model datum. The medium resolution grid sections used in both POM and ROMS simulations are shown as previously in Figures 3.1 and Figure 3.2.

4.1. Model Revisions

To set the stage for the ROMS revised simulations, we first recap the POM revisions in Chapter 3. Within POM the following conditions were employed:

1) The C&D canal width was adjusted to its actual channel width of 121.9 m. It was straightened and made one grid cell wide.
2) The United States Army Corps of Engineers (USACOE) project channel depths were specified for the navigation channels from the Bay to Philadelphia, PA from Philadelphia, PA to Newbold, PA and from Newbold, PA to Trenton, NJ.
3) Several upriver marsh areas were specified at depths of order 1 m.
4) SST was specified by using the nearest surface value of the CT moorings and CTD profiles.
5) A spatially varying bottom roughness was incorporated in the hydrodynamic model, such that over the continental shelf z_0 = 1 cm, from the Bay entrance to the river mouth z_0 linearly decreases to 0.3 cm, from the river mouth to below the Tacony Bridge, NJ it remains at 0.3 cm, and from there to the head of tide it linearly increases to 1.3 cm.

For the ROMS simulations, the following conditions were employed:

1) The C&D canal width was adjusted to its actual channel width of 121.9 m. It was straightened and made two grid cells wide to accommodate the higher order numerical scheme.
2) The USACOE project channel depths were specified using NOS bathymetric surveys.
3) Upriver marsh areas were not explicitly considered.
4) A full bulk flux formulation was used to provide the surface heat fluxes using the MEE forcing files (Patchen, 2008).
5) A spatially varying quadratic friction coefficient set was incorporated in the hydrodynamic model, such that over the continental shelf *rdr* = 0.007, from the Bay entrance to the river mouth *rdr* linearly decreases to 0.005, from the river mouth to the head of tide it linearly increases to 0.009. The revision was incorporated as the CPPDEF option RDR_VAR.
6) To output the wind and sea level atmospheric time series at stations in the stations file and to output these fields, the CPPDEF option MET_OUT was added.

4.2. High Flow Simulation

Wind speed and direction and atmospheric pressure were produced using Barnes (1973) interpolation at three hour intervals with wind speed and direction RMS errors order 2 m/s and 25 ^{o}T, respectively, and sea level atmosphere pressure RMS errors order 1.5 mb. Simulated water levels are compared with observations in Table 4.1 with RMSEs increasing from order 15 cm at the Bay entrance to 25 cm at Philadelphia, PA with a maximum near the head of tide at Trenton, NJ of 37 cm as shown in Figure 4.1 for both models. In this and all subsequent tables, the relative error corresponds to the Willmott et al. (1985) dimensionless (0-1) relative error, with zero representing perfect agreement. Note for the time series plots, the indicator of agreement (IND AGMT) equal to one minus the relative error is given.

Table 4.1. Water Surface Elevation-MLLW (m) High Flow Hindcast:
27 March – April 10, 1984: ROMS Results / POM Results

Station	RMS Error (cm)	Relative Error (-)	Model Mean (cm)	Observed Mean (cm)
Lewes, DE	15/13	0.02/0.02	81/86	86
Cape May, NJ	19/13	0.03/0.01	88/93	93
Indian River, DE	20/22	0.07/0.08	58/62	63
Phila. Pier 11, PA	27/22	0.05/0.03	143/145	133
Trenton, NJ	37/37	0.04/0.04	200/204	191

Current speed and direction model predictions are compared against observations in Tables 4.2 and 4.3, respectively. The current strengths at Station 33 and within the river sections are in reasonable agreement with observations. Current directions are reasonably represented within the Bay and river sections, where the currents are rectilinear. At continental shelf stations 16 and 17 the currents are rotary in nature and both model directions exhibit larger discrepancies from the observations.

Table 4.2. Current Speed (cm/s) High Flow Hindcast:
27 March – April 10, 1984: ROMS Results / POM Results
DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (cm/s)	Relative Error (-)	Model Mean (cm/s)	Observed Mean (cm/s)
16 at 11	13.28/12.76	0.49/0.48	7.96/9.82	15.33
17 at 3	12.27/12.73	0.60/0.59	7.32/14.06	13.34
23 at 8	16.76/15.28	0.16/0.14	43.12/42.40	40.54
33 at 11	25.20/19.46	0.22/0.12	58.17/52.19	58.17
50 at 8	22.65/27.83	0.22/0.38	59.52/46.72	61.78
52 at 4	16.76/17.99	0.20/0.26	41.37/38.65	47.17

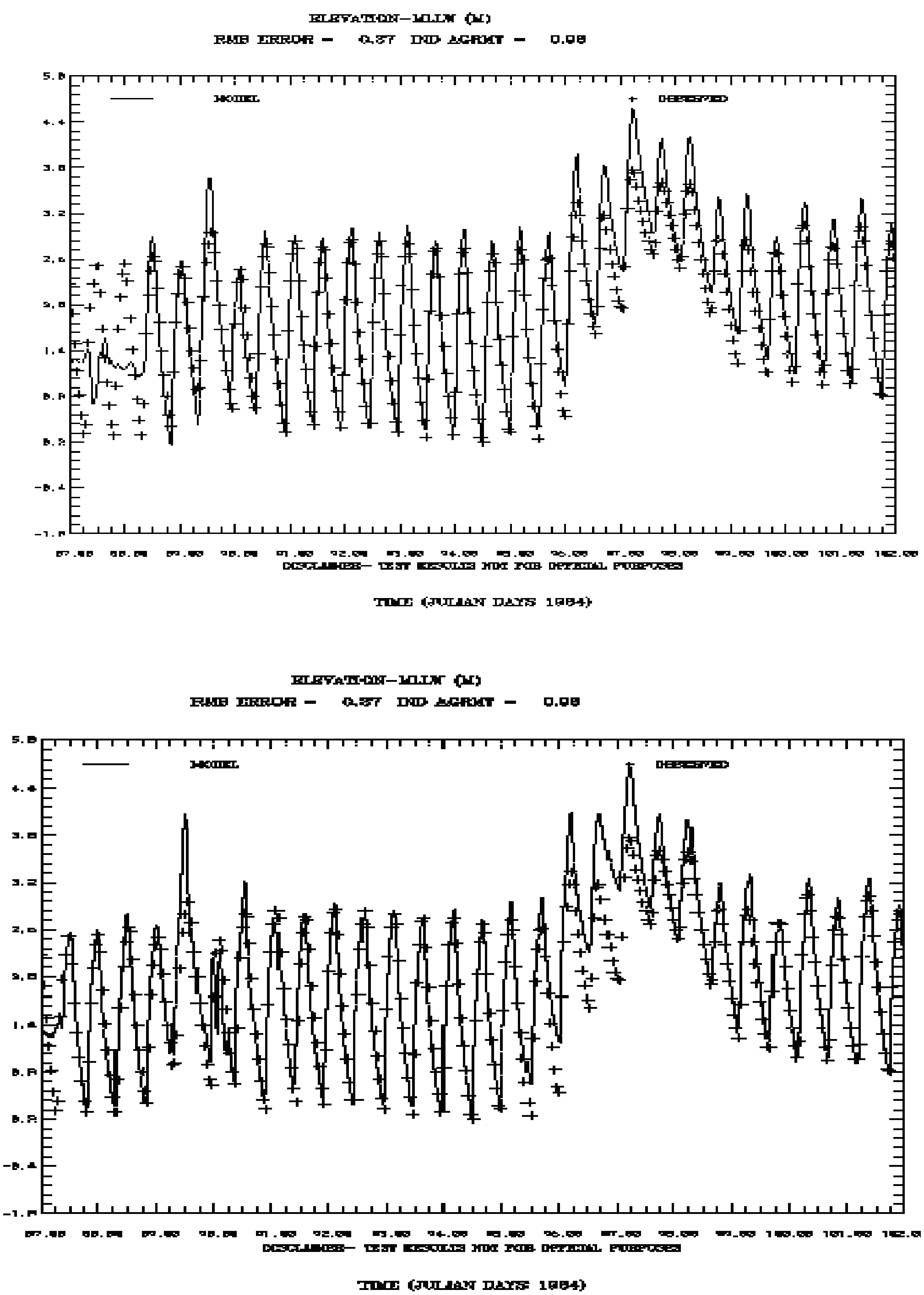


Figure 4.1. High Flow Hindcast (27 March – 10 April 1984) Water Surface Elevation at Trenton, NJ. Top panel: ROMS Hindcast Bottom panel: POM Hindcast Note observations are at one hour intervals.

Table 4.3. Current Direction (^oT) High Flow Hindcast
27 March – April 10, 1984: ROMS Results / POM Results
DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (^oT)	Relative Error (-)	Model Mean (^oT)	Observed Mean (^oT)
16 at 11	57.77/86.25	0.64/0.78	179.40/194.21	228.85
17 at 3	113.22/137.58	0.84/0.83	188.76/178.02	215.01
23 at 8	40.63/31.54	0.05/0.03	234.56/239.16	254.61
33 at 11	41.86/29.10	0.05/0.02	210.39/219.72	226.66
50 at 8	48.80/36.06	0.08/0.04	173.56/170.13	176.83
52 at 4	41.50/30.48	0.06/0.03	154.80/153.85	148.01

The simulated salinities at the corresponding POM model sigma levels (k=1, 15 with 1 representing the near surface) are compared with observations in Table 4.4. One notes as shown in Figure 4.2 at Station 33 in the region of large horizontal gradients, that a reasonable RMSE of order 3.0 PSU is achieved. The simulated temperature response is contrasted with observations in Table 4.5 for both models. With either the SST specification in POM or the bulk heat flux formulation in ROMS, the RMSEs are within order 2 ^oC.

Table 4.4. Salinity (PSU) High Flow Hindcast
27 March – April 10, 1984: ROMS Results / POM Results
DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (PSU)	Relative Error (-)	Model Mean (PSU)	Observed Mean (PSU)
16 at 3	0.80/1.05	0.58/0.65	31.87/31.62	32.58
16 at 8	0.51/0.69	0.56/0.60	31.80/31.60	32.19
16 at 11	0.64/0.78	0.60/0.59	31.76/31.58	32.28
17 at 3	0.93/1.01	0.93/0.89	32.97/32.79	33.78
23 at 8	1.54/1.49	0.45/0.45	25.71/25.33	25.58
33 at 11	2.97/2.72	0.20/0.17	12.63/12.61	13.14

Table 4.5. Temperature (^oC) High Flow Hindcast
27 March – April 10, 1984: ROMS Results / POM Results
DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (^oC)	Relative Error (-)	Model Mean (^oC)	Observed Mean (^oC)
16 at 3	2.16/1.86	0.68/0.69	7.16/6.81	5.01
16 at 8	2.24/1.82	0.66/0.67	7.29/6.82	5.06
16 at 11	2.22/1.74	0.65/0.65	7.38/6.83	5.17
17 at 3	2.19/2.02	0.85/0.85	7.66/7.51	5.51
23 at 8	0.81/0.73	0.24/0.99	7.19/6.43	6.43
33 at 11	0.38/1.40	0.04/0.51	6.74/5.71	6.71

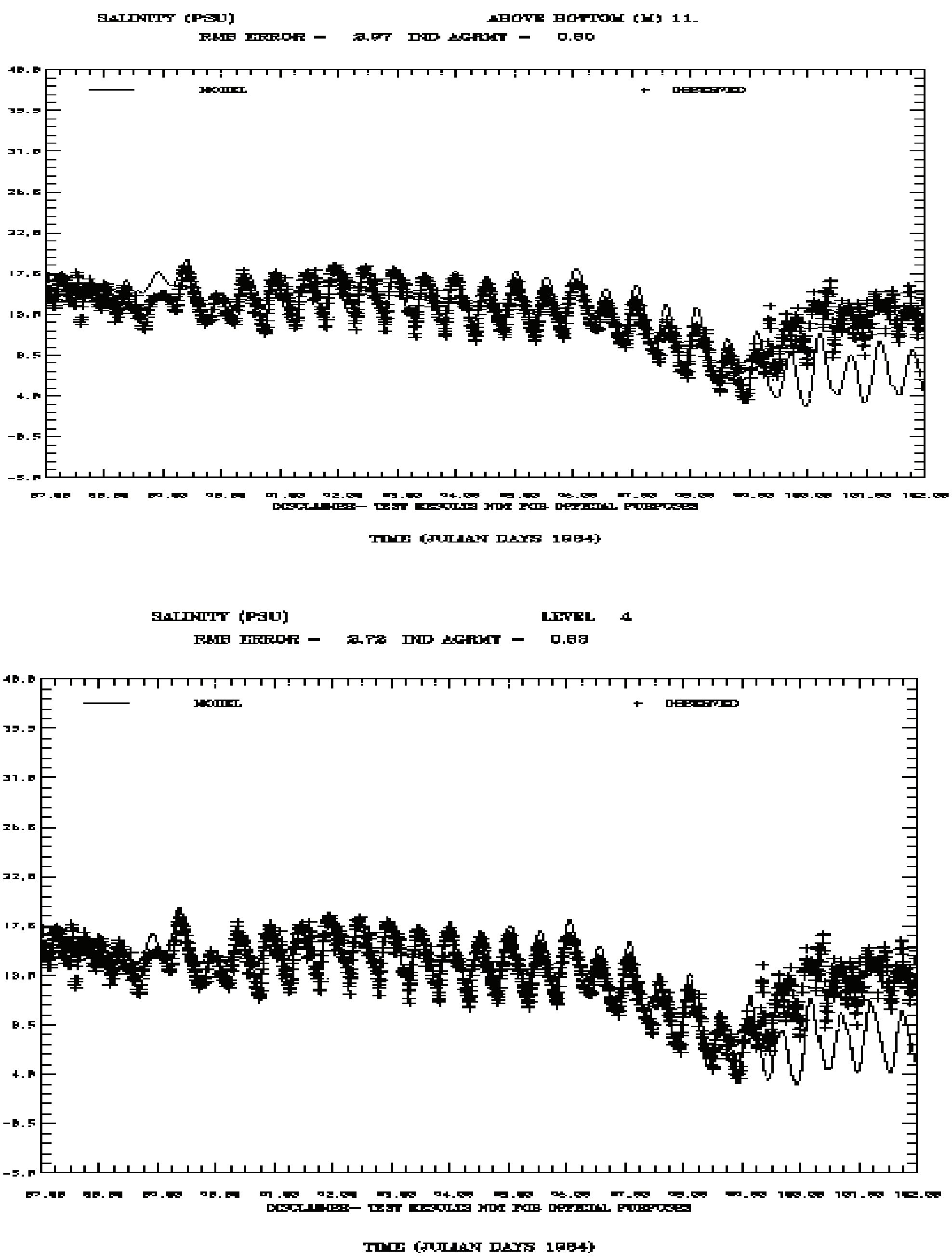


Figure 4.2. Simulated versus Observed (10 minute) Salinity at Station 33 Level 4 at 11m above the bottom. Top panel: ROMS Hindcast Bottom panel: POM Hindcast Note observations are at 10-minute intervals.

4.3 Low Flow Simulation

To examine the effect of the above revisions under low flow conditions, the 10-24 September, 1984 period was simulated. Wind speed and direction and atmospheric pressure as produced by the Barnes (1973) interpolation at three hour intervals are compared with hourly observations and are of the same order RMSE as for the high flow period. Note that mean wind speeds are lower than during the high flow period and are quite gentle. Simulated water levels are contrasted with observations in Table 4.6. RMSEs are generally of the same order as obtained under high flow conditions as shown at Trenton, NJ in Figure 4.3. However, one notes in comparing Tables 4.1 and 4.6, at the Bay entrance and at Philadelphia, PA a decrease in mean water levels of order 15 cm. These results indicate the impact of the long period Sa and Ssa constituents.

Table 4.6. Water Surface Elevation-MLLW (m) Low Flow Hindcast
September 10-24, 1984: ROMS Results/ POM Results

Station	RMS Error (cm)	Relative Error (-)	Model Mean (cm)	Observed Mean (cm)
Lewes, DE	18/17	0.04/0.04	71/62	70
Cape May, NJ	21/21	0.04/0.04	80/73	79
Indian River, DE	17/17	0.07/0.07	48/39	47
Ocean City Pier, MD	14/17	0.04/0.06	58/51	61
Phila. Pier 11, PA	27/27	0.05/0.05	113/104	107
Trenton, NJ	35/37	0.04/0.05	132/122	131

In Tables 4.7 and 4.8, the current speed and direction comparisons are given. One notes at Station 33 the current speed responses are very similar to those obtained for the high flow hindcast. Note that the current speeds are slightly under-predicted at upriver station 51. Current direction errors are comparable under both high and low flow conditions. In Table 4.9, the salinity response is compared with observations. One notes a very favorable comparison, particularly at Station 33 in the region of large horizontal salinity gradients. As shown in Table 4.10, the temperature responses in both models also compare very well to the observations.

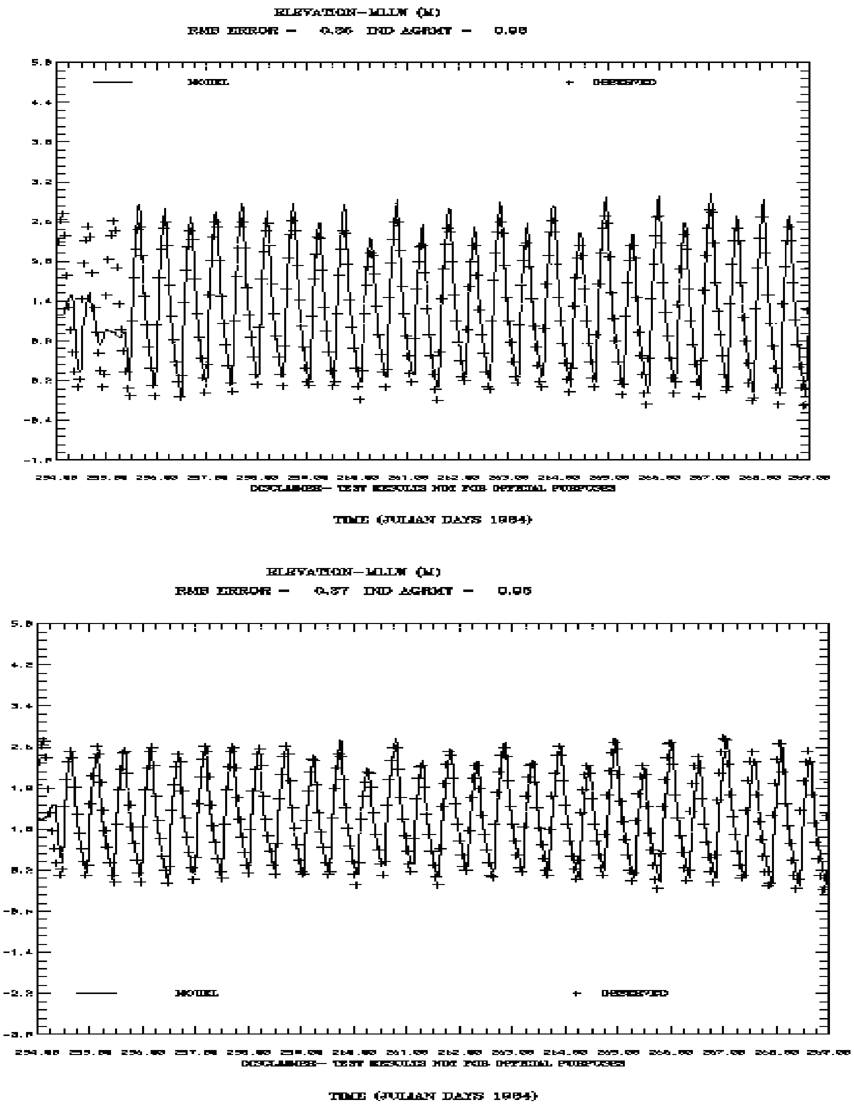


Figure 4.3. Low Flow Hindcast (10 – 24 September, 1984) Water Surface Elevation at Trenton, NJ. Top panel: ROMS Hindcast Bottom panel: POM Hindcast Note observations are at one hour intervals.

Table 4.7. Current Speed (cm/s) Revised Low Flow Hindcast
September 10-24, 1984: ROMS Results/ POM Results

Station Model Level	RMS Error (cm/s)	Relative Error (-)	Model Mean (cm/s)	Observed Mean (cm/s)
2 Level 8	35.00/22.64	0.57/0.29	40.48/42.16	39.01
16 Level 12	10.35/9.18	0.72/0.65	6.96/6.59	14.38
16 Level 6	7.91/7.55	0.59/0.53	7.39/7.44	9.89
17 Level 6	14.59/12.59	0.58/0.54	7.03/9.66	17.71
18 Level 9	8.25/11.47	0.10/0.24	26.95/25.97	25.18
19 Level 13	14.66/15.92	0.21/0.31	34.81/31.55	28.27
19 Level 5	14.02/22.65	0.09/0.27	46.99/44.74	45.45
22 Level 7	11.15/16.52	0.08/0.20	37.37/32.52	41.69
23 Level 11	18.31/20.50	0.40/0.47	31.24/32.84	17.34
24 Level 8	7.99/14.23	0.10/0.31	28.62/30.66	27.69
25 Level 11	7.04/10.90	0.07/0.22	27.94/23.04	29.22
33 Level 15	19.22/16.06	0.40/0.33	33.72/22.06	29.28
51 Level 5	23.62/27.15	0.28/0.36	48.96/43.12	61.46
154 Level 15	33.53/27.18	0.63/0.57	29.16/10.26	31.47

Table 4.8. Current Direction (^{o}T) Revised Low Flow Hindcast
September 10-24, 1984: ROMS Results/ POM Results

Station Model Level	RMS Error (^{o}T)	Relative Error (-)	Model Mean (^{o}T)	Observed Mean (^{o}T)
2 Level 8	71.90/46.54	0.14/0.08	223.04/231.70	212.66
16 Level 6	113.91/59.06	0.43/0.30	142.42/159.53	217.85
17 Level 6	89.17/69.50	0.36/0.31	192.56/196.75	230.55
18 Level 9	7.12/17.12	0.00/0.01	223.29/220.75	238.79
19 Level 13	18.40/29.24	0.01/0.02	220.71/232.75	257.01
19 Level 5	22.42/39.79	0.01/0.05	229.33/234.96	247.18
22 Level 7	9.92/17.88	0.00/0.01	227.50/231.26	231.98
23 Level 11	6.07/6.56	0.00/0.00	238.76/240.77	269.80
24 Level 8	45.35/39.07	0.06/0.05	242.35/234.91	245.13
25 Level 11	119.80/120.56	0.87/0.86	107.83/117.22	184.53
33 Level 15	99.29/48.11	0.30/0.07	231.22/225.88	226.26
51 Level 5	30.09/39.65	0.03/0.04	189.95/186.91	194.25
154 Level 15	91.09/99.01	0.31/0.33	165.19/209.43	187.41

Table 4.9. Salinity (PSU) Revised Low Flow Hindcast
September 10-24, 1984: ROMS Results/ POM Results

Station Model Level	RMS Error (PSU)	Relative Error (-)	Model Mean (PSU)	Observed Mean (PSU)
2 Level 8	0.48/0.40	0.68/0.58	30.04/29.99	30.08
16 Level 12	1.38/1.38	0.93/0.93	31.12/31.08	29.68
16 Level 6	0.27/0.29	0.71/0.78	31.01/31.01	31.15
19 Level 13	0.89/0.41	0.37/0.14	29.20/28.58	28.67
22 Level 7	0.66/1.33	0.12/0.28	26.74/26.28	27.34
23 Level 11	0.76/0.64	0.41/0.45	27.68/27.22	27.44
24 Level 8	0.46/1.11	0.12/0.39	26.41/26.05	26.21
33 Level 15	3.07/2.06	0.56/0.51	19.46/18.01	18.81
154 Level 15	0.65/0.83	0.50/0.71	7.27/6.83	6.59

Table 4.10. Temperature (^oC) Revised Low Flow Hindcast
September 10-24, 1984: ROMS Results/ POM Results

Station Model Level	RMS Error (^oC)	Relative Error (-)	Model Mean (^oC)	Observed Mean (^oC)
2 Level 8	0.63/0.60	0.83/0.81	21.40/20.60	21.04
16 Level 12	1.32/1.19	0.59/0.57	19.15/19.36	20.87
16 Level 6	0.99/0.75	0.78/0.49	21.31/20.48	20.93
19 Level 13	1.56/0.29	0.87/0.60	21.77/20.93	20.67
19 Level 5	1.60/0.34	0.87/0.62	21.79/20.93	20.62
22 Level 7	1.92/0.52	0.87/0.67	22.38/21.22	20.75
23 Level 11	1.24/0.56	0.66/0.80	22.08/21.12	21.20
24 Level 8	2.03/0.61	0.76/0.57	22.46/21.10	20.63
33 Level 15	0.42/0.48	0.72/0.70	23.27/22.85	22.40

4.4 Summary and Additional Considerations

For both 15-day periods, the ROMS simulation results for water levels, currents, salinity, and temperature were very similar to those obtained with POM. Note ,while the same horizontal grid was used, in the vertical POM uses15 sigma levels while ROMS has 10 generalized s coordinate levels. The third order upstream horizontal advection schemes in ROMS as opposed to the second order central differencing schemes in POM necessitated an extra day of model spin-up from rest. Both models used the Mellor-Yamada 2.5 level turbulence scheme and employed similar offshore boundary conditions. Both models were run with a 1 second barotropic time step with POM using a 10 second and ROMS a 20 second baroclinic time step. As previously noted, a major issue is the representation of the C&D Canal and the river sections above Philadelphia, PA. Within the present grid structure, the C&D Canal is one grid cell wide in POM and two grid cells wide in ROMS. Also order 4 grid cells are employed within the upper river sections with only 2 grid cells representing the river at Trenton, NJ. As a result, a higher resolution grid based on the Delft Hydraulics Laboratory grid generation software (Delft Hydraulics, 2004) was developed and additional ROMS simulations performed as presented in the following chapter.

5. ROMS HIGH RESOLUTION GRID HINDCASTS

Previous hydrodynamic simulations in Chapters 2 - 4 indicated the need for a higher resolution grid within the river sections to improve water level and current response from Philadelphia, PA to Trenton, NJ. First, we discuss the construction of a new high resolution river grid and contrast the grid features with those of the previous medium resolution grid. Next, simulation setup, boundary, and forcing conditions are discussed. To compare the model performance on the new high resolution grid (HRG) versus the previous medium resolution grid (MRG) 15 day simulations are performed under both high and low Delaware River flow conditions. To further assess model performance on the new grid, an extended seven month hindcast was performed and the water level response was evaluated over 15 day periods, as in the high and low flow simulation set. Next, a tidal analysis is performed by using a 30 hour low pass filter to extract the tidal signal from the hindcast results during April 1984. The resulting tide signal is compared to predicted water levels based on NOS accepted harmonic constants to determine the tidal error. Three astronomical tide simulations over the HRG are performed for April 1984 using different open boundary conditions to study the influence of the open boundary specification on the water level response. Finally, results are summarized and further considerations are then discussed.

5.1 Medium and High Resolution Grids

The initial medium resolution grid (MRG) shown in Figure 3.1 for the upper Delaware River and in Figure 3.2 for the lower Delaware River and Bay was developed using the SEAGRID software package (USGS Woods Hole Science Center, 2007). The horizontal grid is 150 x 550 and the grid cell length ranges are [110 m, 1665 m] in the x-direction and [140 m, 2645 m] in the y-direction. At head of tide at Trenton, NJ the Delaware River is represented by 2 grid cells across. Bathymetry adjusted to MLLW was placed on the grid via interpolation of NOS sounding data as detailed by Lanerolle (2007).

A 120 x 733 horizontal high resolution grid (HRG) was developed using the DELFT3D RGFGRID software package (Delft Hydraulics, 2004) with resolution order 3 km at the shelf break and order 100 m at the head of tide at Trenton, NJ. Resolution in the C&D Canal is 200 m with grid cell length ranges of [49 m, 6092 m] in the x-direction and [51 m, 3053 m] in the y-direction. At head of tide at Trenton, NJ the Delaware River is represented by 3 grid cells across. In the grid construction process, three separate splines and grid segments were developed for the upper River, the C&D canal, and for the lower Bay-Shelf region, respectively. To generate the final grid, the grid segments were combined using the active-passive option and then the grid was orthogonalized. Grid point locations were reviewed and edited as necessary to improve orthogonality. The SMS software package (Brigham Young University Environmental Modeling Research Laboratory, 2006) was used to place and edit the bathymetry on the grid. In Figure 5.1, the new HRG in the C&D canal region is shown. Note the ability of the grid to exactly follow the canal and to represent the main navigation channel bathymetric features as shown in Figure 5.2.

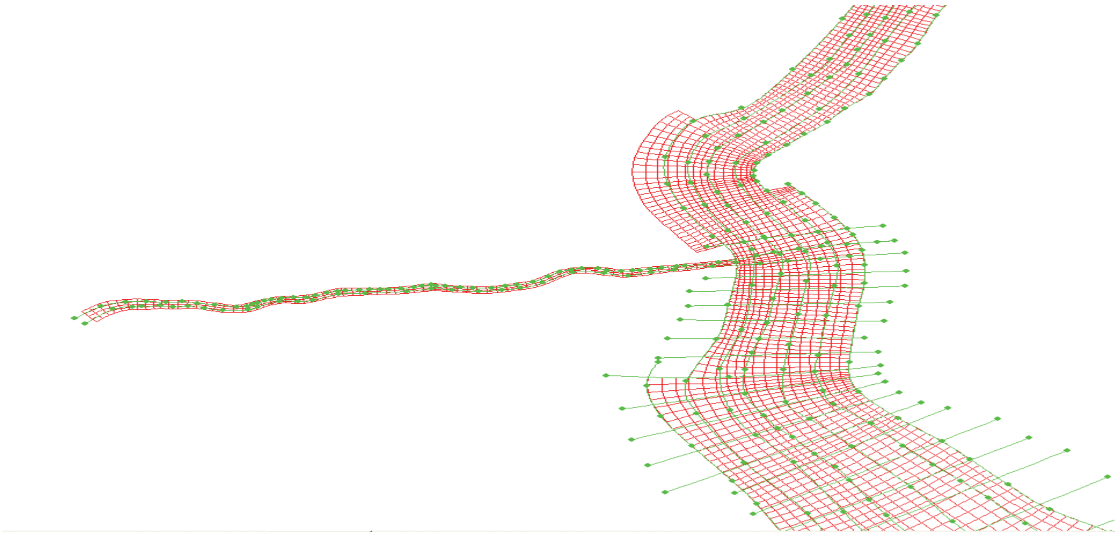


Figure 5.1. Map depicting Delaware River and Bay DELFT-3D High Resolution Grid in the C&D Canal Region. Splines are constructed through the appropriate points along each coordinate direction. Within each rectangle formed by the intersection of the splines, the number of grid cells in each coordinate direction is specified.

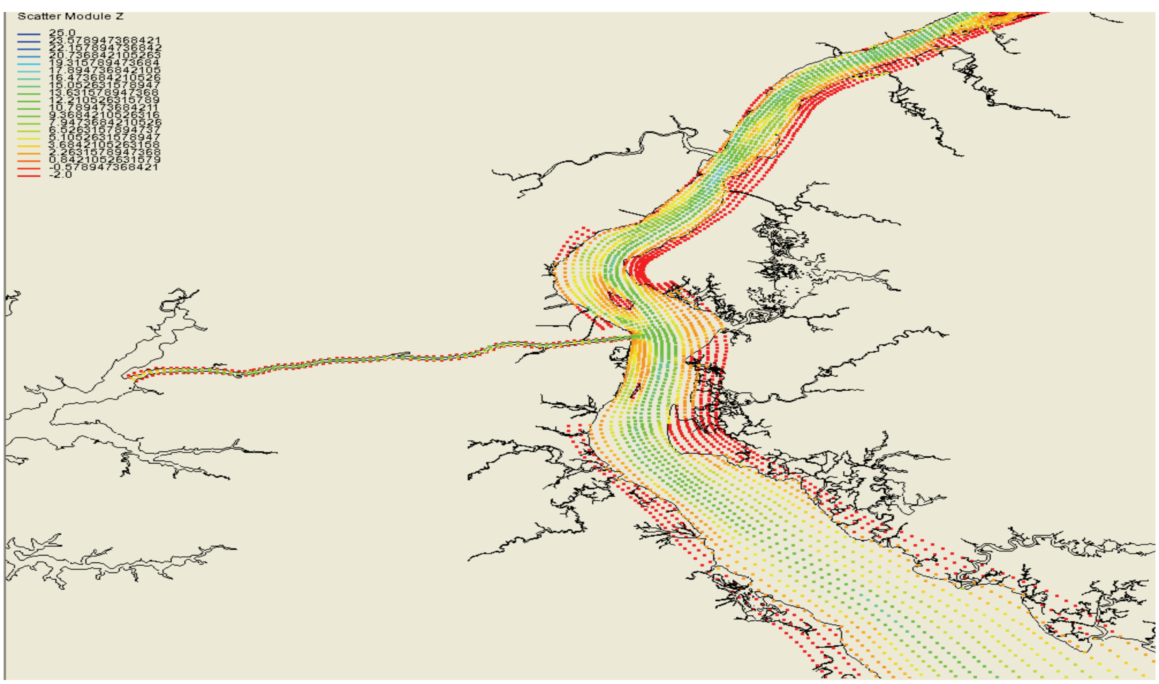


Figure 5.2. Map depicting bathymetry with respect to Model Datum in the C&D Canal Region. Each dot corresponds to a grid cell center with the darker shadings indicating the navigation channel.

MLLW to model datum corrections at NOS water level gauges were used in a $1/r^2$ interpolation procedure to adjust the MLLW bathymetry to model datum over both grids. For the HRG the maximum depth was set to 300m as it extended over a large area at or beyond the shelf break. Both horizontal grids are of high quality with orthogonality errors less than 7 degrees. Ten generalized s coordinate levels are with surface, bottom, and control parameters of 4.5, 0.95 and 6 m, respectively.

5.2 Simulation Setup, Initial, Boundary and Forcing Conditions

All ROMS (Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008) simulations are three-dimensional including baroclinics with: a nonlinear equation of state, the Mellor-Yamada 2.5 turbulence closure, non-normal radiation of the velocity at the boundary, quadratic bottom friction via a spatially varying bottom friction coefficient, spline vertical advection of tracer and momentum, and third order upstream-biased horizontal advection of tracer and momentum. Table 5.1 outlines the simulation setup and additional characteristics of the boundary and forcing conditions particular to

Table 5.1. Simulation Description, Boundary and Forcing Conditions.

Simulation	Period In 1984	CPP DEF Set	Bottom Friction Set	OBC HA Set	OBC TS Set	UBAR VBAR Set	Heat Flux Set	Met Flux Set	River Inflow Set
MRG 15-day high and low flow	3/27-4/10; 9/10-9/25	CPD1	BF1	HA1	ST1	UV1	HF1	MF1	RI1
HRG 15-day high and low flow	3/27-4/10; 9/10-9/25	CPD1	BF2	HA2	ST2	UV1	HF2	MF1	RI1
HRG 7-mo simulation	Mar-Sep	CPD1	BF2	HA2	ST1	UV1	HF2	MF1	RI1
HRG Tide Simulation 1	Apr	CPD1	BF3	HA1	ST2	UV1	HF2	MF2	RI2
HRG Tide Simulation 2	Apr	CPD2	BF3	HA1	ST2	UV1	HF2	MF2	RI2
HRG Tide Simulation 3	Apr	CPD3	BF3	HA1	ST2	UV2	HF2	MF2	RI2

Notes:
CPP DEF Set denotes the boundary ROMS CPPDEF options.
Bottom Friction Set denotes the spatially varying bottom friction coefficient set.
OBC HA Set denotes the open boundary harmonic constituent set.
OBC TS Set denotes the open boundary condition salinity and temperature boundary condition set.
UBAR VBAR Set denotes the u and v vertically integrated velocity set.
Heat flux Set denotes the shortwave and downward longwave radiation set.
Met Flux Set denotes the surface wind and sea-level atmospheric pressure set.
River Inflow Set denotes the river inflow discharge set.

Supplemental Note Set:
CPD1=FSOBC_REDUCED, FSCLAMPED and M2REDUCED at C&D canal and western boundary; FSCHAPMAN and M2FLATHER on southern and eastern boundaries
CPD2=FSCLAMPED and M2REDUCED on all boundaries
CPD3=FSCLAMPED and M2REDUCED at C&D canal, FSCHAPMAN with SSH_TIDES and M2FLATHER with UV_TIDES on southern and eastern boundaries
Refer to Flather (1976) and Chapman (1985) for computational details.
BF1= { .007 J=[1,90] , .007 J=[91,124], .005 J=[125,132], .006 J=[133-158], .007 J=[159,232], .008 J=[233,299], .009 J=[300,550] } where J corresponds to the MRG y-direction grid index
BF2= { .007 J=[1,68] , .007 J=[69,117], .005 J=[118,125], .006 J=[126-209], .007 J=[210,425], .008 J=[426-544], .009 J=[545,732] } where J corresponds to the HRG y-direction grid index
BF3= { .005 J=[1,68] , .007 J=[69,117], .005 J=[118,125], .007 J=[126-209], .008 J=[210,425], .009 J=[426-544], .010 J=[545,732] } where J corresponds to the HRG y-direction grid index
HA1= Ssa and Sa included in the tide signal and not in the residual.
HA2= Ssa and Sa not included in the tide signal but included in the residual.
ST1=Open boundary salinity and temperature from NOAA's World Ocean Atlas 2001 (NODC, www.nodc.noaa.gov)
ST2=Adjustments to ST1 based on NOS 1984 Circulation Survey Data (Klavens et al., 1986)
UV1=Vertically integrated u and v velocities set to zero
UV2=Vertically integrated u and v velocities from tidal inversion using the ADCIRC model for the Western North Atlantic Ocean on the East Coast 1995 grid as developed by Myers (2007; personal communication)
HF1==Radiation fluxes derived from a grid to grid interpolation of NOAA's reanalysis product (NCEP, www.ncep.noaa.gov/mmb/rrean/index.html) on a 32 km grid to the ROMS grid
HF2==Radiation fluxes derived from a Barnes (1973) interpolation of NOAA's reanalysis product at 10 meteorological station locations to the ROMS grid
MF1==Wind and atmospheric pressure derived from a Barnes (1973) interpolation at 10 meteorological stations.
MF2==Winds set to zero and atmospheric pressure set to 1013 mb
RI1==River inflows set to USGS daily mean discharge
RI2==River inflows set to USGS mean annual discharge

each simulation subsequently described. Initial salinity and temperature conditions and lateral river inflow boundary conditions were developed from the NOS circulation survey (Klavens et al., 1984; Richardson and Schmalz, 2006). Salinity and temperature at the open boundaries were determined from NOAA's World Ocean Atlas 2001 (NODC, www.nodc.noaa.gov). Wind speed and direction and atmospheric pressure were produced at three hour intervals using Barnes (1973) interpolation at 10 stations consisting of 2 NOAA buoys and 8 C-Man stations and airports. Using this procedure, wind speed and direction RMS errors are order 2 m/s and 25 ^{o}T, respectively, and sea level atmosphere pressure RMS errors are order 1.5 mb.

The water level subtidal signal at the Chesapeake Bay end of the C&D canal was based on

Chesapeake City, MD as determined via a linear regression (bias=0.003, gain=0.784) from the Baltimore, MD subtidal water level as discussed previously. The subtidal water level signal at Cape May, NJ is empirically reduced by 30% to prescribe the subtidal water level along the outer boundary of both grids at the shelf break. An alternative approach would be to reduce the extent of the grid on the shelf to perhaps the 20 to 50 m contour as used by Celebioglu and Piasecki (2006) and apply the subtidal water level signal at Cape May, NJ without empirical reduction.

Within the Delaware River and Bay system, two datums are used. Along the coast and within the Bay proper MSL is taken as the model datum, while above Philadelphia, PA mean river level (MRL) is assumed equal to NAVD-1988 and is taken as the model datum.

5.3 High Flow Simulation

Simulated water levels are compared with observations in Table 5.2 with RMSEs increasing from order 15 cm at the Bay entrance to 25 cm at Philadelphia, PA with a maximum near the head of tide at Trenton, NJ of 37 cm (see Figure 5.3) on both grids. The difference in mean water levels is order 3 cm at the entrance to the Bay indicating the influence of Sa and Ssa is small during this period (see Table 1). In this and all subsequent tables, the relative error corresponds to the Willmott et al. (1985) dimensionless (0-1) relative error, with zero representing perfect agreement. For the time series plots, the indicator of agreement (IND AGMT) equal to one minus the relative error is given.

Table 5.2. Water Surface Elevation-MLLW (m) High Flow Hindcast
27 March – April 10, 1984: ROMS MRG Results / ROMS HGR Results

Station	RMS Error (cm)	Relative Error (-)	Model Mean (cm)	Observed Mean (cm)
Lewes, DE	15/17	0.02/0.03	81/85	86
Cape May, NJ	19/20	0.03/0.04	88/91	93
Indian River, DE	20/19	0.07/0.04	58/60	63
Phila. Pier 11, PA	27/31	0.05/0.05	143/136	133
Trenton, NJ	37/37	0.04/0.04	200/186	191

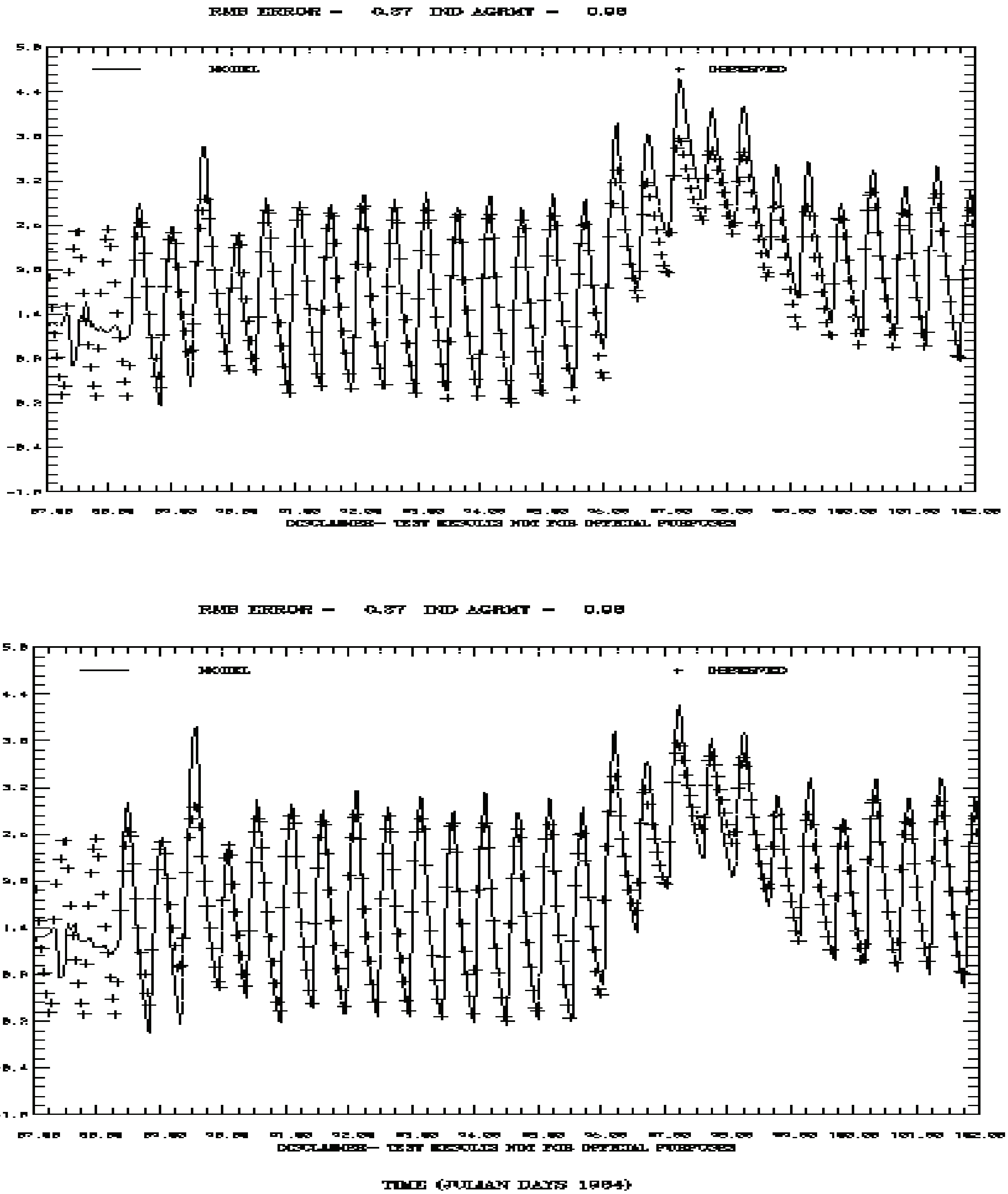


Figure 5.3. High Flow Hindcast (27 March – 10 April 1984) Water Surface Elevation (m-MLLW) at Trenton, NJ. Top panel: ROMS MRG Hindcast. Bottom panel: ROMS HRG Hindcast. Observations are at one hour intervals.

Current speed and direction model predictions are compared against observations in Tables 5.3 and 5.4, respectively. The current strengths at Station 33 and within the river sections are in reasonable agreement with observations, while predicted current strengths on the shelf do not include the mean alongshore flow and are thus weaker than the observations. Current directions are reasonably represented within the Bay and river sections, where the currents are rectilinear. At continental shelf Stations16 and 17 the currents are rotary in nature and current directions on both grids exhibit larger discrepancies from the observations.

Table 5.3. Current Speed (cm/s) High Flow Hindcast
27 March – April 10, 1984: ROMS MRG Results / ROMS HGR Results
DAB denotes distance above the bottom.

Station No at DAB (m)	RMS Error (cm/s)	Relative Error (-)	Model Mean (cm/s)	Observed Mean (cm/s)
16 at 11	13.28/13.45	0.49/0.50	7.96/8.81	15.33
17 at 3	12.27/11.58	0.60/0.51	7.32/7.15	13.34
23 at 8	16.76/16.82	0.16/0.18	43.12/39.88	40.54
33 at 11	25.20/28.96	0.22/0.21	58.17/58.24	58.17
50 at 8	22.65/25.74	0.22/0.27	59.52/55.11	61.78
52 at 4	16.76/16.49	0.20/0.18	41.37/49.18	47.17

Table 5.4. Current Direction (°T) High Flow Hindcast
27 March – April 10, 1984: ROMS MRG Results / ROMS HRG Results
DAB denotes distance above the bottom. Current direction comparisons are only made for currents greater than 0.26 cm/s.

Station at DAB (m)	RMS Error (°T)	Relative Error (-)	Model Mean (°T)	Observed Mean (°T)
16 at 11	57.77/77.25	0.64/0.68	179.40/173.62	228.85
17 at 3	113.22/86.04	0.84/0.82	188.76/210.14	215.01
23 at 8	40.63/39.32	0.05/0.05	234.56/233.53	254.61
33 at 11	41.86/49.09	0.05/0.08	210.39/209.19	226.66
50 at 8	48.80/47.88	0.08/0.07	173.56/176.63	176.83
52 at 4	41.50/45.33	0.06/0.07	154.80/153.11	148.01

The simulated salinities on both grids are compared with observations in Table 5.5.

Table 5.5. Salinity (PSU) High Flow Hindcast
27 March – April 10, 1984: ROMS MRG Results / ROMS HRG Results
DAB denotes distance above the bottom.

Station at DAB (m)	RMS Error (PSU)	Relative Error (-)	Model Mean (PSU)	Observed Mean (PSU)
16 at 3	0.80/0.56	0.58/0.76	31.87/32.80	32.58
16 at 8	0.51/0.64	0.56/0.59	31.80/32.72	32.19
16 at 11	0.64/0.50	0.60/0.51	31.76/32.61	32.28
17 at 3	0.93/0.98	0.93/0.86	32.97/32.90	33.78
23 at 8	1.54/2.56	0.45/0.55	25.71/27.37	25.58
33 at 11	2.97/3.61	0.20/0.32	12.63/15.39	13.14

In Figure 5.4 at Station 33 in the region of large horizontal gradients, while a reasonable RMSE of order 3.0 PSU is achieved, both the ROMS MRG and HRG simulations do not follow the sag in the observed salinity signal. While the simulated temperature response RMSEs in Table 5.6 are within order 2 ^{o}C, the MRG and HRG mean temperatures on the shelf are 2-3 degrees larger than the observations.

Table 5.6. Temperature (^{o}C) High Flow Hindcast
27 March – April 10, 1984: ROMS MRG Results / ROMS HRG Results
DAB denotes distance above the bottom.

Station at DAB (m)	RMS Error (^{o}C)	Relative Error (-)	Model Mean (^{o}C)	Observed Mean (^{o}C)
16 at 3	2.16/3.16	0.68/0.77	7.16/8.16	5.01
16 at 8	2.24/3.12	0.66/0.75	7.29/8.17	5.06
16 at 11	2.22/2.98	0.65/0.72	7.38/8.13	5.17
17 at 3	2.19/2.99	0.85/0.89	7.66/8.48	5.51
23 at 8	0.81/0.81	0.24/0.16	7.19/6.59	6.43
33 at 11	0.38/1.16	0.04/0.16	6.74/6.91	6.71

5.4 Low Flow Simulation

To examine model performance under low flow conditions, the 10-24 September, 1984 period was simulated. Wind speed and direction and atmospheric pressure as produced by the Barnes (1973) interpolation at three hour intervals are compared with hourly observations and are of the same order RMSE as for the high flow period. The mean wind speeds , river flows, and boundary subtidal water levels are lower than during the high flow period and the offshore tidal boundary conditions become more dominant even for the upriver stations. Simulated water levels are contrasted with observations in Table 5.7. While the ROMS MRG RMSEs are reduced from those for the HRG due to an improvement in phase, at the times of peak amplitudes the HRG results correspond more closely to the observations at Trenton, NJ as shown in Figure 5.5. The difference in the mean water levels at the entrance to the Bay is order 10 cm and may be due to the effects of Sa and Ssa (see Table 5.1) with the MRG RMSEs lower than on the HRG.

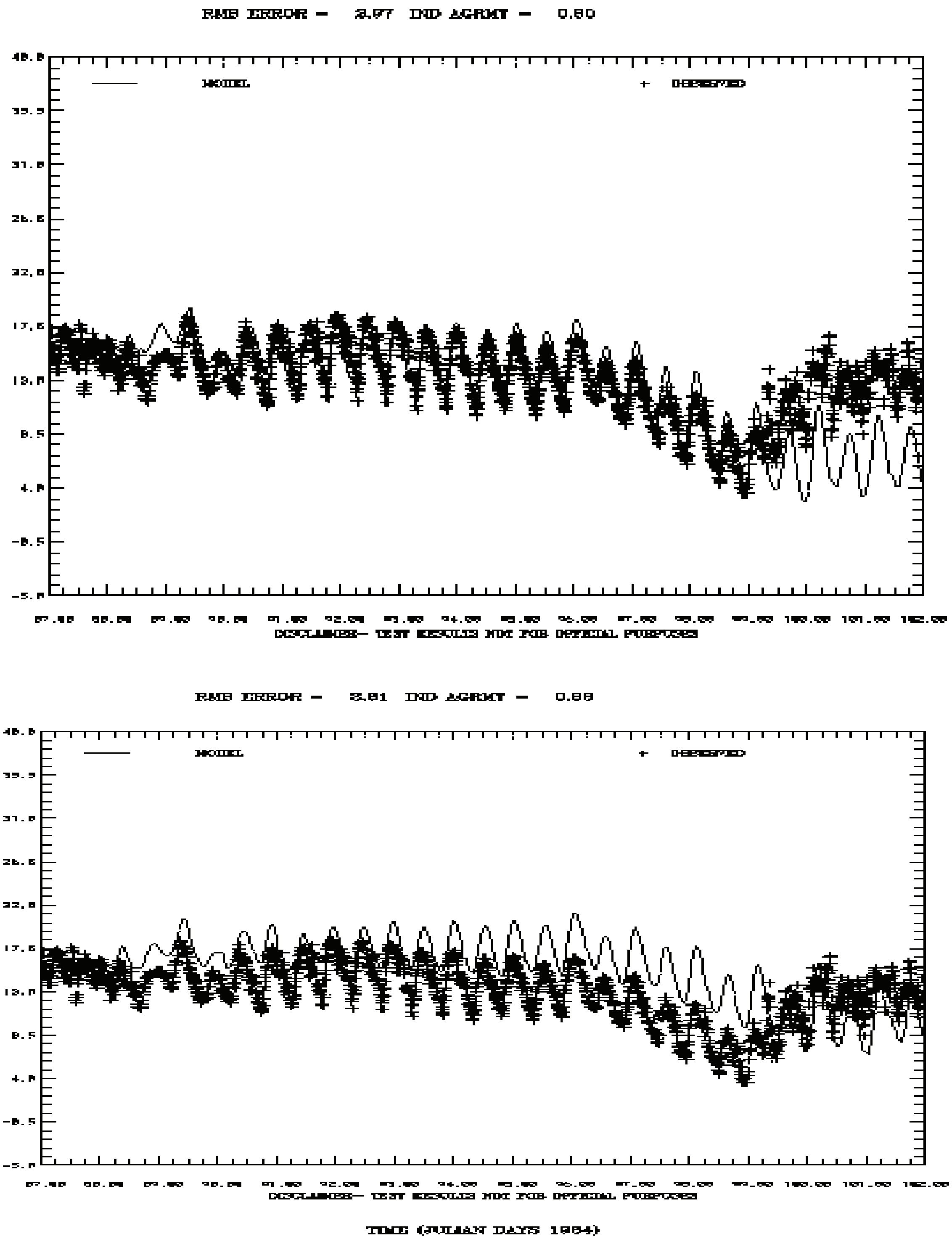


Figure 5.4. Simulated versus Observed (10 minute) Salinity at Station 33 at 11 m above the bottom. Top panel: ROMS MRG Hindcast. Bottom panel: ROMS HRG Hindcast Note observations are at 10-minute intervals.

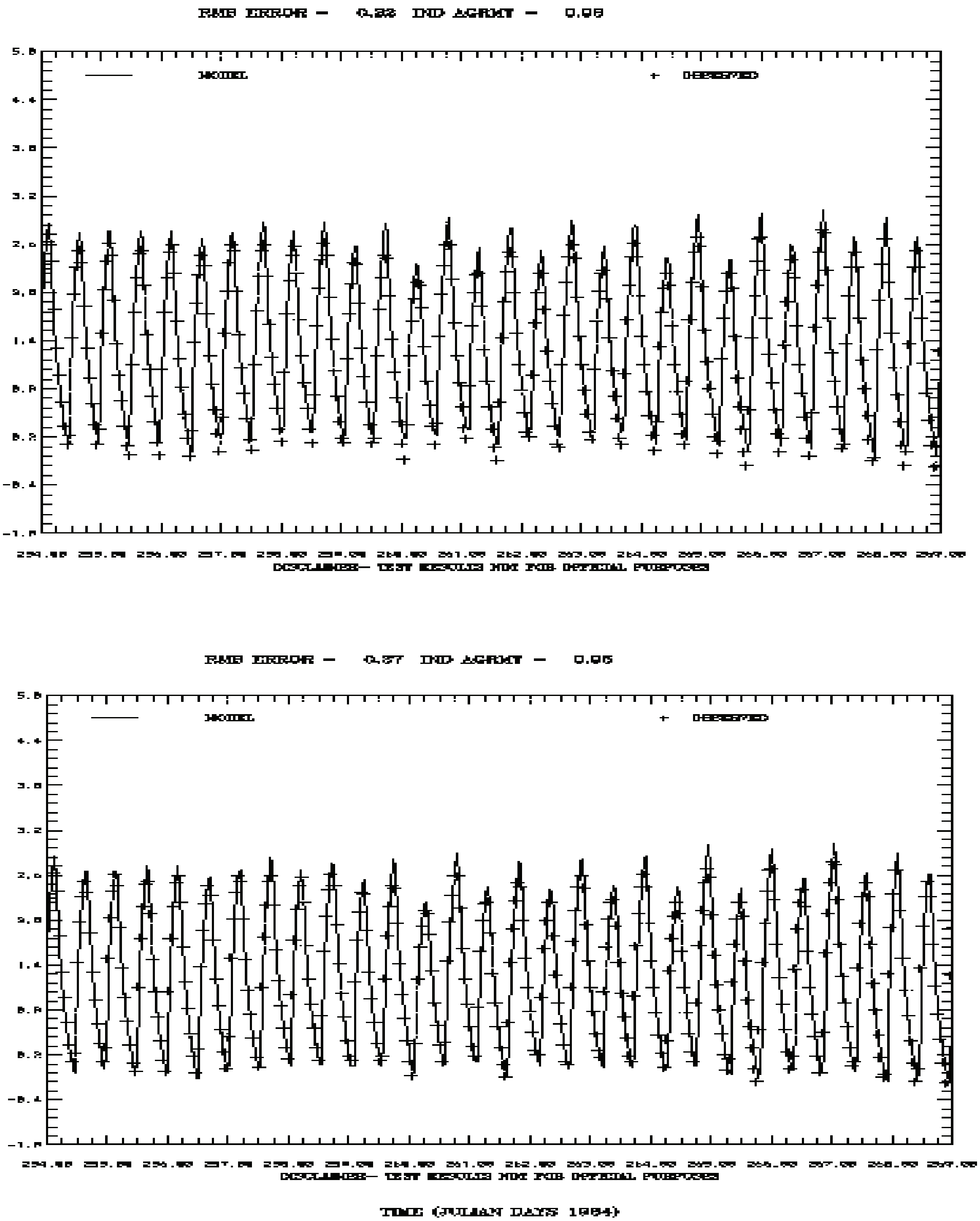


Figure 5.5. Low Flow Hindcast (10 – 24 September, 1984) Water Surface Elevation at Trenton, NJ. Top panel: ROMS MRG Hindcast. Bottom panel: ROMS HRG Hindcast. Observations are at one hour intervals.

Table 5.7. Water Surface Elevation-MLLW (m) Low Flow Hindcast
September 10-24, 1984: ROMS MRG Results/ ROMS HRG Results

Station	RMS Error (cm)	Relative Error (-)	Model Mean (cm)	Observed Mean (cm)
Lewes, DE	11/17	0.01/0.04	73/63	70
Cape May, NJ	14/19	0.02/0.04	82/71	79
Indian River, DE	14/16	0.04/0.06	50/39	47
Ocean City Pier, MD	6/19	0.01/0.07	58/52	61
Phila. Pier 11, PA	18/25	0.02/0.04	117/105	107
Trenton, NJ	22/37	0.02/0.05	136/124	131

In Tables 5.8 and 5.9, the current speed and direction comparisons are given. At Station 33 the current speed responses are reduced from those obtained for the high flow hindcast. The current speeds are slightly under-predicted at upriver Station 51. Current direction errors are comparable under both high and low flow conditions. In Table 5.10, the salinity response is compared with observations. A very favorable comparison for the ROMS HRG, particularly at Station 33 in the region of large horizontal salinity gradients is obtained with the ROMS HRG RMSEs lower at the river Stations 33 and 154 than those on the MRG. As shown in Table 5.11, the temperature responses for both grids are comparable, but with the mean temperatures over the shelf order 1-3 ^{o}C larger than the observations.

Table 5.8. Current Speed (cm/s) Revised Low Flow Hindcast
September 10-24, 1984: ROMS MRG Results/ ROMS HRG Results
Note DAB denotes distance above the bottom.

Station at DAB (m)	RMS Error (cm/s)	Relative Error (-)	Model Mean (cm/s)	Observed Mean (cm/s)
2 at 7	13.30/11.95	0.12/0.11	43.89/39.00	39.01
16 at 11	8.09/9.10	0.59/0.63	9.90/10.52	9.89
17 at 15	14.30/12.78	0.61/0.59	17.72/12.43	17.71
18 at 2	7.84/11.38	0.10/0.20	28.97/29.35	25.18
19 at 2	14.34/18.13	0.20/0.18	37.28/35.64	28.27
19 at 8	14.08/22.65	0.09/0.27	50.58/47.44	45.45
22 at 6	11.06/13.13	0.08/0.10	40.49/42.97	41.69
23 at 2	18.64/18.48	0.41/0.44	33.82/32.53	17.34
24 at 2	8.05/10.95	0.10/0.19	30.65/31.49	27.69
25 at 2	6.95/7.75	0.07/0.09	29.98/29.87	29.22
33 at 2	11.02/13.10	0.13/0.20	35.53/33.20	29.28
51 at 9	17.48/14.96	0.18/0.13	52.60/57.32	61.46
154 at 2	22.48/12.73	0.48/0.23	26.07/29.71	31.47

Table 5.9. Current Direction (^oT) Revised Low Flow Hindcast
September 10-24, 1984: ROMS MRG Results/ ROMS HRG Results
Note DAB denotes distance above the bottom. Current direction comparisons are only made for currents greater than 0.26 cm/s.

Station at DAB (m)	RMS Error (^oT)	Relative Error (-)	Model Mean (^oT)	Observed Mean (^oT)
2 at 7	8.36/8.31	0.00/0.00	223.77/232.74	212.66
16 at 11	104.56/121.72	0.39/0.51	142.69/139.75	217.85
17 at 15	108.20/90.96	0.44/0.53	165.46/190.02	230.55
18 at 2	7.98/12.40	0.00/0.01	225.93/226.27	238.79
19 at 2	18.88/16.10	0.01/0.01	229.55/234.91	257.01
19 at 8	22.63/23.59	0.02/0.02	231.13/238.18	247.18
22 at 6	10.01/27.70	0.00/0.03	231.15/222.89	231.98
23 at 2	5.87/19.88	0.00/0.01	238.76/226.89	269.80
24 at 2	45.53/45.84	0.06/0.06	240.97/225.74	245.13
25 at 2	119.44/117.30	0.87/0.87	107.40/107.5	184.53
33 at 2	6.37/17.12	0.00/0.01	227.65/224.94	226.26
51 at 9	18.16/30.13	0.01/0.03	191.47/194.09	194.25
154 at 2	53.68/14.87	0.12/0.01	161.13/173.16	187.41

Table 5.10. Salinity (PSU) Revised Low Flow Hindcast
September 10-24, 1984: ROMS MRG Results/ ROMS HRG Results
DAB denotes distance above the bottom.

Station at DAB (m)	RMS Error (PSU)	Relative Error (-)	Model Mean (PSU)	Observed Mean (PSU)
2 at 7	0.14/0.73	0.28/0.71	30.40/30.77	30.08
16 at 3	1.52/2.94	0.93/0.96	31.27/32.82	29.68
16 at 11	0.26/1.01	0.65/0.81	31.03/32.14	31.15
19 at 2	1.37/1.40	0.50/0.50	29.86/29.96	28.67
22 at 6	0.81/0.82	0.15/0.12	27.64/27.02	27.34
23 at 2	1.39/1.20	0.56/0.50	28.64/28.45	27.44
24 at 2	0.79/1.14	0.29/0.40	25.48/25.15	26.21
33 at 2	0.90/1.08	0.10/0.13	20.21/18.14	18.81
154 at 2	0.76/1.68	0.57/0.50	7.00/5.05	6.59

Table 5.11. Temperature (^oC) Revised Low Flow Hindcast
September 10-24, 1984: ROMS MRG Results/ ROMS HRG Results
DAB denotes distance above the bottom.

Station at DAB (m)	RMS Error (^oC)	Relative Error (-)	Model Mean (^oC)	Observed Mean (^oC)
2 at 7	1.57/2.82	0.92/0.95	21.99/24.11	21.04
16 at 3	2.67/0.81	0.74/0.55	17.82/21.21	20.87
16 at 11	1.22/2.97	0.56/0.67	21.93/23.89	20.93
19 at 2	2.38/3.56	0.92/0.95	23.41/24.40	20.67
19 at 8	2.43/3.60	0.91/0.95	23.42/24.40	20.62
22 at 6	3.13/3.33	0.92/0.92	24.13/24.41	20.75
23 at 2	2.88/3.25	0.72/0.74	24.04/24.42	21.20
24 at 2	2.93/3.28	0.83/0.85	24.16/24.54	20.63
33 at 2	2.07/2.01	0.91/0.91	24.38/24.23	22.40

5.5 Extended Hindcast March – September 1984

To further assess the ability of the ROMS HRG to replicate conditions in Delaware Bay a seven month hindcast was performed. Water level results were examined in 15 day increments to assess the variability of the skill as shown in Table 5.12. The range of RMSE over the fourteen 15 day periods decreases from 17 cm at Trenton, NJ to 7 cm at the Capes, indicating the influence of the flow variations in the Delaware River. Similar water level RMSEs were obtained for two 30-day simulations using the MRG. The percent of the RMSE to the mean tidal range at each station is given to assess the deviation from 10%, which is being considered as a supplemental water level skill assessment target to the formal targets outlined in NOS (1999) and in Hess et al. (2003). To meet this

Table 5.12. Seven Month ROMS HRG Hindcast March-September 1984 Water Level RMSE (cm) Summary. The analyses are for 15 days, thus there are two entries for each month. PMTR denotes the RMSE expressed as a percentage of the mean tide range. ROMS MRG 30-day simulation water level RMSE (cm) are denoted by * over 27 Mar – 25 Apr 1984 and + over 26 Aug – 24 Sep 1984.

Station	Mar	Apr	May	Jun	Jul	Aug	Sep	Seven Month RMSE	RMSE Range	PMRT
Trenton, NJ	33/26 29*	33/25	39/34	42/35	33/39	35/34 31+	28/39	34	17	13.7
Phila., PA	27/21 22*	27/21	30/24	32/28	31/32	25/26 24+	20/25	27	12	14.8
Lewes, DE	17/13 12*	15/11	18/13	17/15	15/17	18/16 17+	14/18	16	7	12.9
Cape May, NJ	21/14 16*	20/15	21/15	18/16	16/18	14/19 20+	15/20	17	7	11.4

supplemental skill assessment target, the RMSEs would need to be reduced at Trenton, NJ by 9 cm, at Phila, PA by 9 cm, at Lewes, DE by 4 cm, and at Cape May, NJ by 2 cm, respectively.

5.6 Tidal Analysis and Simulations

To further analyze the water level response, an estimate of the tidal error (TE) given in Table 5.13 was made by subtracting the 30 hour low pass filtered water level hindcast results from the hindcast total water levels. The tidal errors range from order 15 cm at the Capes to order 25 cm at the head of tide at Trenton, NJ. Based on these results, it is of benefit to further seek improvements in tide only simulations directly. Towards this end, three tidal simulations were performed using yearly average river flows. Wind, atmospheric pressure anomalies, and subtidal water levels were set to zero. However, salinity and temperature were initialized to observed non-uniform conditions and time and depth varying boundary conditions applied. Surface heat flux computations were made using the bulk flux formulation. For all three simulations at the C&D canal boundary the CLAMPED and M2REDUCED options were used for the water level and two-dimensional vertically integrated boundary velocities, respectively. Conditions varied along the southern and eastern open ocean boundaries for the water level and two-dimensional vertically integrated boundary velocities in each of the three simulations as shown in Table 5.1. RMSEs and relative errors are given in Table 5.13 for each of these three simulations. Simulation 2 exhibited the lowest errors at the entrance to Delaware Bay, but at the head of tide at Trenton, NJ, all the simulation results were similar as shown in Figure 5.6. Of interest is the behavior of the simulations at several grid cells one grid cell in along the open boundaries as indicated by the last seven OBC entries in Table 5.13. Simulation 2 exhibited water levels with the closest agreement to the boundary water level specification.

In Table 5.14, tidal current speed RMSEs and relative errors are considered. Tidally extracted current components are determined by subtracting the low pass filtered current component from the total current hindcast component. In general, RMSE and relative errors for all three tidal simulations are near the tidally extracted currents.

5.7 Summary and Additional Considerations

On the high resolution grid the C&D Canal and main navigation channel are well represented with the currents at Station 154 and in the upper river sections improved. For the high flow 15-day period, the ROMS MRG and HRG simulation results for water levels were very similar, while for the 15-day low flow period the ROMS MRG results were superior. For both 15-day periods, the ROMS MRG and HRG simulation results for Bay currents, salinity, and temperature were comparable. This version of the model, DBOFS Version 1.0, was ported to NCEP and run in semi-operational mode in early June 2009. Significant variations in water level RMSEs at Trenton, NJ were exhibited during the seven month ROMS HRG hindcast using DBOFS Version 1.0 from March through September 1984 and indicated additional modification of the seven bottom roughness zones used by Walters (1992a; 1992b) should be pursued. In Chapter 6, efforts are first described to adjust the seven bottom roughness zone values under astronomical tide conditions.

Table 5.13. Water Surface Elevation-MSL (m)
Tidal Extraction from Hindcast and Tidal Simulations 1-3: April 1984

Station	RMS Error (cm)				Relative Error (-)			
	TE	S1	S2	S3	TE	S1	S2	S3
Marcus Hook, PA	24	21	10	16	0.04	0.04	0.01	0.02
Cape May, NJ	15	13	7	12	0.02	0.01	0.00	0.01
Ship John Shoal, NJ	20	17	8	15	0.03	0.02	0.00	0.01
Tacony Bridge, NJ	21	17	12	16	0.02	0.02	0.01	0.01
Burlington, NJ	21	18	18	19	0.02	0.01	0.01	0.02
Phila. USCG, PA	20	17	8	14	0.03	0.02	0.00	0.01
Phila. Pier 11, PA	18	13	16	16	0.02	0.01	0.02	0.02
Delaware City, DE	18	14	8	13	0.03	0.02	0.01	0.01
Reedy Point, DE	17	13	8	12	0.02	0.01	0.01	0.01
Brandywine Shoal, DE	17	15	7	13	0.03	0.02	0.00	0.01
Lewes, DE	13	11	6	11	0.02	0.01	0.00	0.01
Indian River, DE	15	12	15	18	0.05	0.03	0.05	0.06
Ocean City Pier, MD	14	14	5	10	0.04	0.04	0.00	0.02
Chesapeake City, MD	14	13	10	12	0.04	0.04	0.02	0.03
Trenton, NJ	24	19	21	22	0.02	0.01	0.02	0.02
W-OBC	n/a	3	2	2	n/a	0.00	0.00	0.00
S-OBC 1	n/a	18	2	10	n/a	0.08	0.00	0.02
S-OBC2	n/a	12	2	8	n/a	0.04	0.00	0.01
S-OBC3	n/a	9	1	8	n/a	0.02	0.00	0.01
S-OBC4/E-OBC1	n/a	8	2	7	n/a	0.02	0.00	0.01
E-OBC2	n/a	8	2	7	n/a	0.01	0.00	0.01
E-OBC3	n/a	9	3	9	n/a	0.01	0.00	0.01

Table 5.14. Current Speed (cm/s)
Tidal Extraction from Hindcast and Tidal Simulations 1-3: April 1984
DAB denotes distance above the bottom.

Station DAB (m)	RMS Error (cm/s)				Relative Error (-)			
	TE	S1	S2	S3	TE	S1	S2	S3
2 at 7	11.51	11.60	9.38	13.39	0.01	0.02	0.01	0.02
3 at 5	16.62	15.58	9.92	16.08	0.02	0.02	0.01	0.02
5 at 5	20.03	17.99	7.19	15.05	0.03	0.02	0.00	0.01
11 at 3	4.49	3.64	5.87	5.31	0.03	0.02	0.04	0.04
16 at 8	6.01	6.37	3.69	6.15	0.52	0.57	0.21	0.38
17 at 15	5.87	9.60	8.01	8.77	0.12	0.25	0.20	0.17
18 at 2	9.45	8.15	13.33	11.59	0.03	0.02	0.05	0.04
19 at 8	15.40	13.10	9.04	15.71	0.02	0.02	0.01	0.02
21 at 2	11.08	9.88	15.56	14.94	0.03	0.03	0.06	0.06
22 at 6	14.67	11.86	18.21	14.57	0.02	0.02	0.05	0.02
23 at 8	11.78	9.89	8.41	12.13	0.02	0.01	0.01	0.02
24 at 2	11.93	10.68	16.37	14.29	0.04	0.03	0.07	0.05
25 at 2	35.27	34.91	37.40	37.21	0.82	0.82	0.83	0.82
33 at 11m	18.25	14.01	21.13	18.47	0.02	0.01	0.04	0.02
51 at 9	30.81	26.89	26.80	29.51	0.11	0.09	0.10	0.10
154 at 8	50.05	47.67	34.87	39.77	0.26	0.25	0.14	0.17

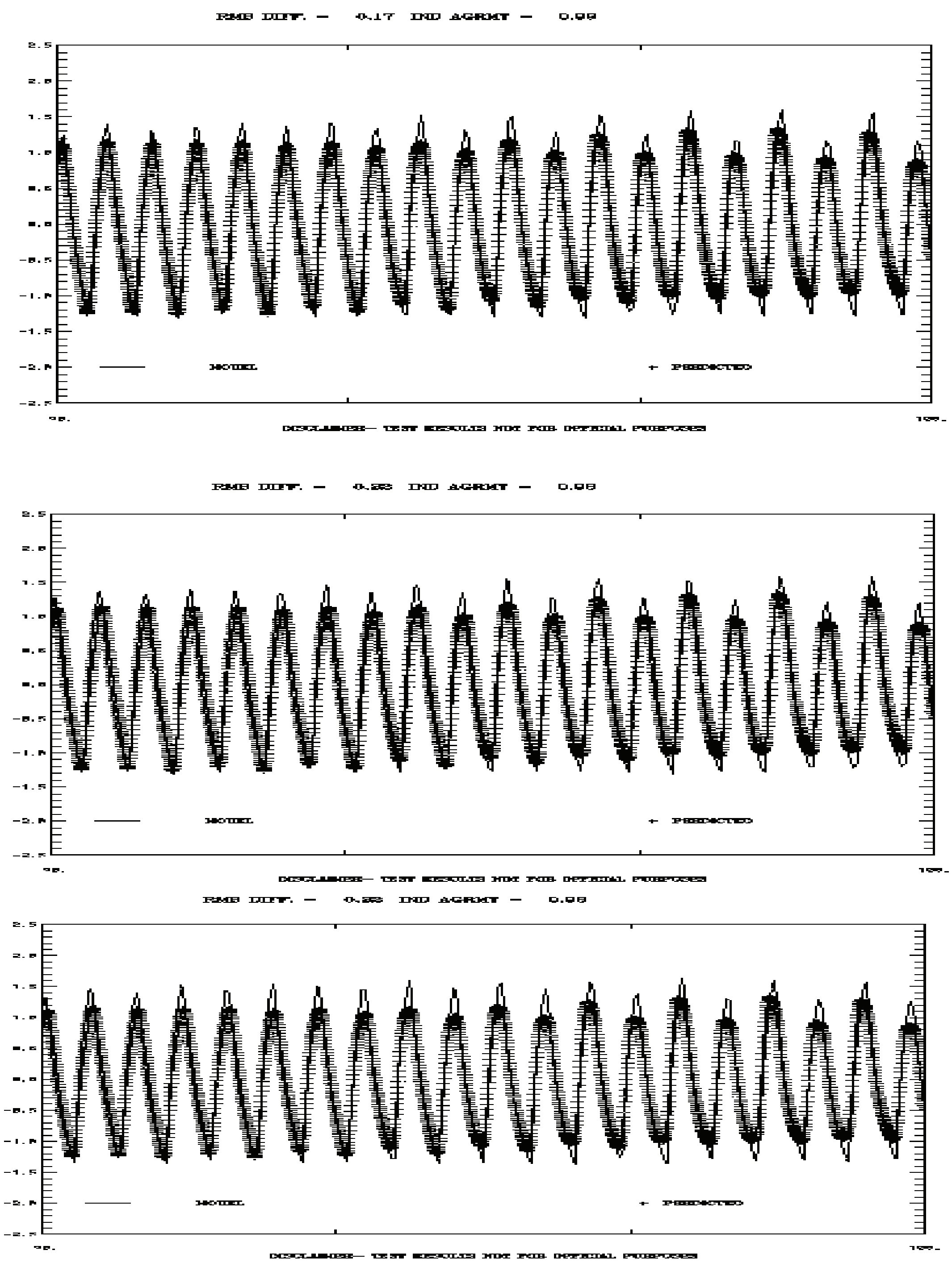


Figure 5.6. Tidal Water Level (m-demeaned) at Trenton, NJ for Julian Days 90-100, 1984. Top, Middle, and Bottom Panel: Simulation 1, Simulation 2 and Simulation 3. Simulations 1 and 2 employ external and Simulation 3 internal to ROMS tidal water level specification. Note predictions are at 6-minute intervals.

6. ROMS HIGH RESOLUTION GRID EXTENDED HINDCASTS

Prior to performing the 13 month extended hindcast, as suggested in Chapter 5, improvements were sought in the tidal response. The following approach was used. The simulation 2 CPPDEF options in Table 5.1 of Chapter 5 (FSCLAMPED and M2REDUCED) were used on the open ocean boundaries. To further adjust the offshore tidal harmonic constants, harmonic analyses of simulated water levels were performed at all water level stations and compared to NOS accepted harmonic constants. Before performing the comparison, coastal water level time series were reconstructed from the 37 accepted NOS tidal harmonics. Next, the reconstructed time series were harmonically analyzed to see how closely the tidal constituents could be recovered. Once it was determined, that the tidal constituents could be recovered, eighteen one-month tidal simulation were performed in which the off shore boundary tidal water level constituents were varied along with the bottom roughness zone values to seek to optimize the tidal response. Upon completion of the tidal response optimization, an extended 13-month tidal simulation was performed and evaluated, followed by a 13-month hindcast simulation both over the period from March 1984 through March 1985.

6.1 29-day Harmonic Analysis Considerations

One notes the following issues associated with this process.

1. When one predicts a water level series from the harmonic constants, the constituent equilibrium arguments, $[(V_o+u)_i]^p$, i=1,37, are based on 1 January hour zero of the year of the prediction, while the constituent node factors, $[f_i]^p$, i=1,37, are based on the middle of the year of prediction.

2. When one performs a harmonic analysis from the predicted water level series, the constituent equilibrium arguments, $[(V_o+u)_i]^a$, i=1,37, are based on the start month, day, and hour of the series, while the constituent reduction factors, $[F_i]^a$, i=1,37, are based on the middle of the prediction period.

3. Note $F_i=1/f_i$ and thus the reduction factors are the reciprocals of the node factors, which vary slowly over the year and are taken equal to the mid-year value.

4. Therefore the two sets of node factors are nearly equal. That is $[f_i]^p$, i=1,37 ~ $[f_i]^a$, i=1,37. However, the two set of equilibrium arguments are significantly different, unless the prediction period starts at the beginning of the year. That is $[(V_o+u)_i]^p$, i=1,37 ≠ $[(V_o+u)_i]^a$, i=1,37.

The above points are illustrated by:

First, a prediction of water level series from the 37 NOS accepted harmonic constituents at Ocean City Pier, MD, Chesapeake City, MD, Cape May, NJ, and Lewes, DE starting on 27 March 1984 over a period of 33 days.

Second, the performance of a 29-day harmonic analysis of the water level series is conducted with a comparison of the 24 tidal constituents derived from the analysis shown in the corresponding Tables 6.1-6.4. In Table 6.5, a NOS accepted constituent amplitude weighted ratio of the 29-day harmonic analysis amplitude to the NOS accepted amplitude is given as the weighted gain. The weighted phase in Table 6.5 is the difference in phase in hours weighted analogously, while the estimated RMS error is based on the method described by Hess (1994).

Table 6.1. Water Level Harmonic Constant Comparison at Ocean City Pier, MD.

Constituent	Model Amplitude (m)		NOS Accepted		Difference	
	Amp (m)	Phase (o)	Amp (m)	Phase (o)	Amp (m)	Phase (o)
M(2)	0.4990	215.70	0.5010	215.90	-.0020	-0.20
S(2)	0.0940	233.20	0.0970	234.60	-.0030	-1.40
N(2)	0.1220	199.70	0.1170	199.90	0.0050	-0.20
K(1)	0.0760	113.60	0.0880	119.10	-.0120	-5.50
M(4)	0.0070	293.10	0.0070	291.60	0.0000	1.50
O(1)	0.0870	115.60	0.0850	115.50	0.0020	0.10
M(6)	0.0140	236.40	0.0140	236.50	0.0000	-0.10
S(4)	0.0040	269.20	0.0030	271.30	0.0010	-2.10
NU(2)	0.0240	201.90	0.0230	199.00	0.0010	2.90
Q(1)	0.0170	116.50	0.0160	105.00	0.0010	11.50
P(1)	0.0250	113.80	0.0310	117.90	-.0060	-4.10
L(2)	0.0170	194.30	0.0140	231.80	0.0030	-37.50
K(2)	0.0260	234.60	0.0250	232.90	0.0010	1.70

Table 6.2. Water Level Harmonic Constant Comparison at Chesapeake City, MD.

Constituent	Model Amplitude (m)		NOS Accepted		Difference	
	Amp (m)	Phase (o)	Amp (m)	Phase (o)	Amp (m)	Phase (o)
M(2)	0.4320	308.60	0.4340	309.00	0.4340	309.00
S(2)	0.0650	344.40	0.0590	341.50	0.0060	2.90
N(2)	.0810	290.30	0.0750	294.00	0.0060	-3.70
K(1)	0.0180	271.60	0.0320	268.90	-.0140	2.70
M(4)	0.0260	208.70	0.0260	208.80	0.0000	-0.10
O(1)	0.0150	286.20	0.0140	292.70	0.0010	-6.50
M(6)	0.0090	25.60	0.0090	26.50	0.0000	-0.90
S(4)	0.0020	261.80	0.0020	261.60	0.0000	0.20
NU(2)	0.0160	292.80	0.0210	285.50	-.0050	7.30
Q(1)	0.0030	293.50	0.0090	274.10	-.0060	19.40
P(1)	0.0060	272.70	0.0100	256.20	-.0040	16.50
L(2)	0.0120	284.90	0.0300	303.00	-.0180	-18.10
K(2)	0.0180	347.30	0.0180	340.50	0.0000	6.80

Table 6.3. Water Level Harmonic Constant Comparison at Cape May, NJ.

Constituent	Model Amplitude (m)		NOS Accepted		Difference	
	Amp (m)	Phase (o)	Amp (m)	Phase (o)	Amp (m)	Phase (o)
M(2)	0.7120	243.40	0.7140	243.60	-.0020	-0.20
S(2)	0.1260	265.40	0.1250	265.30	0.0010	0.10
N(2)	0.1650	227.10	0.1590	227.50	0.0060	-0.40
K(1)	0.1650	227.10	0.1590	227.50	0.0060	-0.40
M(4)	0.0100	168.40	0.0100	171.10	0.0000	-2.70
O(1)	0.0860	116.50	0.0840	115.80	0.0020	0.70
M(6)	0.0080	302.50	0.0080	306.00	0.0000	-3.50
S(4)	0.0010	280.80	0.0000	0.00	0.0010	-79.20
NU(2)	0.0320	229.30	0.0320	224.80	0.0000	4.50
Q(1)	0.0170	115.30	0.0130	117.10	0.0040	-1.80
P(1)	0.0320	118.90	0.0360	124.40	-.0040	-5.50
L(2)	0.0240	221.70	0.0370	256.20	-.0130	-34.50
K(2)	0.0340	267.20	0.0330	264.00	0.0010	3.20

Table 6.4. Water Level Harmonic Constant Comparison at Lewes, DE.

Constituent	Model Amplitude (m)		NOS Accepted		Difference	
	Amp (m)	Phase (o)	Amp (m)	Phase (o)	Amp (m)	Phase (o)
M(2)	0.6140	245.90	0.6160	246.10	-.0020	-0.20
S(2)	0.1110	264.40	0.1080	266.80	0.0030	-2.40
N(2)	0.1410	228.00	0.1340	228.40	0.0070	-0.40
K(1)	0.0950	122.30	0.1030	126.40	-.0080	-4.10
M(4)	0.0120	255.80	0.0130	256.40	-.0010	-0.60
O(1)	0.0840	119.50	0.0830	118.80	0.0010	0.70
M(6)	0.0060	271.40	0.0060	274.70	0.0000	-3.30
S(4)	0.0010	267.80	0.0000	0.00	0.0010	-92.20
NU(2)	0.0270	230.40	0.0280	228.80	-.0010	1.60
Q(1)	0.0160	118.10	0.0130	115.90	0.0030	2.20
P(1)	0.0310	122.10	0.0340	124.30	-.0030	-2.20
L(2)	0.0200	222.50	0.0200	260.30	0.0000	-37.80
K(2)	0.0300	265.90	0.0300	261.40	0.0000	4.50

Table 6.5. Open Boundary Condition Tidal Error Summary

Station	Weighted Gain (-)	Weighted Phase (hrs)	Estimated RMSE (cm)
Ocean City Pier, MD	0.99	-0.05	1
Chesapeake City, MD	0.91	0.07	2
Cape May, NJ	0.99	-0.07	2
Lewes, DE	1.00	-0.06	2

One important detail about the 29-day harmonic analysis program is that it only calculates 10 constituents directly by Fourier series from the input 29-day time series. These constituents are M_2, S_2, N_2, K_1, O_1, and the overtides M_4, M_6, S_4, S_6, and M_8. The program next infers the 14 additional constituents which cannot be resolved with only 29 days of data by redistributing the energy in the 10 calculated constituents according to the standard ratios in the astronomical tide potential driving force as discussed by Shureman (1958) on page 79. The input prediction has 37 accepted constituents which were obtained by least squares analysis of several full years of data, so the ratios of the small constituents to the large ones are determined by the actual data.

6.2 April 1984 Tidal Simulation Validation

To obtain accurate water levels from the coast to the head of tide, it was necessary to adjust: 1) the amplitude and phase of the M_2, N_2, and S_2 constituents , 2) the bottom friction coefficients in the seven zones used by Walters (1992a; 1992b), and 3) the bathymetric cutoff depths. The simulations performed were for the 30 days of April 1984 and are summarized in Table 6.6. The boundary harmonic constants sets are given in Table 6.7, the bottom friction sets in Table 6.8, and the bathymetric sets are given in Table 6.9. The associated water level station M_2 amplitude and phase rms errors for the 18 simulations given in Table 6.6 are shown in Table 6.10. Note simulations 1-4 used free slip lateral boundary conditions, while the remaining simulations used a lateral boundary condition half-way between free slip and no slip as used in POM. No difference in results was obtained using the different lateral boundary conditions as noted in the comparison between simulations 4 and 5. Simulation 1 corresponds to DBOFS Version 1.0 while simulation 18 corresponds to DBOFS Version 1.1 as implemented at NCEP. DBOFS Version 1.0 and Version 1.1 results are given in Tables 6.11 and 6.12, respectively. One notes the significant improvement in water surface elevation RMSE at the Entrance to the Bay of order 10 cm (also see Figure 6.1), at Philadelphia, PA of order 12 cm (also see Figure 6.2), and at the head of tide at Trenton, NJ of order 11 cm (also see Figure 6.3). Principal component direction current strength RMSEs are generally less than 26 cm/s (0.5 kt) at all stations and where they exceed this value, this may be due to the discrepancy in the principal component directions exhibited in the model versus the data. In these comparisons, the model currents are resolved along the measured principal component direction. DBOFS Version 1.1 simulated currents are shown for JD 100-110, 1984 as one proceeds from the shelf at Stations 17 and 2 in Figures 6.4 and 6.5 through the Bay from Stations 19, 23, and 33 in Figures 6.6 – 6.8 and into the river at Station 154 and 51 in Figures 6.9 and 6.10, respectively.

Table 6.6. Tidal Validation Simulation Summary
Note Expmm.comf and Expmm.1.o use the Flather (1976) and Chapman (1985) boundary conditions, while the remaining simulations use the clamped and reduced boundary conditions.

Simulation No. and Name	Date Performed	Bathymetric Set	Bottom Friction Set	HA Set
1 Expmm.comf	11/16/2009	1	1	0
2 Expmm.1.o	10/23/2009	1	1	0
3 Expmm.1	10/29/2009	2	1	0
4 Expmm.11	10/30/2009	2	1	1
5 Expmm.111	11/6/2009	2	1	1
6 Expmm.1111	11/9/2009	2	2	2
7 Expmm.11111	11/10/2009	2	3	2
8 Expmm.1.6	11/10/2009	2	4	2
9 Expmm.1.7	11/10/2009	2	5	2
10 Expmm.1.8	11/19/2009	2	6	2
11 Expmm.1.9	11/19/2009	2	7	2
12 Expmm.1.10	11/20/2009	2	8	3
13 Expmm.1.11	11/23/2009	2	9	3
14 Expmm.1.12	11/23/2009	2	10	3
15 Expmm.1.13	11/23/2009	2	11	3
16 Expmm.1.14	11/24/2009	2	12	4
17 Expmm.1.15	11/25/2009	2	12	4
18 Expmm.1.16	11/30/2009	3	12	4

Table 6.7. Water Level Open Boundary Major Harmonic Constituent Sets
853-4720 at Atlantic City, NJ

Set No.	M2 Amp (m)	M2 Phase (o)	S2 Amp (m)	S2 Phase (o)	N2 Amp (m)	N2 Phase (o)
0	0.594	210.4	0.116	227.8	0.141	193.7
1	0.494	210.4	0.136	218.8	0.210	152.7
2	0.524	210.4	0.116	227.8	0.201	200.0
3	0.524	210.4	0.116	227.8	0.201	200.0
4	0.524	215.4	0.116	227.8	0.171	200.0

Table 6.7. (Cont.) Water Level Open Boundary Major Harmonic Constituent Sets
857-0280 at Ocean City Pier, MD

Set No.	M2 Amp (m)	M2 Phase (o)	S2 Amp (m)	S2 Phase (o)	N2 Amp (m)	N2 Phase (o)
0	0.501	215.9	0.097	234.6	0.117	199.9
1	0.495	210.6	0.117	213.5	0.177	143.8
2	0.470	215.9	0.097	234.6	0.170	179.0
3	0.470	215.9	0.097	234.6	0.170	179.0
4	0.470	220.9	0.097	234.6	0.140	179.0

Table 6.7. (Cont.) Water Level Open Boundary Major Harmonic Constituent Sets 857-3927 at Chesapeake City, MD

Set No.	M2 Amp (m)	M2 Phase (o)	S2 Amp (m)	S2 Phase (o)	N2 Amp (m)	N2 Phase (o)
0	0.434	309.0	0.059	341.5	0.075	294.0
1	0.314	296.0	0.049	328.5	0.065	275.0
2	0.332	303.0	0.049	335.5	0.075	294.0
3	0.332	303.0	0.049	335.5	0.055	284.0
4	0.332	303.0	0.049	335.5	0.055	284.0

Table 6.8. Bottom Friction Coefficient Sets.

Zone No.	Description	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6
1	OB to Bay Entrance	0.005	0.005	0.005	0.005	0.005	0.005
2	Bay Entrance to Ship John Shoal	0.007	0.007	0.007	0.007	0.007	0.010
3	Ship John Shoal to Station 33	0.005	0.005	0.005	0.005	0.005	0.014
4	Station 33 to Station 154	0.009	0.009	0.009	0.009	0.009	0.018
5	Station 154 to Station 51	0.010	0.010	0.010	0.010	0.010	0.020
6	Station 51 to Station 52	0.011	0.012	0.015	0.025	0.045	0.036
7	Station 52 to TTN	0.012	0.013	0.016	0.066	0.066	0.039

Table 6.8. (Cont.) Bottom Friction Coefficient Sets.

Zone No.	Description	Set 7	Set 8	Set 9	Set 10	Set 11	Set 12
1	OB to Bay Entrance	0.005	0.005	0.005	0.005	0.005	0.005
2	Bay Entrance to Ship John Shoal	0.010-0.014	0.010	0.010	0.010	0.010	0.010
3	Ship John Shoal to Station 33	0.014-0.018	0.012	0.012	0.012	0.010	0.012
4	Station 33 to Station 154	0.018-0.020	0.014	0.014	0.014	0.010-0.014	0.012
5	Station 154 to Station 51	0.020-0.022	0.016	0.016	0.016	0.014-0.016	0.012
6	Station 51 to Station 52	0.022-0.028	0.025	0.020	0.018	0.016-0.019	0.014
7	Station 52 to TTN	0.028-0.036	0.028	0.025	0.020	0.019-0.022	0.016

Table 6.9. Bathymetric Sets

Set No.	Free Surface Open Ocean Boundary Condition	C&D Canal River Entrance Adjustment	Shelf Cutoff Depth (m)	Bay Cutoff Depth (m)	River Cutoff Depth (m)
1	Chapman	No	300	5	5
2	Clamped	Yes	130	5	5
3	Clamped	Yes	130	5	2

Table 6.10. M_2 Tidal Constituent Amplitude (cm) and Phase (o) Errors.

Station	Sim. 1 Amp (cm)	Sim. 1 Phase (o)	Sim. 2 Amp (cm)	Sim. 2 Phase (o)	Sim. 3 Amp (cm)	Sim. 3 Phase (o)	Sim. 4 Amp (cm)	Sim. 4 Phase (o)
Ocean City Pier, MD	4.0	6.7	2.9	0.3	2.9	0.3	-2.4	-2.8
Chesapeake City, MD	9.8	8.0	10.2	5.9	10.2	5.8	0.8	2.3
Lewes, DE	8.9	3.1	6.7	-2.8	6.7	-2.8	0.6	-4.1
Cape May, NJ	9.2	3.4	6.7	-2.6	6.7	-2.6	0.1	-4.1
Brandywine Shoal, DE	10.9	4.7	8.5	-1.4	8.5	-1.4	1.8	-2.9
Ship John Shoal, DE	14.0	0.7	11.4	-5.9	11.4	-5.9	4.4	-7.8
Reedy Point, DE	10.0	-2.2	7.8	-8.7	7.7	-8.6	1.9	-10.6
Delaware City, DE	9.5	-1.5	7.7	-7.9	7.6	-7.9	1.8	-9.9
Marcus Hook, PA	2.7	3.2	1.3	-3.4	1.3	-3.4	-3.8	-5.3
Phila. USCG, PA	10.4	-3.8	9.0	-10.6	9.0	-10.6	3.5	-12.6
Phila. Pier 11, PA	13.7	-10.8	12.4	-17.7	12.4	-17.7	6.8	-19.7
Tacony Bridge, NJ	15.6	-6.7	14.2	-13.7	14.2	-13.7	8.2	-15.7
Burlington, PA	17.7	-11.1	16.1	-18.1	16.1	-18.1	9.3	-20.3
Trenton, NJ	17.2	-12.7	15.2	-19.8	15.2	-19.8	8.0	-22.0

Table 6.10. (Cont.) M_2 Tidal Constituent Amplitude (cm) and Phase (o) Errors.

Station	Sim. 5 Amp (cm)	Sim. 5 Phase (o)	Sim. 6 Amp (cm)	Sim. 6 Phase (o)	Sim. 7 Amp (cm)	Sim. 7 Phase (o)	Sim. 8 Amp (cm)	Sim. 8 Phase (o)
Ocean City Pier, MD	-2.4	-2.8	-2.4	-2.8	-2.4	-2.8	-2.4	-2.8
Chesapeake City, MD	0.8	2.3	1.2	2.2	1.3	2.2	1.6	2.6
Lewes, DE	0.6	-4.1	0.3	-4.2	0.3	-4.2	0.6	-4.1
Cape May, NJ	0.1	-4.1	0.8	-4.2	0.7	-4.1	0.2	-4.1
Brandywine Shoal, DE	1.8	-2.9	2.1	-2.9	2.0	-2.9	1.9	-2.8
Ship John Shoal, DE	4.4	-7.8	5.0	-8.0	5.0	-7.8	4.9	-7.3
Reedy Point, DE	1.9	-10.6	2.9	-10.9	3.5	-10.7	5.0	-10.0
Delaware City, DE	1.8	-9.9	2.9	-10.2	3.7	-10.1	5.6	-9.6
Marcus Hook, PA	-3.8	-5.3	-2.8	-6.4	-1.9	-7.4	1.1	-9.6

Phila. USCG, PA	3.5	-12.6	3.3	-12.6	1.9	-12.3	-0.9	-13.6
Phila. Pier 11, PA	6.8	-19.7	6.5	-19.7	4.9	-19.3	1.7	-20.5

Table 6.10. (Cont.) M_2 Tidal Constituent Amplitude (cm) and Phase (o) Errors.

Station	Sim. 5		Sim. 6		Sim. 7		Sim. 8	
	Amp (cm)	Phase (o)	Amp (cm)	Phase (o)	Amp (cm)	Phase (o)	Amp (cm)	Phase (o)
Tacony Bridge, NJ	8.2	-15.7	7.8	-15.6	5.8	-14.7	-0.2	-13.6
Burlington, PA	9.3	-20.3	8.9	-19.9	6.4	-18.5	-2.1	-13.1
Trenton, NJ	8.0	-22.0	7.6	-21.5	4.9	-19.9	-4.9	-12.4

Table 6.10. (Cont.) M_2 Tidal Constituent Amplitude (cm) and Phase (o) Errors.

Station	Sim. 9		Sim. 10		Sim. 11		Sim. 12	
	Amp (cm)	Phase (o)	Amp (cm)	Phase (o)	Amp (cm)	Phase (o)	Amp (cm)	Phase (o)
Ocean City Pier, MD	-2.4	-2.8	-2.3	-2.9	-2.3	-2.9	-2.4	2.1
Chesapeake City, MD	1.8	2.8	-0.2	3.9	-0.8	3.9	-0.3	5.7
Lewes, DE	0.5	-4.0	0.4	-5.4	-0.6	-5.9	0.3	-0.5
Cape May, NJ	0.1	-4.0	-0.7	-4.7	0.4	-6.3	-0.8	0.3
Brandywine Shoal, DE	1.8	-2.7	0.7	-3.2	0.4	-4.6	0.5	1.7
Ship John Shoal, DE	4.9	-7.0	0.8	-5.8	-1.9	-4.9	0.3	-0.7
Reedy Point, DE	6.0	-9.8	-3.3	-7.6	-5.5	-7.3	-2.2	-3.3
Delaware City, DE	6.9	-9.4	-3.4	-6.9	-5.7	-6.6	-2.3	-2.6
Marcus Hook, PA	2.7	-11.2	-12.3	-3.8	-15.2	-1.4	-10.1	0.7
Phila. USCG, PA	-4.3	-12.1	-13.6	-6.6	-13.2	-6.5	-9.2	-3.2
Phila. Pier 11, PA	-1.9	-18.7	-10.9	-13.5	-10.4	-13.5	-6.4	-10.2
Tacony Bridge, NJ	-4.1	-11.3	-11.9	-7.8	-10.9	-8.5	-6.8	-4.9
Burlington, PA	-6.2	-11.5	-13.6	-10.5	-12.3	-11.8	-7.9	-8.1
Trenton, NJ	-9.3	-11.1	-17.0	-11.3	-15.5	-12.8	-10.7	-9.1

Table 6.10. (Cont.) M_2 Tidal Constituent Amplitude (cm) and Phase (o) Errors.

Station	Sim. 13		Sim. 14		Sim. 15		Sim. 16	
	Amp (cm)	Phase (o)	Amp (cm)	Phase (o)	Amp (cm)	Phase (o)	Amp (cm)	Phase (o)
Ocean City Pier, MD	-2.4	2.1	-2.4	2.1	-2.4	2.1	-2.3	2.0
Chesapeake City, MD	-0.4	5.5	-0.4	5.4	-0.3	5.5	-0.6	5.1
Lewes, DE	0.3	-0.4	0.3	-0.5	0.5	-0.5	0.3	-0.6
Cape May, NJ	-0.8	0.3	-0.7	0.2	-0.4	-0.2	-0.8	0.1
Brandywine Shoal, DE	0.5	1.8	0.5	1.7	0.8	1.4	0.4	1.5
Ship John Shoal, DE	0.3	-0.7	0.4	-0.9	0.9	-1.3	-0.2	-0.9
Reedy Point, DE	-2.6	-3.4	-2.8	-3.6	-2.6	-4.0	-3.0	-3.5
Delaware City, DE	-2.8	-2.6	-3.1	-2.8	-2.9	-3.1	-2.9	-2.8

Marcus Hook, PA	-10.8	1.6	-11.3	2.0	-11.1	1.9	-8.7	1.5
Phila. USCG, PA	-8.1	-3.5	-7.6	-3.5	-7.1	-4.0	-3.3	-4.9

Table 6.10. (Cont.) M_2 Tidal Constituent Amplitude (cm) and Phase (o) Errors.

Station	Sim. 13 Amp (cm)	Sim. 13 Phase (o)	Sim. 14 Amp (cm)	Sim. 14 Phase (o)	Sim. 15 Amp (cm)	Sim. 15 Phase (o)	Sim. 16 Amp (cm)	Sim. 16 Phase (o)
Phila. Pier 11, PA	-5.3	-10.5	-4.6	-10.5	-4.1	11.1	-0.2	-12.0
Tacony Bridge, NJ	-5.4	-5.7	-4.3	-6.1	-3.9	-6.6	0.6	-7.9
Burlington, PA	-6.1	-9.0	-4.8	-10.1	-4.3	-10.5	0.8	-12.1
Trenton, NJ	-8.8	-10.1	-7.3	-11.5	-6.8	-11.8	-1.3	-13.7

Table 6.10. (Cont.) M_2 Tidal Constituent Amplitude (cm) and Phase (o) Errors.

Station	Sim. 17 Amp (cm)	Sim. 17 Phase (o)	Sim. 18 Amp (cm)	Sim. 18 Phase (o)
Ocean City Pier, MD	-2.3	1.8	-2.3	2.0
Chesapeake City, MD	1.0	11.1	-0.5	5.1
Lewes, DE	-0.1	-1.9	0.3	-0.6
Cape May, NJ	-1.2	-0.8	-0.8	0.1
Brandywine Shoal, DE	-0.2	0.7	0.4	1.6
Ship John Shoal, DE	-2.8	2.3	-0.2	-0.8
Reedy Point, DE	-6.0	0.9	-2.5	-3.4
Delaware City, DE	-6.8	2.3	-2.3	-2.7
Marcus Hook, PA	-15.0	9.0	-8.1	0.6
Phila. USCG, PA	-10.8	5.1	-4.0	-5.4
Phila. Pier 11, PA	-7.9	- 2.1	-1.0	-12.5
Tacony Bridge, NJ	-7.5	2.3	-0.5	-7.4
Burlington, PA	-7.9	-0.9	-0.3	-9.9
Trenton, NJ	-10.5	-1.3	-2.2	-10.0

Table 6.11. DBOFS Version 1.0 and Version 1.1 April 1984 Tidal Simulation Results: Water Surface Elevation.

Station	RMSE (m) Version 1.0	RMSE (m) Version 1.1	Relative Error (-) Version 1.0	Relative Error (-) Version 1.1
Marcus Hook, PA	13	10	0.01	0.01
Cape May, NJ	13	4	0.01	0.00
Ship John Shoal, NJ	15	7	0.01	0.00
Tacony Bridge, NJ	19	12	0.02	0.01
Burlington, NJ	25	16	0.03	0.01
Phila. USCG, PA	16	10	0.01	0.01

Table 6.11. (Cont.) DBOFS Version 1.0 and Version 1.1 April 1984 Tidal Simulation Results: Water Surface Elevation.

Station	RMSE (m)		Relative Error (-)	
	Version 1.0	Version 1.1	Version 1.0	Version 1.1
Phila. Pier 11, PA	21	17	0.03	0.02
Delaware City, DE	14	7	0.01	0.00
Reedy Point, DE	13	7	0.01	0.00
Brandywine Shoal, DE	14	6	0.02	0.00
Lewes, DE	11	3	0.01	0.00
Indian River, DE	18	14	0.06	0.04
Ocean City Pier, MD	10	5	0.02	0.00
Chesapeake City, MD	9	4	0.02	0.00
Trenton, NJ	30	19	0.03	0.01
W-OBC	1	6	0.00	0.01
S-OBC 1	10	5	0.02	0.00
S-OBC2	8	5	0.02	0.01
S-OBC3	8	5	0.01	0.01
S-OBC4/E-OBC1	8	5	0.01	0.01
E-OBC2	7	6	0.01	0.01
E-OBC3	9	7	0.01	0.01

Table 6.12. DBOFS Version 1.0 and Version 1.1 April 1984 Tidal Simulation Results: Principal Component Direction Current.

Station	RMSE (cm/s)		Relative Error (-)	
DAB (m)	Version 1.0	Version 1.1	Version 1.0	Version 1.1
2 at 7	12.7	15.3	0.02	0.03
3 at 5	17.6	7.8	0.02	0.01
5 at 5	16.8	8.0	0.02	0.00
11 at 3	5.6	3.8	0.04	0.02
16 at 8	6.5	4.0	0.42	0.24
17 at 15	8.4	7.0	0.15	0.11
18 at 2	12.2	7.2	0.04	0.02
19 at 8	16.3	8.4	0.02	0.01
21 at 2	16.1	11.5	0.06	0.04
22 at 6	14.8	14.1	0.02	0.02
23 at 8	11.7	6.9	0.01	0.01
24 at 2	12.7	9.8	0.05	0.03
25 at 2	33.9	30.3	0.81	0.81
33 at 11	16.7	17.5	0.02	0.02
51 at 9	33.7	29.6	0.13	0.11
154 at 8	35.6	33.2	0.12	0.11

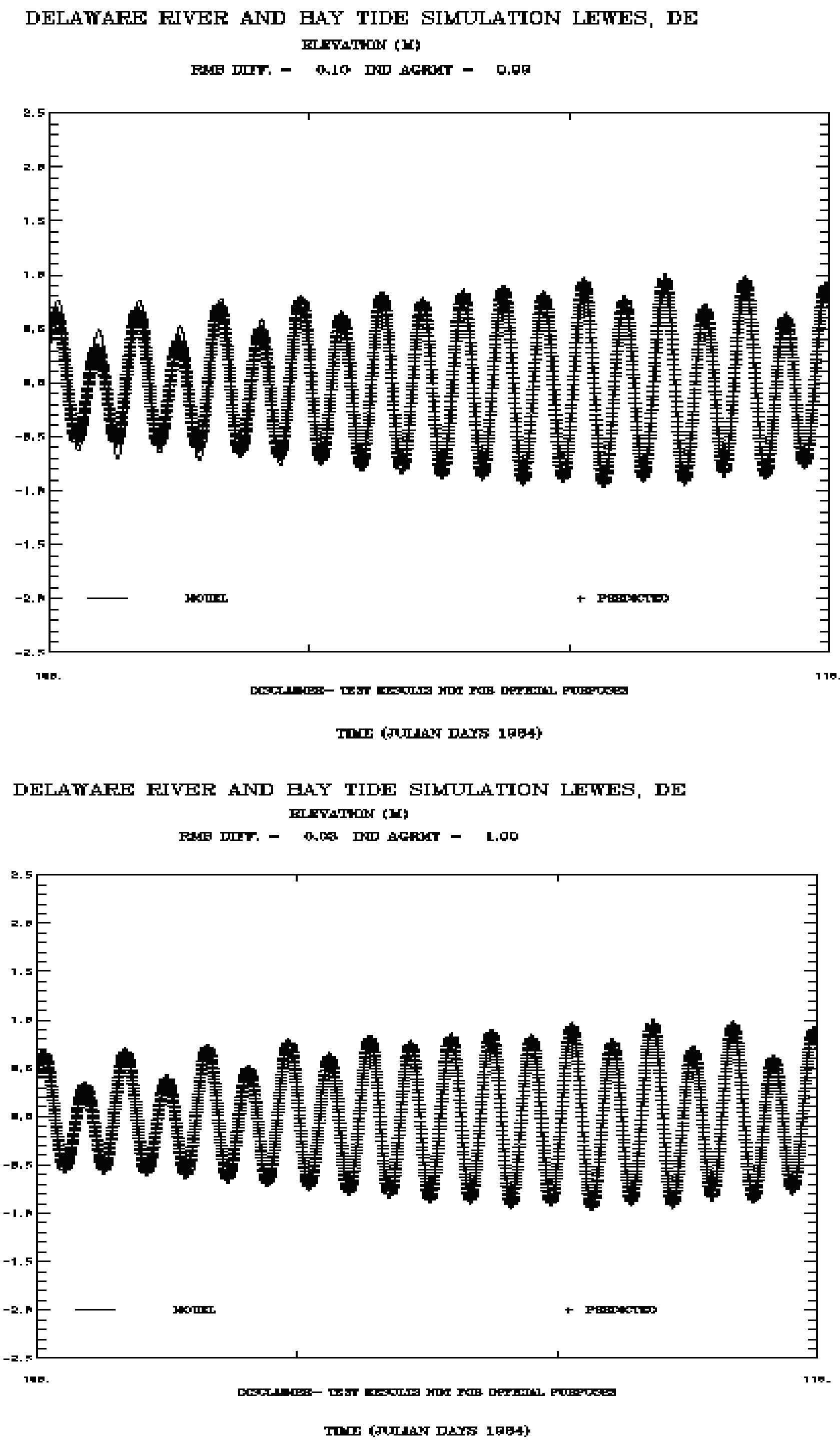
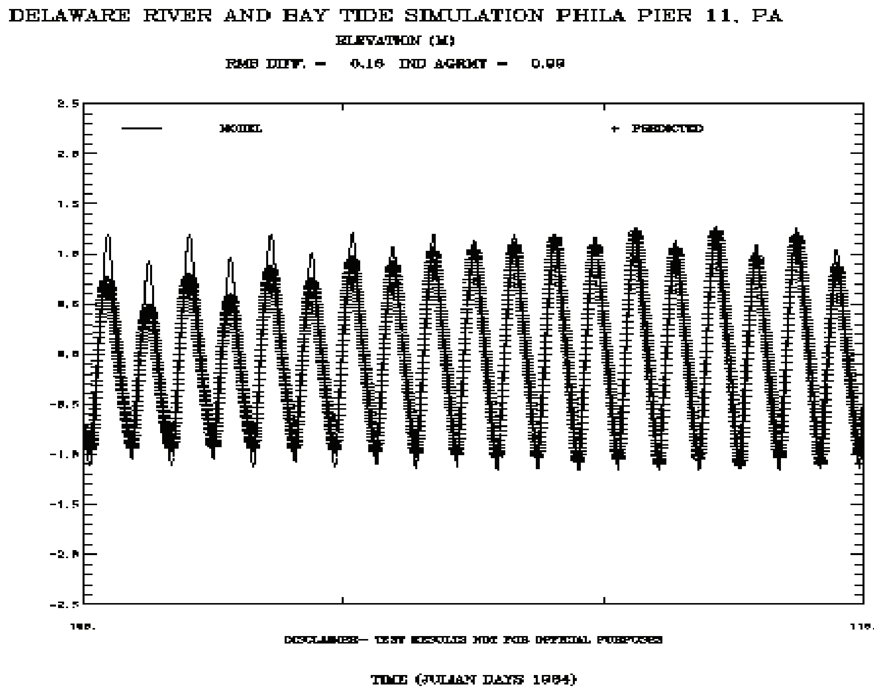


Figure 6.1. Simulated Astronomical Tide JD 100-110, 1984 at Lewes, DE . Top panel shows DBOFS Version 1.0 results. Bottom panel shows DBOFS Version 1.1 results. Predictions are at 6-minute intervals.



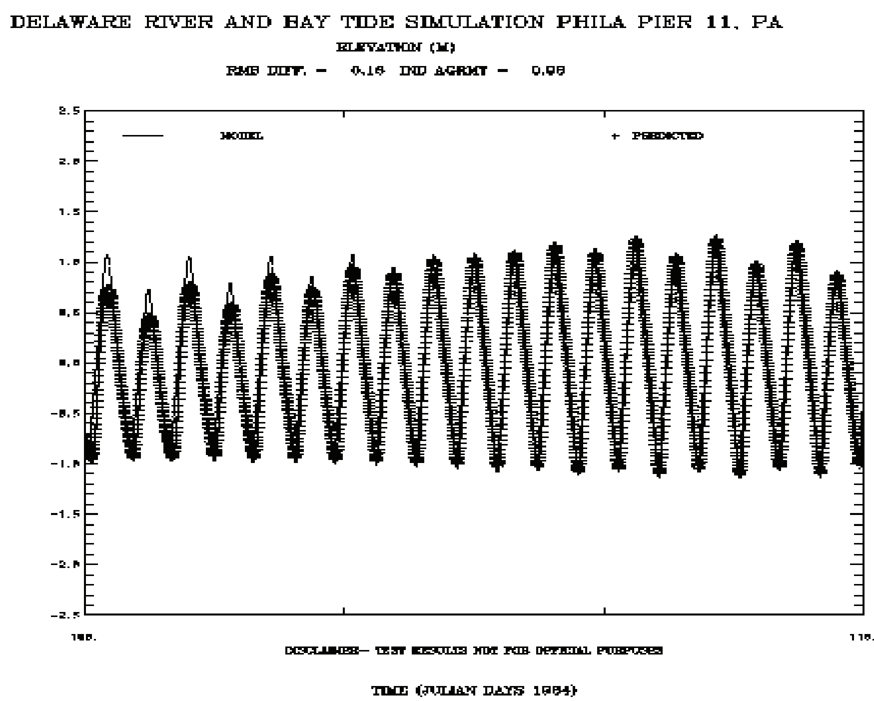


Figure 6.2. Simulated Astronomical Tide JD 100-110, 1984 at Philadelphia, PA . Top panel shows DBOFS Version 1.0 results. Bottom panel shows DBOFS Version 1.1 results. Predictions are at 6-minute intervals.

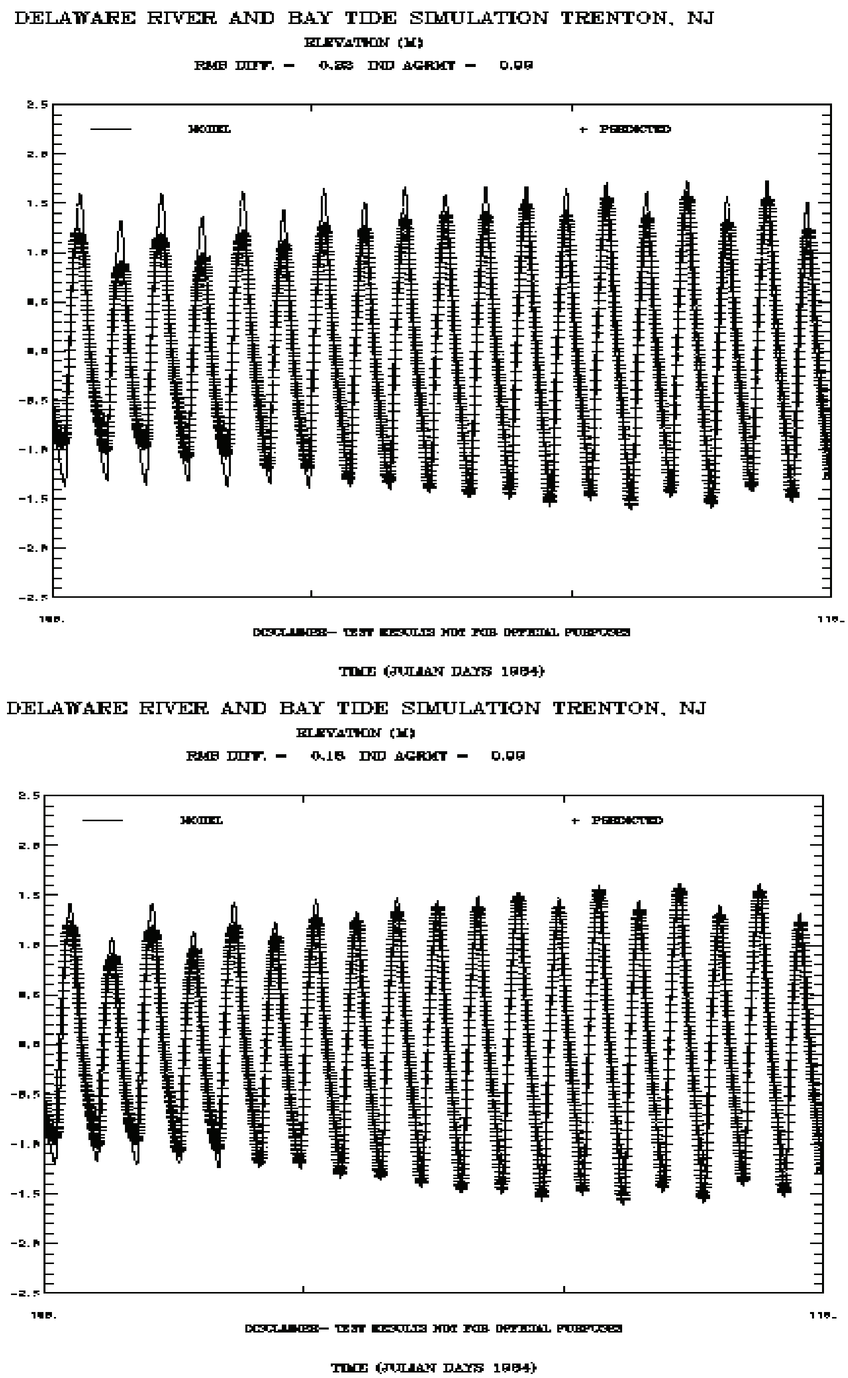


Figure 6.3. Simulated Astronomical Tide JD 100-110, 1984 at Trenton, NJ. Top panel shows DBOFS Version 1.0 results. Bottom panel shows DBOFS Version 1.1 results. Predictions are at 6-minute intervals.

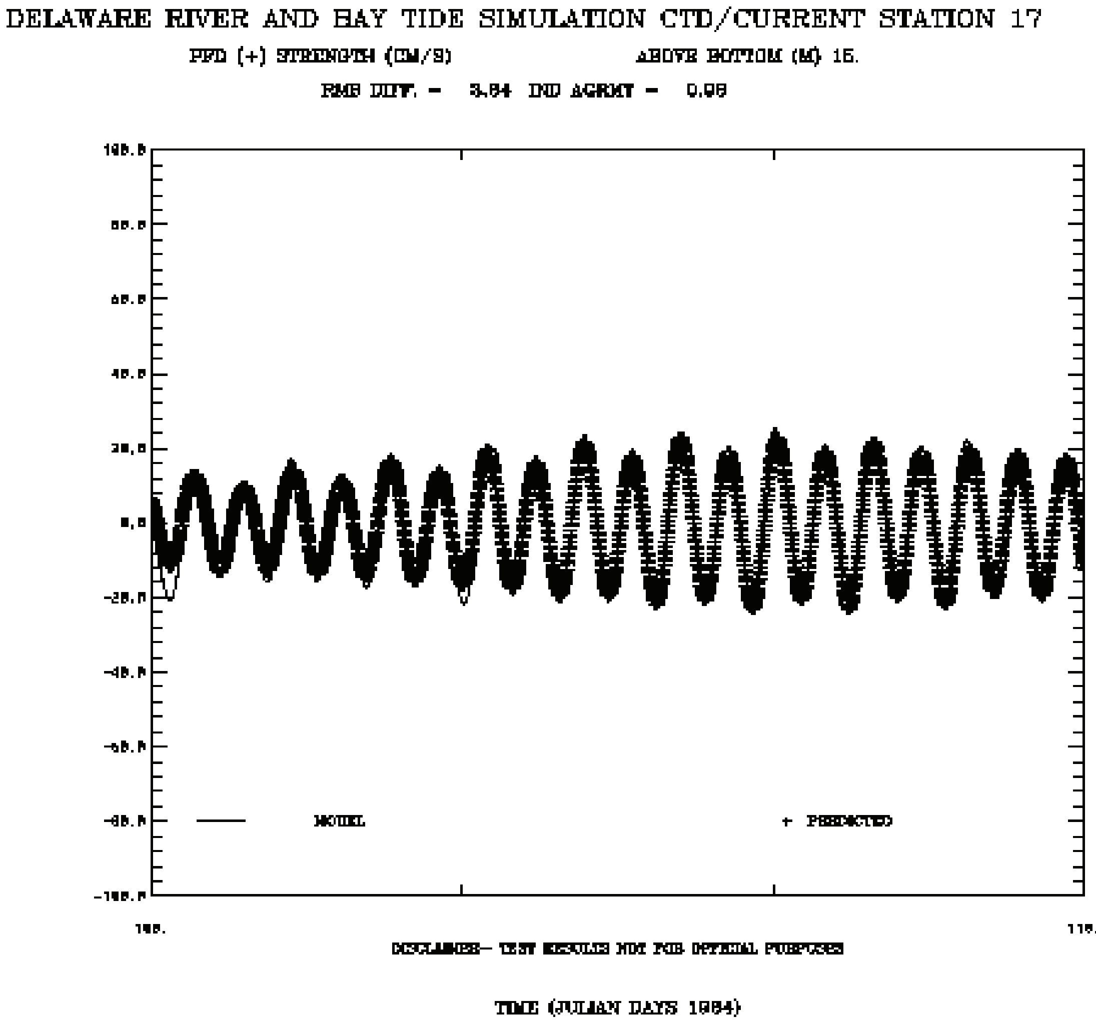


Figure 6.4. DBOFS Version 1.1 Tidal Current JD 100-110, 1984 at Station 17. Predictions are at 6-minute intervals.

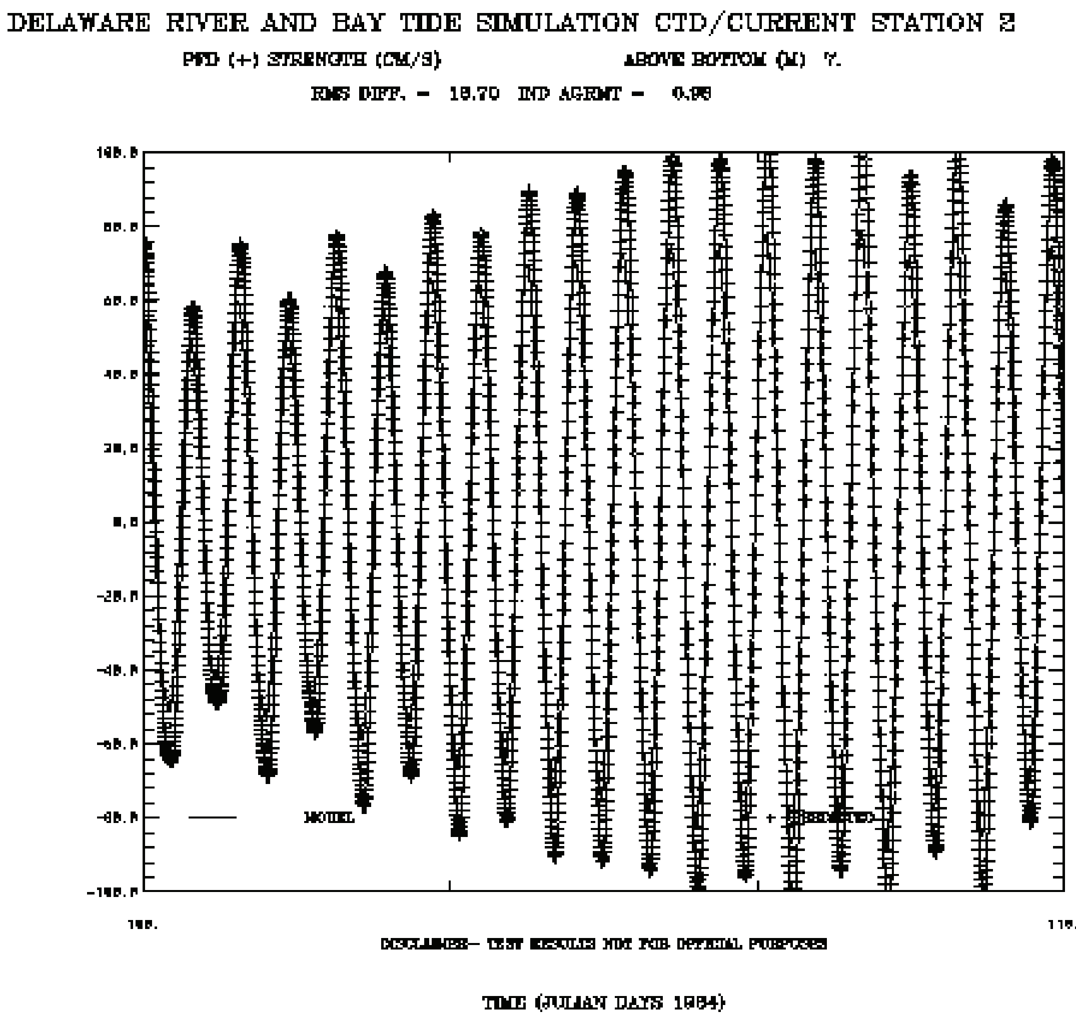


Figure 6.5. DBOFS Version 1.1 Tidal Current JD 100-110, 1984 at Station 2. Predictions are at 6-minute intervals.

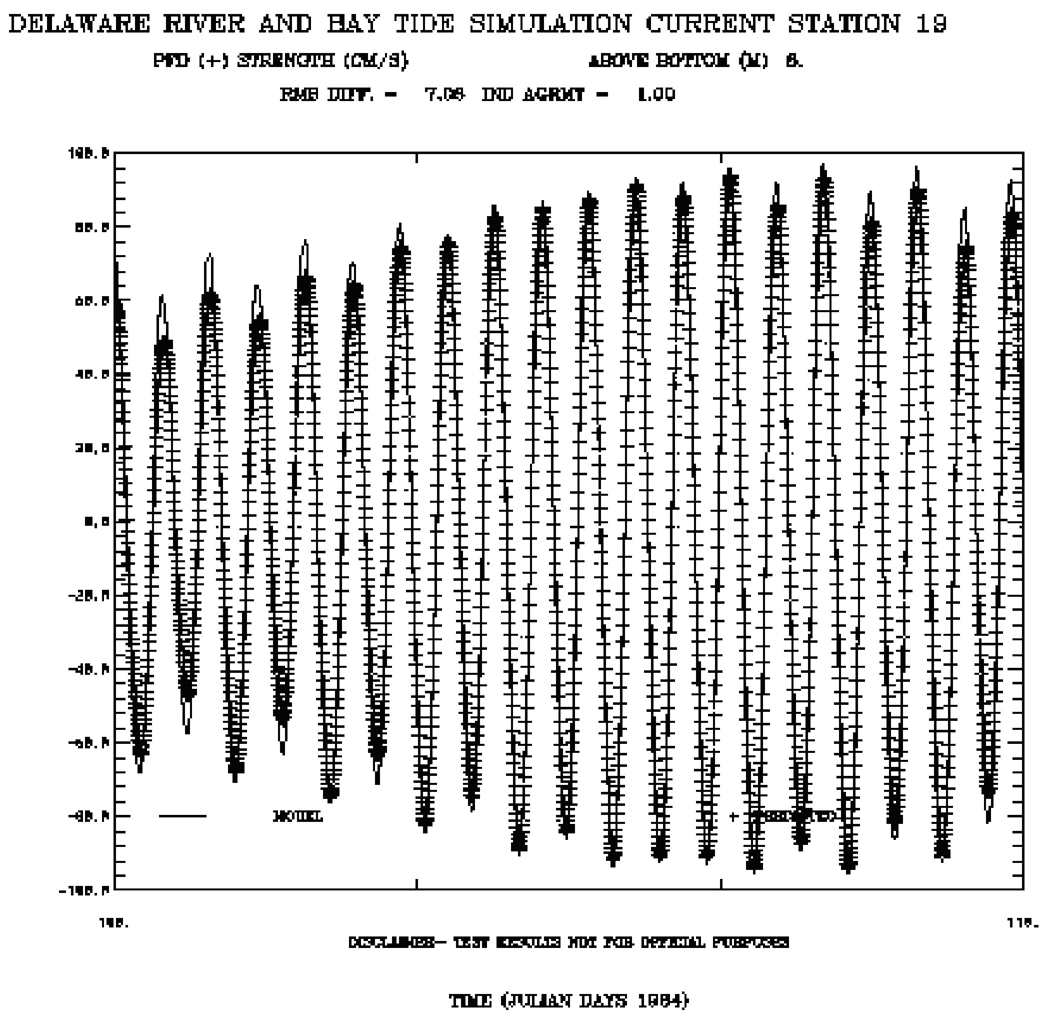


Figure 6.6. DBOFS Version 1.1 Tidal Current JD 100-110, 1984 at Station 19. Predictions are at 6-minute intervals.

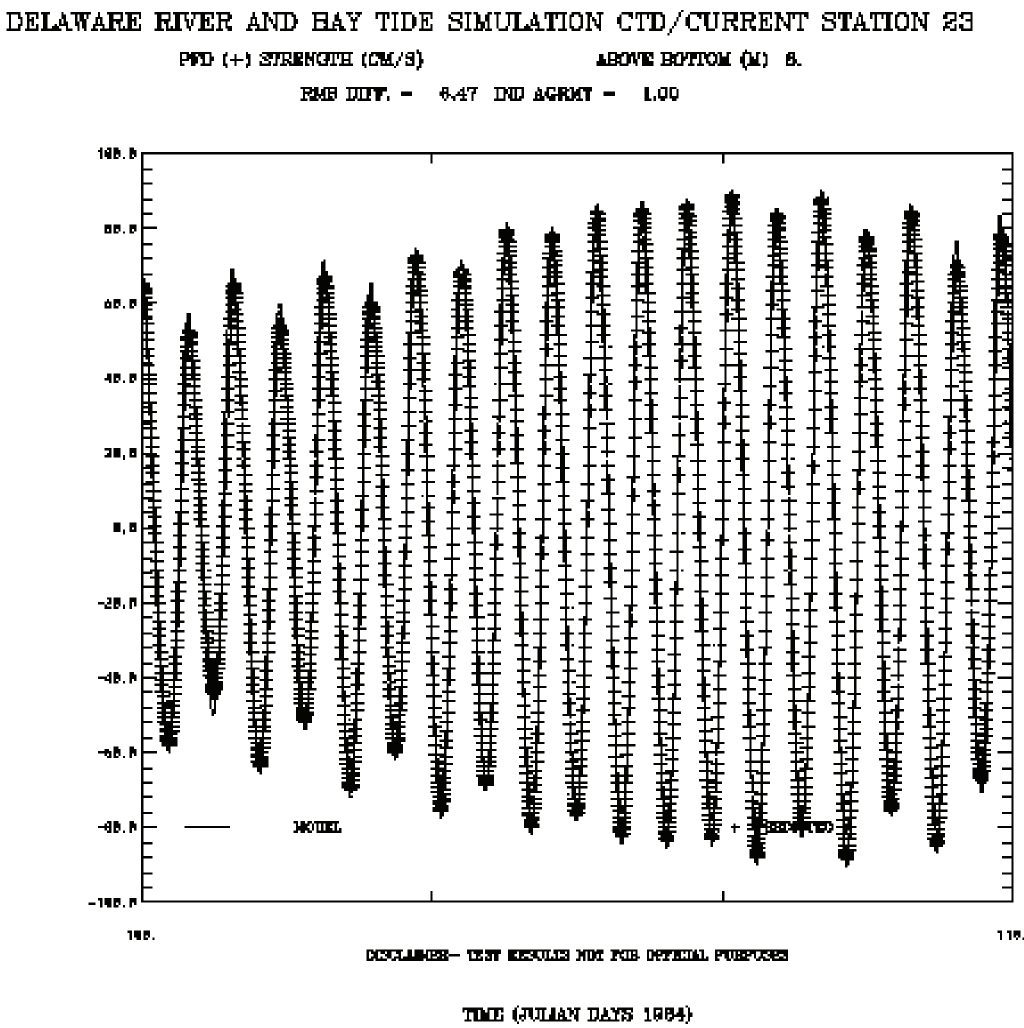


Figure 6.7. DBOFS Version 1.1 Tidal Current JD 100-110, 1984 at Station 23. Predictions are at 6-minute intervals.

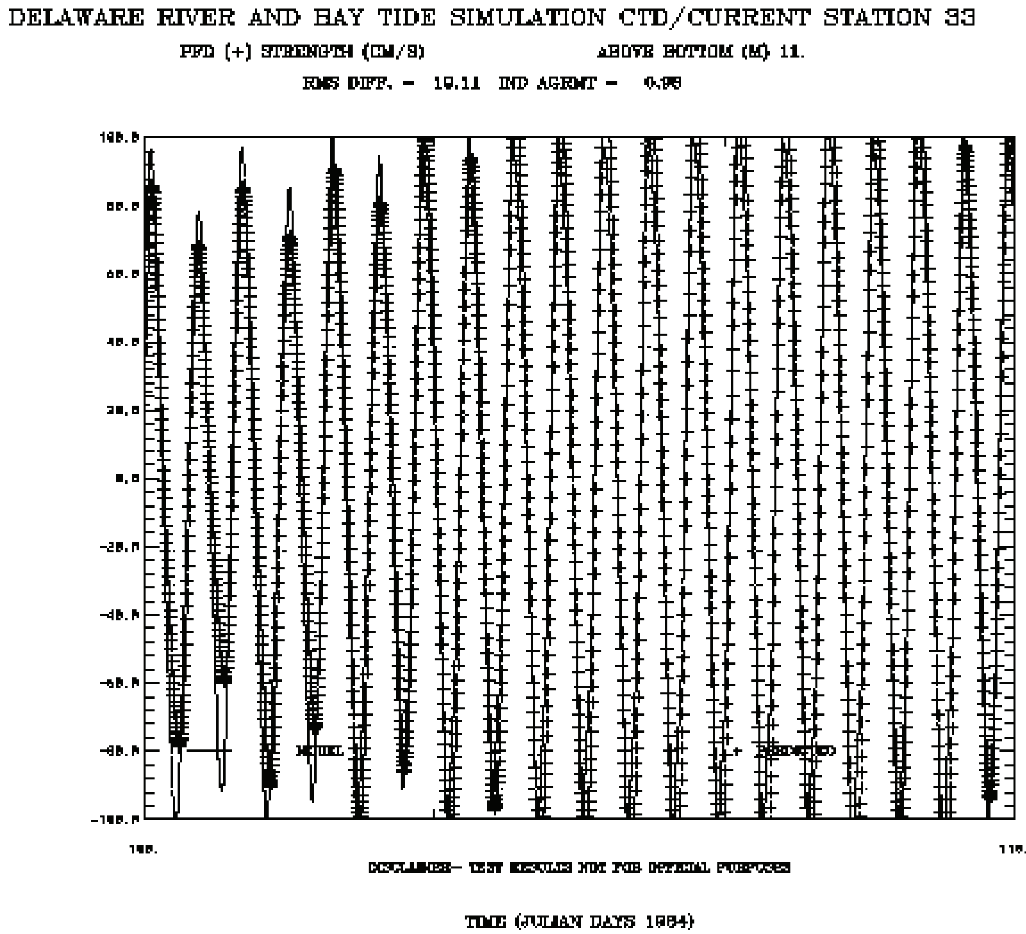


Figure 6.8. DBOFS Version 1.1 Tidal Current JD 100-110, 1984 at Station 33. Predictions are at 6-minute intervals.

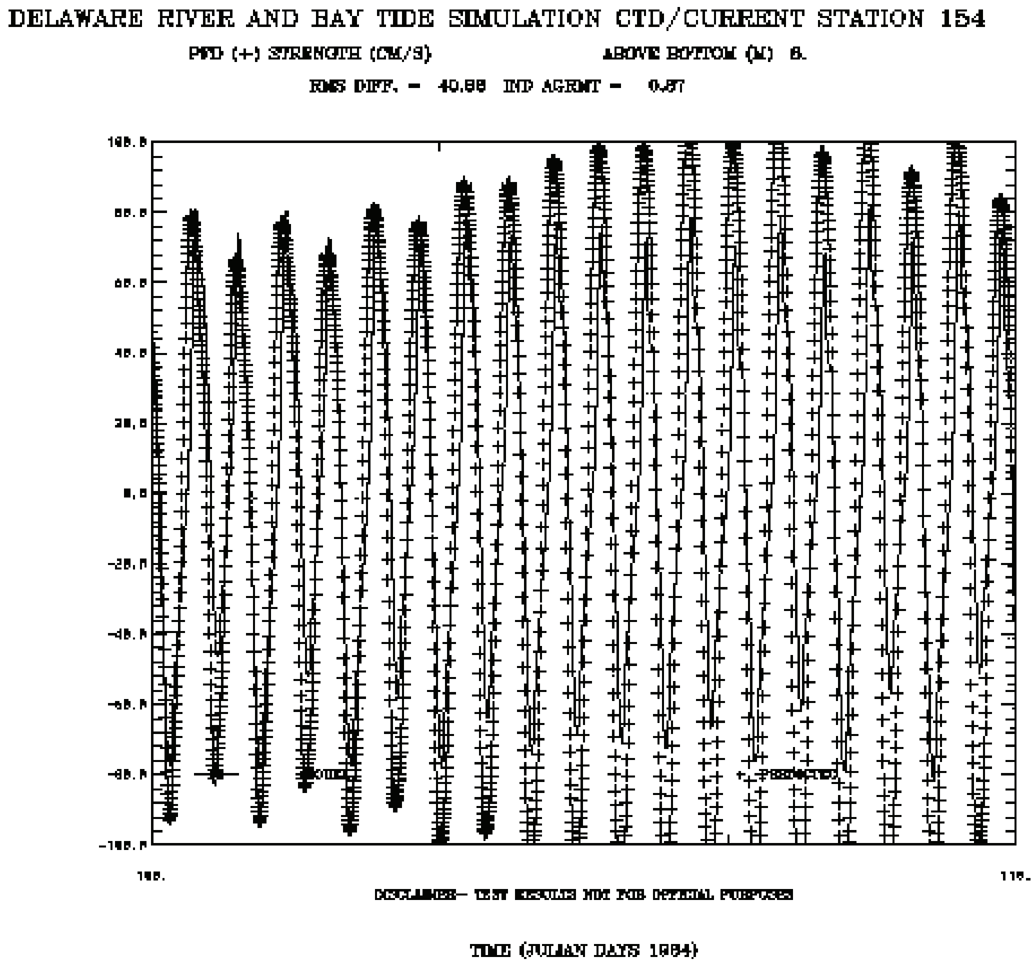


Figure 6.9. DBOFS Version 1.1 Tidal Current JD 100-110, 1984 at Station 154. Predictions are at 6-minute intervals.

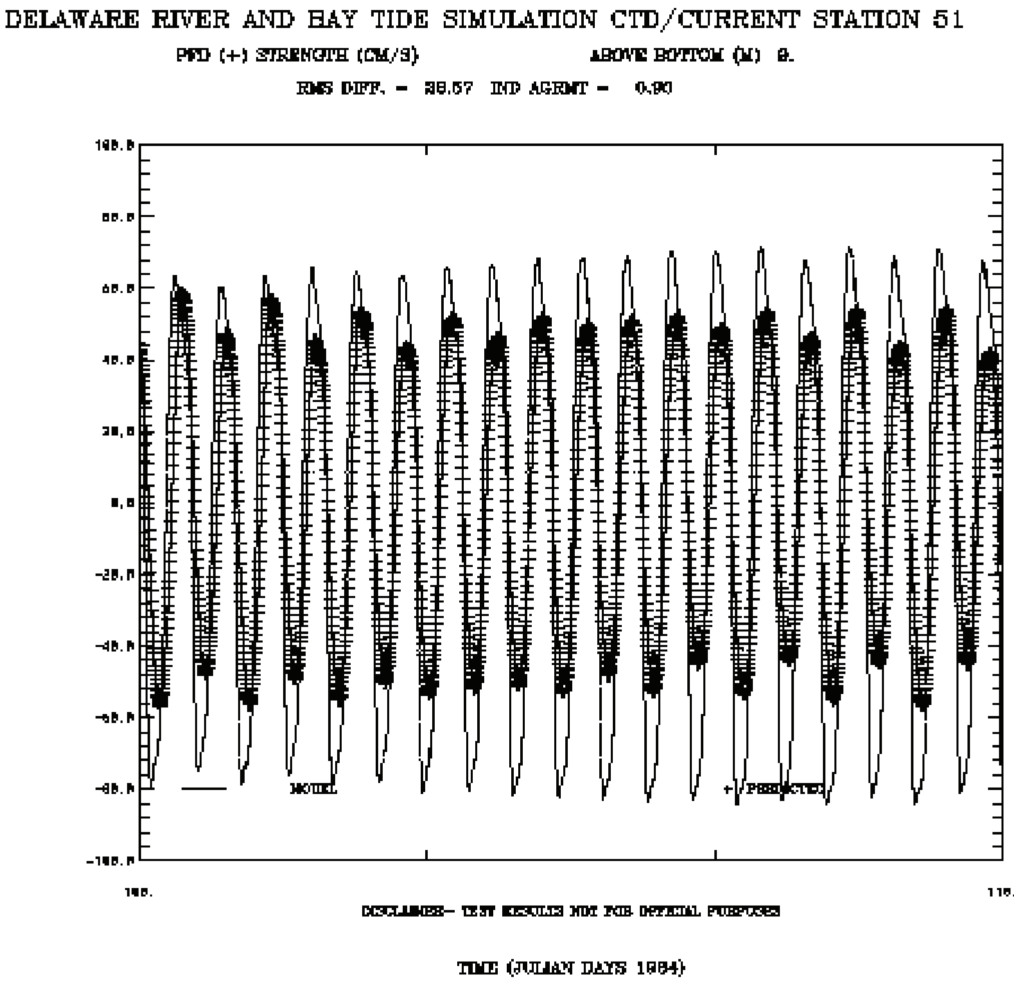


Figure 6.10. DBOFS Version 1.1 Tidal Current JD 100-110, 1984 at Station 51. Predictions are at 6-minute intervals.

6.3 March1984 – March 1985 Tidal Simulation Validation

An extended 13-month tidal simulation was performed over the period March 1984-March 1985. The objective was to assess the tidal dynamics over an extended time frame and compare with the results for April 1984. Since the Sa and Ssa long period constituents are included, the seasonal heating and cooling effects are also included in the tidal dynamics. USGS daily mean flow values were used as inflows, with salinity set to zero and temperature specified from the NOS historical Delaware River and Bay circulation survey dataset (Klavans et al., 1986). Water surface elevation results are shown in Table 6.13 compared to NOS tidal predictions in terms of RMSE and Willmott (1985) relative error. The results at the entrance to Delaware Bay, at Philadelphia, PA and at Trenton, NJ are consistent with the results for April 1984 and vary gradually from month to month. Note all model and predicted time series are at 6 minute intervals and were demeaned.

Model principal component direction currents are compared to NOS predictions in Table 6.14 in terms of RMSE and Willmott (1985) relative error and are generally consistent with the results for April 1984 and vary slightly from month to month. Model currents are resolved along the observed flood direction. All model and current time series are at 6 minute intervals and were not demeaned.

Table 6.13. DBOFS Version 1.1 March 1984-March 1985 Tide Simulation Results.

Station	March	April	May	June	July	August	Sept
Marcus Hook, PA	12/1	10/1	11/1	11/1	12/1	12/1	11/1
Cape May, NJ	7/0	4/0	5/0	8/1	9/1	8/1	6/0
Ship John Shoal, DB	9/1	8/0	9/1	12/1	12/1	11/1	8/0
Tacony Bridge, NJ	15/1	13/1	13/1	14/1	16/2	17/2	16/2
Burlington, NJ	18/2	17/1	17/1	19/2	21/2	21/2	21/2
Phila. USCG, PA	12/1	10/1	11/1	12/1	14/1	14/1	14/2
Phila. Pier 11, PA	19/2	18/2	17/2	18/2	20/3	21/3	22/3
Delaware City, DE	9/1	7/0	8/1	9/1	11/1	10/1	9/1
Reedy Point, DE	8/1	7/0	8/0	9/1	11/1	11/1	9/1
Brandywine Shoal, DB	8/1	6/0	7/0	9/1	10/1	8/1	6/0
Lewes, DE	7/1	3/0	5/0	8/1	9/1	8/1	5/0
Ocean City Pier, MD	7/1	5/0	5/1	7/1	8/1	7/1	6/1
Chesapeake City, MD	4/1	4/0	4/0	4/0	4/0	4/0	4/0
Trenton, NJ	22/2	20/2	20/2	21/2	24/2	25/2	25/2

Table 6.13. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Tide Simulation Results.

Station	Oct	Nov	Dec	Jan	Feb	Mar
Marcus Hook, PA	10/1	11/1	11/1	10/1	10/1	10/1
Cape May, NJ	5/0	6/0	7/1	8/1	7/1	7/1
Ship John Shoal, DB	8/0	9/1	10/1	10/1	8/1	8/1
Tacony Bridge, NJ	14/1	13/1	12/1	12/1	14/1	13/1
Burlington, NJ	18/2	17/1	16/1	16/1	16/1	17/1
Phila. USCG, PA	12/1	11/1	10/1	10/1	11/1	11/1
Phila. Pier 11, PA	19/2	18/2	16/1	17/2	19/3	20/3

Table 6.13. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Tide Simulation Results.

Station	Oct	Nov	Dec	Jan	Feb	Mar
Delaware City, DE	7/0	7/0	8/1	9/1	9/1	8/1
Reedy Point, DE	8/0	8/1	8/0	8/1	8/1	8/1
Brandywine Shoal, DB	7/0	7/1	8/1	9/1	7/1	6/1
Lewes, DE	4/0	5/0	6/1	8/1	7/1	6/1
Ocean City Pier, MD	5/1	5/1	7/1	8/1	7/1	6/1
Chesapeake City, MD	4/0	5/1	5/1	5/1	5/0	5/1
Trenton, NJ	22/2	20/2	19/2	19/1	20/2	20/2

Table 6.14. DBOFS Version 1.1 March 1984-March 1985 Tide Simulation PCD Current Results.

Station DAB (m)	March	April	May	June	July	August	Sept
2 at 7	24/8	25/9	22/7	27/11	28/11	27/10	21/5
3 at 5	8/1	6/0	6/0	7/0	8/1	8/1	7/1
5 at 5	11/1	9/1	9/1	9/1	10/1	10/1	10/1
11 at 3	4/2	4/2	4/2	4/2	4/2	3/2	3/2
16 at 8	3/21	3/22	2/15	4/30	4/29	3/18	3/22
17 at 15	5/8	6/11	6/11	7/13	6/9	5/8	6/12
18 at 2	8/2	7/2	8/2	8/2	8/2	8/2	8/2
19 at 8	13/3	12/2	12/2	13/3	14/3	14/3	12/2
21 at 2	12/4	12/4	12/4	12/4	13/4	13/4	12/4
22 at 6	23/9	23/9	22/8	22/8	23/9	24/9	23/8
23 at 8	15/4	15/4	13/3	15/4	16/4	16/4	14/3
24 at 2	11/4	10/3	9/3	10/3	11/4	12/4	11/4
33 at 11	34/13	35/15	33/13	34/14	35/14	36/14	34/13
51 at 9	20/8	20/8	19/7	20/7	21/8	22/9	20/8
154 at 8	38/17	36/15	36/15	33/13	35/13	37/15	39/18

Table 6.14. **(Cont.)** DBOFS Version 1.1 March 1984-March 1985 Tide Simulation PCD Current Results.

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
2 at 7	20/6	20/5	19/5	19/6	20/5	21/7
3 at 5	7/1	7/1	7/1	7/0	7/0	7/0
5 at 5	10/1	9/1	10/1	9/1	9/1	9/0
11 at 3	4/2	4/2	4/2	4/1	3/1	3/2
16 at 8	3/19	3/20	3/20	3/19	3/16	3/16
17 at 15	11/30	9/20	9/17	6/12	5/7	5/8
18 at 2	8/2	8/2	8/2	8/2	8/2	8/2
19 at 8	11/2	11/2	12/2	11/2	11/2	11/2
21 at 2	12/4	12/4	12/5	12/4	12/4	12/4
22 at 6	22/9	20/7	20/7	21/7	22/8	23/9
23 at 8	13/3	12/3	13/3	13/3	13/3	14/3
24 at 2	10/4	10/3	9/3	10/3	11/4	11/4
33 at 11	34/14	33/14	33/14	33/12	33/13	34/14
51 at 9	21/8	20/8	19/7	19/7	20/8	21/8
154 at 8	36/16	36/15	36/15	35/15	35/15	36/15

6.4 March1984 – March 1985 Hindcast Simulation Validation

The specification of the meteorological forcings was accomplished via Barnes (1973) interpolation of surface meteorological observations as previously described. Of interest is to note that the forcings were computed at 3 hour intervals and compared with observations at one hour intervals as shown in Tables 6.15 – 6.17 at 15-day intervals for atmospheric pressure, wind speed, and wind direction, respectively. In most 15-day segments, the wind speed errors are less than 4 m/s (< 10 kts) and the wind direction errors are less than 22.5 degrees (within an octant), indicating that the 3 hour interpolation interval is sufficient. The extended hindcast was analyzed in 15-day segments for water levels, currents, salinity, and temperature in terms of RMSE and Willmott (1985) relative error as discussed in turn.

Water Levels

In Table 6.18, the water level comparisons are given in 15-day segments. One notes that the RMSEs are generally very consistent over the initial 7-8 month period, while over the winter period there are data issues within the upper estuary caused by icings as indicated by the missing values in Table 6.18.. One also notes that there are datum problems for the observed water levels at Burlington, PA, Newbold, PA, and at Chesapeake City, MD. In general RMSEs increase from order 8 cm at the Entrance to order 10 cm at Marcus Hook, PA and are order 15 cm at Philadelphia, PA before increasing to order 20 cm at Trenton, NJ. Simulated water surface elevation time series plots from the Bay entrance at Lewes, DE, up river to Philadelphia Pier 11, PA, and finally to the head of tide at Trenton, NJ are shown in Figures 6.11 – 6.13 for JD 70-91, 1984, respectively, in Figures 6.14 - 6.16 for JD 92 – 107, respectively, in Figures 6.17 – 6.19 for JD 137-152, respectively, in Figures 6.20 – 6.22 for JD 153-168, respectively, in Figures 6.23 – 6.25 for JD 229-244, respectively, in Figures 6.26-6.28, respectively for JD 306-321, respectively, in Figures 6.29-6.31, respectively for JD 351-366, in Figures 6.32-6.34, respectively for JD 47-60, and in Figures 6.35-6.37 in Figures 6.38-6.40, respectively for JD 75-90. Several interesting aspects of the water level response occur. Flow events at the Trenton, NJ location are noted in the JD 92-107 and JD 137-152 time series plots, with the influences extending to Philadelphia, PA. Average daily inflow values are used for the present forcings, but it may be necessary during high flow events to use 3-6 hour interval flows. During the JD 306-321, 1984 and JD 33-47, 1985 period, the water level gage at Philadelphia, PA goes flat to zero indicating potential ice problems. During 1985, there may also be an issue with the recorded water level gage datum at Trenton, NJ.

Currents

In Tables 6.20 and 6.21, the simulated currents are compared to observed currents in 15-day segments for speed and direction, respectively. In general, the RMSEs are very consistent from one 15-day period to another with the RMSEs at most stations under 26 cm/s (<0.5kt). The direction comparisons are more problematical at Stations 154 and 51 in the river and at Station 16 on the shelf. In Tables 6.22 and 6.23, the mean of the simulated currents speeds and directions are compared to the mean observed current speed and directions, respectively. At most stations there is good agreement and consistent results from one 15-day period to the next. Current speed and direction time series plots are shown for Stations 23, 33, and 51 progressing from the lower Bay into the river below Philadelphia, PA in Figures 6.41-6.43, respectively for JD 76-91, 1984, in Figures

6.44-6.46, respectively for JD 153-168, in Figures 6.47-6.49, respectively for JD 229-254, in Figures 6.50-6.52, for JD 351-366, and in Figure 6.53 at Station 23 and in Figure 6.54 at Station 51 for JD 75-90, 1985. There are limited observation data, but favorable comparisons are achieved at Stations 33 and 51 during JD 229-254, 1984 and at Stations 23 and 51 during JD 75-90, 1985.

Salinity

In Table 6.24, the simulated salinities are compared to observed salinities in 15-day segments. In general, the RMSEs are very consistent from one 15-day period to another with the RMSEs at most stations under 3 PSU. The comparisons are more problematical at Stations 23 and 33 in the upper Bay in the region of the large salinity gradient. In Table 6.25, the mean of the simulated salinities are compared to the mean observed salinities. At most stations there is good agreement and consistent results from one 15-day period to the next. The simulated salinities appear to be too low at Stations 23 and 33 during the first 7 months, but then come in closer agreement to the observations over the last 5 months indicating that there may be some issues with the initial condition specification. Salinity time series plots at Stations 23 and 33 are shown in Figures 6.55 and 6.56, respectively, for JD 76-91, 1984, in Figures 6.57 and 6.58, respectively, for JD 153-168, in Figures 6.59 and 6.60, respectively, for JD 229-244, in Figures 6.61 and 6.62, respectively, for JD 351-366, and in Figure 6.63 at Station 23 for JD 75-90, 1985. One notes the large amplitude order 5 to 6 PSU in the simulated salinity at Station 33, indicating that it is located in the region of strong salinity gradient. During the JD 153-168, 1984 period there is evidence that the simulated salinity is too low at Station 33. The amplitude of the simulated salinity at Station 23, further down estuary, mid-Bay, is generally less than 4 PSU and is reduced from that at Station 33, indicating that the gradients in salinity are not as strong at this station.

Temperature

In Table 6.26, the simulated temperatures are compared to observed temperatures in 15-day segments. In general, the RMSEs are very consistent from one 15-day period to another with the RMSEs at most stations under 3 ^{o}C . There is consistent over-heating by order 5 ^{o}C during the first 8 months of the simulation and ice forms during the winter. However, during the spring of 1985 the temperatures recover in close agreement to observations. This behavior is further confirmed by examining the temperature time series plots at Station 23 and 33, for JD 76-91, 1984, in Figures 6.64 and 6.65, in Figures 6.66 and 6.67 for JD 153-168, and in Figures 6.68 and 6.69 for JD 229-244, respectively, in Figure 6.70 at Station 33 for JD 351-366, and in Figure 6.71 at Station 23 for JD 75-90, 1985. In general, the heating and cooling cycle is well represented, as shown in Table 6.27, but there may be some issues with the radiation balance.

Table 6.15. DBOFS Version 1.1 March 1984-March 1985 Atmospheric Pressure: RMSE (mb)/RE(%).

Station No.	March	April	May	June	July	August	Sept
61N Indian River, DE	2/1	-	-	-	-	-	-
N91 Cape May, NJ	4/6	-	-	-	-	-	-
44009	1/0	0/0	0/0	0/0	0/0	0/0	0/0
44012	-	-	-	0/0	0/0	0/0	0/0

Table 6.15. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Atmospheric Pressure: RMSE (mb)/RE(%).

Station No.	Oct	Nov	Dec	Jan	Feb	Mar
61N Indian River, DE	-	-	-	-	-	-
N91 Cape May, NJ	-	-	-	-	-	-
44009	0/0	0/0	0/0	-	-	-
44012	0/0	0/0	0/0	-	-	-

Table 6.16. DBOFS Version 1.1 March 1984-March 1985 Wind Speed: RMSE(m/s)/ RE(%).

Station No.	March	April	May	June	July	August	Sept
61N Indian River, DE	3/30	-	-	-	-	-	-
N91 Cape May, NJ	3/24	-	-	-	-	-	-
44009	1/4	1/7	1/4	1/3	1/4	0/4	1/4
44012	-	-	-	1/3	1/4	0/4	1/4

Table 6.16. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Wind Speed: RMSE (m/s)/RE(%).

Station No.	Oct	Nov	Dec	Jan	Feb	Mar
61N Indian River, DE	-	-	-	-	-	-
N91 Cape May, NJ	-	-	-	-	-	-
44009	1/3	0/1	1/3	-	-	-
44012	0/2	0/1	0/2	-	-	-

Table 6.17. DBOFS Version 1.1 March 1984-March 1985 Wind Direction: RMSE (oT)/RE(%).

Station No.	March	April	May	June	July	August	Sept
61N Indian River, DE	39/6	-	-	-	-	-	-
N91 Cape May, NJ	40/7	-	-	-	-	-	-
44009	22/2	22/2	17/1	16/1	16/1	15/1	15/0
44012	-	-	-	15/1	16/1	15/1	12/0

Table 6.17. **(Cont.)** DBOFS Version 1.1 March 1984-March 1985 Wind Direction: RMSE (oT)/RE(%).

Station No.	Oct	Nov	Dec	Jan	Feb	Mar
61N Indian River, DE	-	-	-	-	-	-
N91 Cape May, NJ	-	-	-	-	-	-
44009	14/1	13/0	15/1	-	-	-
44012	12/0	13/0	15/1	-	-	-

Table 6.18. DBOFS Version 1.1 March 1984-March 1985Water Surface Elevations: RMSE (cm)/RE(%)

Station No.	March	April	May	June	July	August	Sept
Trenton, NJ	25/23 2/2	23/16 2/1	17/26 1/2	22/20 1/1	25/20 2/1	20/23 1/2	18/18 1/1
Phila. Pier 11, PA	17/15 2/1	12/11 1/1	11/11 1/1	13/12 1/1	17/16 2/2	11/11 1/1	10/15 1/1
Lewes, DE	14/12 2/1	9/9 1/1	10/9 1/1	11/10 1/2	12/11 1/2	11/10 1/1	8/8 1/1
Cape May, NJ	15/11 2/1	9/10 1/1	9/9 1/1	10/11 1/1	10/11 1/1	10/8 1/1	7/8 1/1

Table 6.18. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Mean Water Surface Elevations: RMSE (cm)/RE(%)

Station No.	Oct	Nov	Dec	Jan	Feb	Mar
Trenton, NJ	23/20 2/1	23/25 2/2	19/16 1/1	33/33 4/4	-/- -/-	21/22 2/2
Phila. Pier 11, PA	16/11 2/1	-/- -/-	13/13 1/1	-/- -/-	-/23 -/4	13/16 1/2
Lewes, DE	8/8 1/1	9/9 1/1	10/10 1/1	11/13 1/2	12/9 1/1	10/9 1/1
Cape May, NJ	8/7 1/0	8/8 1/1	9/9 1/1	11/12 1/1	12/9 1/1	9/9 1/1

Table 6.19. DBOFS Version 1.1 March 1984-March 1985 Mean Water Surface Elevations (cm): Model/Observed.

Station No.	March	April	May	June	July	August	Sept
Trenton, NJ	124/125 146/153	200/197 169/172	153/158 158/156	157/165 135/144	147/151 132/139	133/143 136/140	133/134 131/130
Phila. Pier 11, PA	95/91 117/117	137/136 128/126	112/114 111/110	114/115 111/112	109/117 105/110	112/115 115/112	112/107 116/110
Lewes, DE	55/57 78/82	81/81 76/78	61/62 60/60	62/65 67/68	56/61 61/65	70/75 76/75	75/75 81/81
Cape May, NJ	62/65 83/87	87/91 83/88	68/71 67/69	68/72 74/76	63/65 68/69	76/77 82/83	81/82 81/83

Table 6.19. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Mean Water Surface Elevations (cm): Model/Observed.

Station No.	Oct	Nov	Dec	Jan	Feb	Mar
Trenton, NJ	135/133 140/142	134/130 121/118	120/118 124/121	125/117 108/99	120/115 113/113	120/119 122/120
Phila. Pier 11, PA	116/110 119/118	-	96/94 99/96	- -	- 87/83	91/89 97/90
Lewes, DE	81/81 78/78	78/76 63/61	58/57 59/56	64/62 47/43	62/64 43/43	50/50 59/59
Cape May, NJ	87/89 84/86	85/86 70/71	65/67 66/68	72/75 55/58	69/74 51/54	57/61 66/69

Table 6.20. DBOFS Version 1.1 March 1984-March 1985 Hindcast Current Speed Skill Results: RMSE (cm/s) / RE (%).

Station DAB (m)	March	April	May	June	July	August	Sept
2 at 14							x-24/ x-15
5 at 2							
5 at 5							
11 at 3							
16 at 3				x-6/ x-54	5-4/ 41-46	7-9/ 53-54	7-x/ 63-x
16 at 8							
16 at 11							
17 at 3				x-5/ x-42	5-5/ 48-38	7-4/ 58-32	
17 at 15							14-15/ 75-63
17 at 23		x-22/ x-76	27-31/ 75-73	30-16/ 79-71	17-9/ 68-48		
18 at 2							x-8/ x-8
19 at 2							x-10/ x-10
19 at 8							
22 at 2					x-11/ x-18		
22 at 6							x-17/ x-16
23 at 2							11-14/ 21-32
23 at 8							
24 at 2							x-6/ x-6
25 at 2							x-9/ x-13

Table 6.20. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Current Speed Skill Results: RMSE (cm/s) / RE (%).

Station DAB (m)	March	April	May	June	July	August	Sept
33 at 2					23-20/ 46-33	19-17/ 31-22	13-x/ 19-x
33 at 11				20-29/ 12-20	23-33/ 11-26	27-29/ 17-21	23-x/ 14-x
51 at 2							15-18/ 20-37
51 at 9						18-18/ 16-17	16-19/ 14-19
154 at 2						17-24/ 25-26	15-32/ 17-27
154 at 8							

Table 6.20. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Current Speed Skill Results: RMSE (cm/s) / RE (%).

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
2 at 7						17-13/ 15-16
2 at 14	20-21/ 17-12	18-17/ 14-9	16-x/ 20-x			
5 at 2	x-10/ x-4	11-11/ 8-6				
5 at 5	x-10/ x-3	12-14/ 7-7				
11 at 3	x-7/ x-25	6-5/ 28-18				
16 at 8	14-8/ 46-47	8-7/ 63-53				
16 at 11	15-9/ 43-50	9-7/ 62-53				
17 at 15	17-11/ 51-51	14-13/ 68-64				
17 at 23						
18 at 2	8-12/ 15-38					
19 at 2	9-12/ 12-24					
19 at 8	10-10/ 7-9					
22 at 6	16-17/ 20-23					
23 at 2	6-13/ 7-21	9-10/ 16-13				

Table 6.20. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Current Speed Skill Results: RMSE (cm/s) / RE (%).

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
23 at 8	10-21/10-24	10-12/ 8-8				17-14/ 18-15
24 at 2	7-13/13-53					
25 at 2	9-17/22-68					
33 at 2						
33 at 11						
51 at 2	26-24/ 77-73	22-x/ 68-x	25-25/ 67-59		x-18/ x-27	17-16/ 22-20
51 at 9	18-17/ 20-17	17-16/ 17-16	11-x/ 8-x		x-14/ x-13	16-14/ 14-10
154 at 8	21-22/ 17-23				x-28/ x-39	31-25/ 30-26

Table 6.21. DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Current Speed (cm/s) Skill Results: Model/Observed.

Station DAB (m)	March	April	May	June	July	August	Sept
2 at 14							x-49/x-64
5 at 2							
5 at 5							
11 at 3							
16 at 3				x-8/x-8	9-8/7-7	8-7/11-12	8-x/11-x
16 at 8							
16 at 11							
17 at 3				x-10/x-10	11-9/11-8	12-10/8-9	
17 at 15							17-20/15-22
17 at 23		x-27/x-14	33-38/13-14	38-22/11-14	23-23/18-11		
18 at 2							x-29/x-28
19 at 2							x-49/x-49
19 at 8							
22 at 2					x-11/x-18	31-x/26-x	
22 at 6							x-44/x-45
23 at 2							30-32/19-17
23 at 8							
24 at 2							x-29/x-29
25 at 2							x-27/x-32
33 at 2					33-29/51-39	30-30/40-40	28-x/31-x
33 at 11				69-56/70-60	64-58/65-62	64-58/62-61	60-x/57-x
51 at 2							37-38/48-45
51 at 9						54-53/64-64	53-53/62-63
154 at 2						32-31/39-47	30-x/32-x
154 at 8							x-41/x-59

Table 6.21. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Current Speed (cm/s) Skill Results: Model/Observed.

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
2 at 7						43-37/48-39
2 at 14	42-51/49-56	41-48/46-51	43-x/35-x			
5 at 2	x-50/x-48	42-48/38-41				
5 at 5	x-59/x-61	50-57/52-58				
11 at 3	x-16/x-17	14-16/13-13				
16 at 8	12-11/19-13	9-12/12-13				
16 at 11	13-11/20-13	10-12/12-12				
17 at 15	16-17/22-15	19-20/14-14				
17 at 23						
18 at 2	26-31/22-14					
19 at 2	31-37/25-20					
19 at 8	42-51/40-32					
22 at 6	40-46/36-32					
23 at 2	27-33/25-28	27-32/23-27				
23 at 8	37-45/31-26	36-43/31-37				44-40/41-36
24 at 2	25-30/23-14					
25 at 2	23-28/20-9					
33 at 2						
33 at 11						
51 at 2	36-40/42-47	36-x/43-x	37-37/48-38		x-37/x-48	38-37/51-50
51 at 9	51-55/59-62	51-54/56-59	52-x/51-x		x-52/x-57	54-52/62-60
154 at 8	42-41/47-42				x-41/x-34	43-39/53-45

Table 6.22. DBOFS Version 1.1 March 1984-March 1985 Hindcast Current Direction Skill Results: RMSE (oT) / RE (%).

Station DAB (m)	March	April	May	June	July	August	Sept
2 at 14							
5 at 2							
5 at 5							
11 at 3							
16 at 3						70-56/ 62-22	
16 at 8							
16 at 11							
17 at 3							
17 at 15							104-79/ 57-34
17 at 23		x-95/ x-40	72-114/ 8-22	64-103/ 58-42	66-x/ 12-x		

Table 6.22.(Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Current Direction Skill Results: RMSE (oT) / RE (%).

Station DAB (m)	March	April	May	June	July	August	Sept
18 at 2							x-8/ x-0
19 at 2							x-9/ x-0
19 at 8							
22 at 2					x-18/ x-1	12-x/ 1-x	
22 at 6							x-17/ x-1
23 at 2							6-5/ 0-0
23 at 8							
24 at 2							x-46/ x-6
25 at 2							x-122/ x-60
33 at 2					47-39/ 9-5	31-23/ 3-2	15-x/ 1-x
33 at 11				11-42/ 0-5	18-37/ 1-4	26-30/ 2-3	23-x/ 2-x
51 at 2							9-25/ 0-2
51 at 9						21-23/ 1-2	19-28/ 1-2
154 at 2						12-35/ 0-4	35-x/ 4-x
154 at 8							x-57/ x-13

Table 6.22. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Current Direction Skill Results: RMSE (oT) / RE (%).

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
2 at 7						22-12/ 2-1
2 at 14	18-20/ 1-1	13-13/ 1-1	7-x/ 0-x			
5 at 2	x-7/ x-0	13-20/ 1-1				
5 at 5	x-9/ x-0	16-24/ 1-2				
11 at 3	x-34/ x-3	21-x/ 69-x				

Table 6.22. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Current Direction Skill Results: RMSE (oT) / RE (%).

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
16 at 8	30-46/ 46-4	42-x/ 15-x				
16 at 11	25-48/ 38-7	36-x/ 39-x				
17 at 15	58-66/ 29-12	72-36/ 55-4				
17 at 23						
18 at 2	10-4/ 0-49					
19 at 2	8-6/ 0-0					
19 at 8	15-6/ 1-0					
22 at 6	17-18/ 1-1					
23 at 2	7-7/ 0-0	11-11/ 0-0				
23 at 8	5-4/ 0-0	11-11/ 0-0				18-17/ 1-1
24 at 2	39-x/ 4-x					
25 at 2	124-8/ 91-79					
33 at 2						
33 at 11						
51 at 2	68-67/ 15-15	64-x/ 13-x	132-125/ 57-52		x-8/ x-0	9-8/ 0-0
51 at 9	28-25/ 2-2	24-26/ 2-2	4-x/ 0-x		x-4/ x-0	21-12/ 1-0
154 at 8	41-44/ 5-6				x-116/ x-47	52-42/ 9-6

Table 6.23. DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Current Direction (oT) Skill Results: Model/Observed.

Station DAB (m)	March	April	May	June	July	August	Sept
2 at 14							
5 at 2							
5 at 5							
11 at 3							
16 at 3						176-185/212-260	
16 at 8							
16 at 11							

Table 6.23. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Current Direction (oT) Skill Results: Model/Observed.

Station DAB (m)	March	April	May	June	July	August	Sept
17 at 3							
17 at 15							167-168/ 217-242
17 at 23		x-255/ x-213	245-266/ 187-138	295-263/ 262-92	207-x/ 118-x		
18 at 2							x-226/ x-233
19 at 2							x-229/ x-255
19 at 8							
22 at 2					x-232/ x-237	235-x/ 243-x	
22 at 6							x-223/ x-235
23 at 2							227-233/ 271-269
23 at 8							
24 at 2							x-182/ x-248
25 at 2							x-107/ x-184
33 at 2					227-223/ 289-266	227-224/ 258-258	228-x/ 259-x
33 at 11				212-201/ 229-229	210-206/ 225-229	207-210/ 232-220	210-x/ 228-x
51 at 2							193-192/ 197-190
51 at 9						195-193/ 201-195	193-193/ 195-194
154 at 2						165-175/ 150-164	175-x/ 174-x
154 at 8							x-184/ x-208

Table 6.23. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Current Direction (oT) Skill Results: Model/Observed.

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
2 at 7						237-238/ 224-226
2 at 14	230-231/ 216-216	232-232/ 221-222	229-x/ 212-x			
5 at 2	x-218/ x-220	219-215/ 220-218				
5 at 5	x-216/ x-222	217-214/ 219-219				

Table 6.23. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Current Direction (oT) Skill Results: Model/Observed.

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
11 at 3	x-210/ x-237	208-x/ 288-x				
16 at 8	153-172/ 229-185	132-x/ 66-x				
16 at 11	157-174/ 219-184	131-x/ 55-x				
17 at 15	164-180/ 223-195	166-160/ 218-164				
17 at 23						
18 at 2	226-225/ 244-315					
19 at 2	227-231/ 261-220					
19 at 8	236-237/ 247-231					
22 at 6	224-222/ 243-219					
23 at 2	227-235/ 257-252	238-236/ 267-256				
23 at 8	242-245/ 257-246	245-243/ 255-253				245-246/ 241-245
24 at 2	170-x/ 252-x					
25 at 2	105-109/ 183-181					
33 at 2						
33 at 11						
51 at 2	192-193/ 200-199	193-x/ 199-x	194-194/ 200-204		x-196/ x-223	196-193/ 205-204
51 at 9	192-193/ 196-203	192-194/ 201-198	195-x/ 176-x		x-196/ x-213	196-194/ 198-197
154 at 8	182-178/ 180-154				x-152/ x-164	151-158/ 153-164

Table 6.24. DBOFS Version 1.1 March 1984-March 1985 Hindcast Salinity Skill Results: RMSE (PSU)/ RE (%).

Station DAB (m)	March	April	May	June	July	August	Sept
2 at 2					x-0.8/ x-41	0.5-1.4/ 54-71	4.2-x/ 66-x
2 at 7							x-0.4/ x-42
2 at 14							
5 at 2							
5 at 5							
11 at 3							

Table 6.24. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Salinity Skill Results: RMSE (PSU)/ RE (%).

Station DAB (m)	March	April	May	June	July	August	Sept
16 at 3				x-0.7/ x-62	0.7-0.5/ 62-82	1.2-1.6/ 52-64	1.4/ 59-
16 at 8							
16 at 11							
17 at 3				x-0.8/ x-85	1.1-1.1/ 84-91		
17 at 15							0.3-0.5/66-56
17 at 23			x-1.5/ x-66	1.4-1.3/ 81-79	1.2-0.5/ 67-62		
18 at 2							x-2.2/ x-51
19 at 2							x-1.8/ x-47
19 at 8							
22 at 2					x-3.4/ x-49	1.8-x/ 35-x	
22 at 6							x-1.1/ x-16
23 at 2							0.8-1.4/ 46-48
23 at 8							
24 at 2							x-1.8/ x-60
25 at 2							
33 at 2					9.0-9.1/ 78-67	8.1-6.4/ 70-53	4.6-x/ 55-x
33 at 11				6.6-6.8/ 60-67	2.9-7.2/ 28-67	6.5-7.9/ 62-70	3.2-x/ 46-x
51 at 2							0.0-0.0/0-0
51 at 9						0.0-0.0/ 0-0	0.0-0.0/0-100
154 at 2						3.9-5.4/ 91-70	4.7-x/84-x
154 at 8							x-4.4/ x-70

Table 6.24. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Salinity Skill Results: RMSE (PSU)/ RE (%).

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
2 at 7	0.4-0.3/ 19-44	0.4-0.3/ 37-22	0.4-x/ 43-x			1.5-1.3/ 77-49
2 at 14	0.7-0.2/ 55-71	0.3-0.2/ 45-12	0.1-x/ 24-x			
5 at 2	x-0.5/ x-8	0.2-x/ 3-x				

Table 6.24. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Salinity Skill Results: RMSE (PSU)/ RE (%).

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
5 at 5	x-0.5/ x-8	1.4-1.3/ 21-22				
11 at 3	x-0.5/ x-57	0.4-0.2/ 51-28				
16 at 8	0.6-0.5/ 92-60	0.5-0.2/ 53-60				
16 at 11	0.8-0.5/ 97-76	1.2-1.0/ 72-76				
17 at 15	1.0-0.9/ 69-73	0.4-0.2/ 79-53				
17 at 23						
18 at 2	2.1-0.7/ 52-24					
19 at 2	1.6-0.2/ 57-5					
19 at 8	0.2-0.3/ 5-13					
22 at 6	1.7-1.6/ 36-41					
23 at 2	1.2-0.4/ 50-61	0.4-1.0/ 23-74				
23 at 8	0.2-0.4/ 8-25	0.4-0.9/ 20-75				3.2-2.5/ 60-59
24 at 2	2.0-1.8/ 68-78					
25 at 2						
33 at 2						
33 at 11						
51 at 2	0.0-0.2/ 74-83	0.3-x/ 100-x	0.5-0.5/ 100-100		x-0.0/ x-100	0.0-0.0/ 100-0
51 at 9	0-0.2/ 100-100	0.3-0.4/ 100-100	0.5-x/ 100-x		x-0.0/ x-100	0.0-0.0/ 99-58
154 at 8	3.6-2.6/ 67-62				x-1.9/ x-59	2.0-2.3/ 59-89

Table 6.25. DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Salinity (PSU) Skill Results: Model/Observed.

Station DAB (m)	March	April	May	June	July	August	Sept
2 at 2					x-31.0/ x-31.7	31.0-31.1/ 30.4-29.9	30.8-x/ 26.8-x
2 at 7							x-30.7/ x-30.8
2 at 14							x-30.6/ x-30.3
5 at 2							

Table 6.25. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Salinity (PSU) Skill Results: Model/Observed.

Station DAB (m)	March	April	May	June	July	August	Sept
5 at 5							
11 at 3							
16 at 3				x-31.5/ x-32.0	31.9-32.0/ 32.5-31.7	31.8-31.7/ 30.8-30.2	31.8-x/ 30.5-x
16 at 8							
16 at 11							
17 at 3				x-32/2/ x-33.0	32.2-32.1/ 33.2-33.2	31.9-31.8/ 33.1-32.8	
17 at 15							32.0-32.1/ 31.9-32.3
17 at 23		x-32.5/ x-33.0	32.6-32.4/ 31.7-30.9	32.0-31.8/ 30.7-30.5	31.8-31.8/ 30.7-31.5		
18 at 2							x-27.0/ x-26.2
19 at 2							x-29.5 x-28.1
19 at 8							
22 at 2					x-25.3/ x-28.4	25.9-x/ 27.5-x	
22 at 6							x-26.9/ x-26.9
23 at 2							28.0-28.4 27.3-27.1
23 at 8							
24 at 2							x-24.4/ x-26.1
25 at 2							
33 at 2					9.7-11.2/ 17.1-20.0	11.8-15.5/ 19.6-21.3	16.3-x/ 20.6-x
33 at 11				4.8-8.1/ 11.9-13.8	8.8-7.8/ 11.2-14.6	10.2-12.9/ 16.5-19.4	15.1-x/ 18.2-x
51 at 2							0.0-0.0/ 0-1
51 at 9						0.0-0.0/ 0-0	0.0-0.0/ 0-0
154 at 2						1.1-1.2/ 4.5-6.4	2.2-x/ 6.7-x
154 at 8							x-3.5/ x-8.2

Table 6.25. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Salinity (PSU) Skill Results: Model/Observed.

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
2 at 7	30.9-30.8/ 30.7-31.0	31.1-30.7/ 31.4-31.0	31.3-x/ 31.6-x			31.3-31.6/ 32.7-32.9
2 at 14	30.7-30.8/ 30.1-30.8	31.0-30.7/ 31.1-30.7	31.1-x/ 31.0-x			
5 at 2	x-31.0/ x-30.7	30.7-x/ 31.0-x				
5 at 5	x-31.0/ x-30.7	30.6-30.4/ 30.0-28.3				
11 at 3	x-32.6/ x-32.2	32.8-32.8/ 32.4-32.6				
16 at 8	32.0-32.0/ 32.0-32.2	32.6-32.8/ 32.2-32.8				
16 at 11	32.0-32.0/ 31.6-31.7	32.6-32.8/ 31.4-31.7				
17 at 15	32.1-32.3/ 33.0-33.2	32.6-32.9/ 32.9-33.0				
17 at 23						
18 at 2	27.2-27.5/ 27.4-27.5					
19 at 2	29.8-30.0/ 29.3-30.2					
19 at 8	29.8-29.9/ 29.7-30.0					
22 at 6	27.3-27.4/ 27.6-28.8					
23 at 2	28.7-28.8/ 27.7-28.9	29.1-29.2/ 29.2-30.1				
23 at 8	28.7-28.8/ 28.6-28.7	29.1-29.2/ 29.1-30.1				28.4-29.9/ 26.9-27.7
24 at 2	24.9-25.5 26.6-27.1					
25 at 2						
33 at 2						
33 at 11						
51 at 2	0.0-0.2/ 7-4	0.3-x/ 0.0-x	0.5-0.5/ 0.0-0.0		x-0.0/ x-0.0	0.0-0.0/ 0.0-0.0
51 at 9	0.0-0.2/ 0-0	0.3-0.4/ 0.0-0.0	0.5-x/ 0.0-x		x-0.0/ x-0.0	0.0-0.0/ 0.0-0.0
154 at 8	5.5-7.2/ 8.9-9.8				x-6.5/ x-3.1	2.1-2.9/ 4.0-3.9

Table 6.26. DBOFS Version 1.1 March 1984-March 1985 Hindcast Temperature Skill Results: RMSE (oC)/ RE (%).

Station DAB (m)	March	April	May	June	July	August	Sept
2 at 2							5.7-x/ 67-x
2 at 7							x-3.8/ x-72
2 at 14							x-3.7/ x-71
5 at 2							
5 at 5							
11 at 3							
16 at 3						6.1-x/ 54-x	
16 at 8							
16 at 11							
17 at 3							
17 at 15							4.7-4.5/ 62-65
17 at 23		x-4.1/ x-81	2.9-2.7/ 57-47	3.8-2.7/ 74-52	2.7-x/ 52-x		
18 at 2							x-3.3/ x-60
19 at 2							x-3.1/ x-74
19 at 8							
22 at 2						5.9-x/ 68-x	
22 at 6							x-2.9/ x-67
23 at 2							3.3-3.1/ 93-70
23 at 8							
24 at 2							x-2.5/ x-54
33 at 2					4.4-5.4/ 89-80	4.0-5.4/ 62-80	2.3-x/ 50-x
33 at 11				3.0-3.5/ 87-81	2.6-3.8/ 70-76	3.4-3.8/ 67-76	2.7-x/ 55-x
51 at 2							0.2-0.4/ 10-6
51 at 9							
154 at 2							
154 at 8							x-0.7/ x-21

Table 6.26. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Temperature Skill Results: RMSE (oC)/ RE (%).

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
2 at 7	4.3-3.1/ 88-83	3.5-5.3/ 53-64	4.8-/ 89-x			1.6-1.68/ 66-82
2 at 14	4.3-3.1/ 88-82	3.5-5.3/ 51-65	5.1-x/ 96-x			
5 at 2	x-2.7/ x-83	3.8-5.0/ 46-76				
5 at 5	x-2.7/ x-82	3.8-5.1/ 46-76				
11 at 3	x-3.9/ x-93	3.7-4.8/ 62-89				
16 at 8	3.9-2.2/ 85-80	3.8-5.2/ 63-65				
16 at 11	3.8-2.3/ 84-76	3.1-4.2/ 67-60				
17 at 15	1.5-1.0/ 75-71	1.9-1.5/ 52-43				
17 at 23						
18 at 2	3.2-2.7/ 82-95					
19 at 2	3.9-3.6/ 79-97					
19 at 8	3.8-3.4/ 81-97					
22 at 6	2.9-2.6/ 74-96					
23 at 2	3.1-2.2/ 77-73	2.3-3.3/ 31-48				
23 at 8	3.2-2.4/ 90-74	2.3-3.3/ 31-48				1.2-0.9/ 49-42
24 at 2	2.4-1.9/ 76-91					
33 at 2						
33 at 11						
51 at 2	0.4-0.5/ 11-69		1.1-5.4/ 40-74			x-0.9/ x-94
51 at 9					x-1.0/ x-76	1.1-0.6/ 44-35
154 at 8	0.9-0.4/ 39-31				x-0.8/ x-59	0.7-0.6/ 15-22

Table 6.27. DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Temperature (oC) Skill Results: Model/Observed.

Station DAB (m)	March	April	May	June	July	August	Sept
2 at 2						x-25.2/ x-22.7	24.6-x/ 19.3-x
2 at 7							x-23.8/ x-19.5
2 at 14							x-23.8/ x-19.6
5 at 2							
5 at 5							
11 at 3							
16 at 3						22.5-22.5/ 13.2-18.8	22.4-x/ 17.0-x
16 at 8							
16 at 11							
17 at 3							
17 at 15							21.0-20.2/ 16.6-17.1
17 at 23		x-11.1/ x-7.1	13.0-15.9/ 10.1-13.3	18.9-21.2/ 15.1-18.9	23.3-23.5/ 19.1-15.8		
18 at 2							x-23.4/ x-20.0
19 at 2							x-23.6/ x-20.4
19 at 8							
22 at 2					x-25.7/ x-16.6	26.8-x/ 20.8-x	
22 at 6							x-23.5/ x-20.5
23 at 2							25.7-23.6/ 21.9-20.5
23 at 8							
24 at 2							x-22.9/ x-20.3
25 at 2							
33 at 2					26.4-27.4/ 23.1-22.1	27.9-27.4/ 24.0-24.9	25.6-x/ 23.5-x
33 at 11				22.1-25.4/ 22.6-22.1	26.6-27.5/ 24.1-23.8	28.2-27.5/ 24.8-24.8	25.6-x/ 23.2-x
51 at 2							24.4-21.6/ 23.8-21.9
51 at 9							
154 at 2							
154 at 8							x-21.7/ x-19.5

Table 6.27. (Cont.) DBOFS Version 1.1 March 1984-March 1985 Hindcast Mean Temperature (oC) Skill Results: Model/Observed.

Station DAB (m)	Oct	Nov	Dec	Jan	Feb	Mar
2 at 7	21.6-20.3/ 17.2-17.3	18.9-15.5/ 15.5-10.2	13.5-x/ 9.9-x			7.2-7.7/ 5.6-6.2
2 at 14	21.5-20.3/ 17.2-17.3	18.8-15.4/ 15.4-10.1	13.4-x/ 9.4-x			
5 at 2	x-20.2/ x-17.6	18.2-14.7/ 14.6-9.9				
5 at 5	x-20.2/ x-17.6	18.2-14.7/ 14.5-9.9				
11 at 3	x-21.0/ x-17.0	19.4-x/ 15.8-x				
16 at 8	19.9-17.5/ 17.0-16.8	19.0-x/ 15.4-x				
16 at 11	20.0-17.9/ 17.1-17.1	19.1-x/ 16.1-x				
17 at 15	17.8-16.1/ 16.8-16.4	13.9-13.3/ 15.2-12.9				
17 at 23						
18 at 2	20.1-19.8/ 16.9-16.8					
19 at 2	21.0-19.9/ 17.0-16.6					
19 at 8	20.9-19.9/ 17.1-16.7					
22 at 6	20.1-19.9/ 17.2-16.9					
23 at 2	20.4-19.8/ 17.3-17.6	17.6-12.6/ 15.3-9.6				
23 at 8	20.4-19.8/ 16.9-17.5	17.6-12.6/ 15.3-9.6				6.5-7.3/ 5.6-6.4
24 at 2	19.0-19.2/ 16.6-16.6					
25 at 2						
33 at 2						
33 at 11						
51 at 2	17.7-17.6/ 18.0-17.5		6.3-6.6/ 6.0-1.4			x-7.1/ x-9.0
51 at 9					x-1.8/ x-5.3	6.0-7.1/ 7.0-7.7
154 at 8	17.8-18.2/ 17.0-17.1				x-2.9/ x-5.5	5.7-6.9/ 6.2-7.4

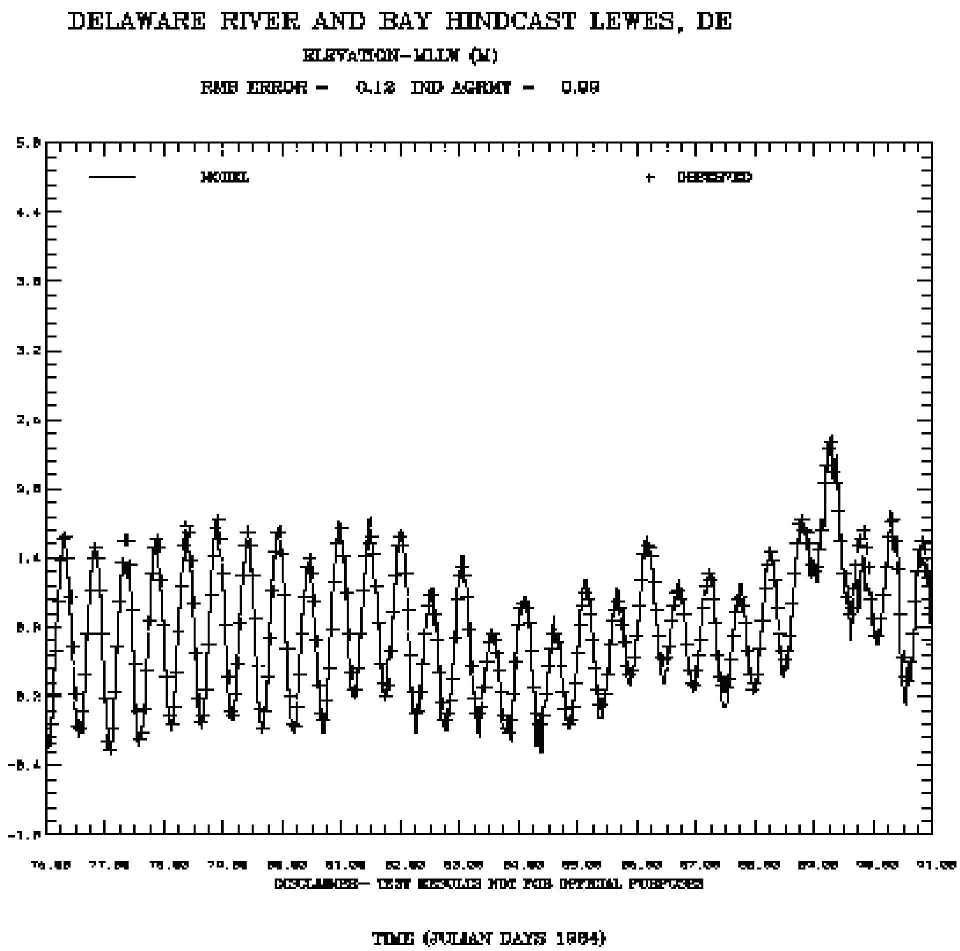


Figure 6.11. DBOFS Version 1.1 Water Surface Elevation JD 70-91, 1984 at Lewes, DE. Observations are at one hour intervals.

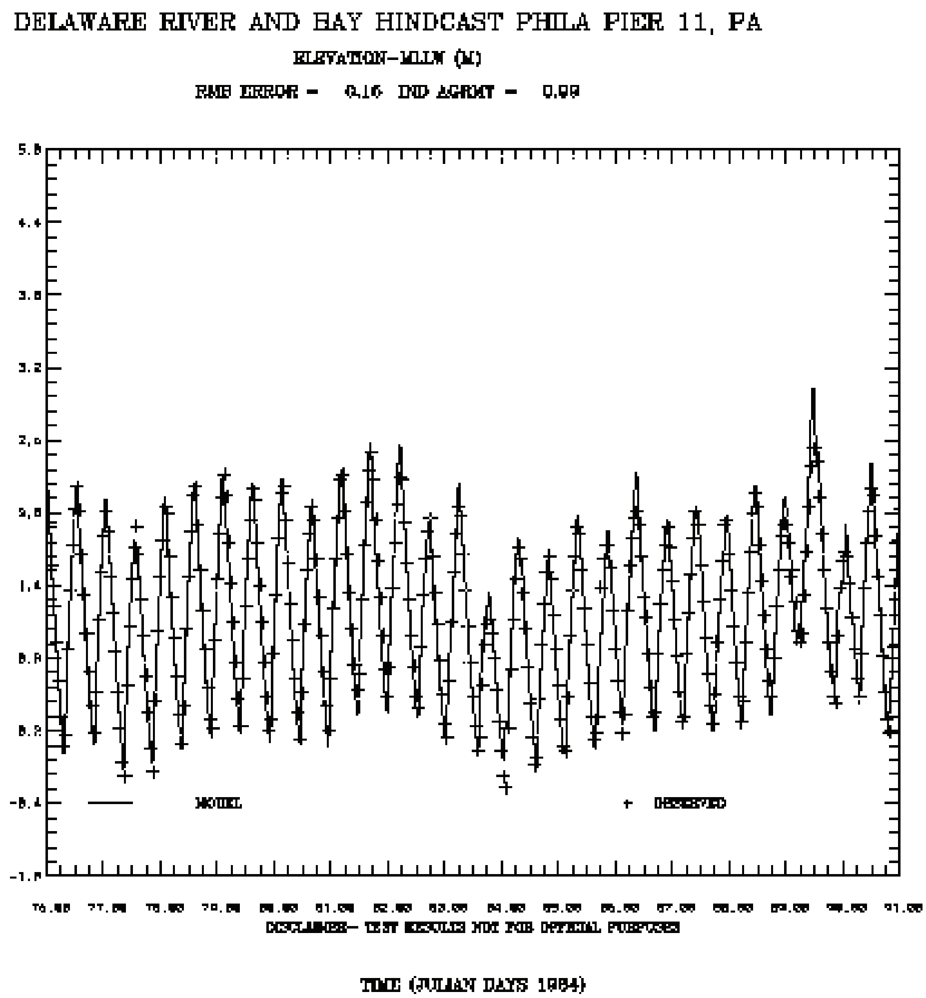


Figure 6.12. DBOFS Version 1.1 Water Surface Elevation JD 70-91, 1984 at Philadelphia, PA. Observations are at one hour intervals.

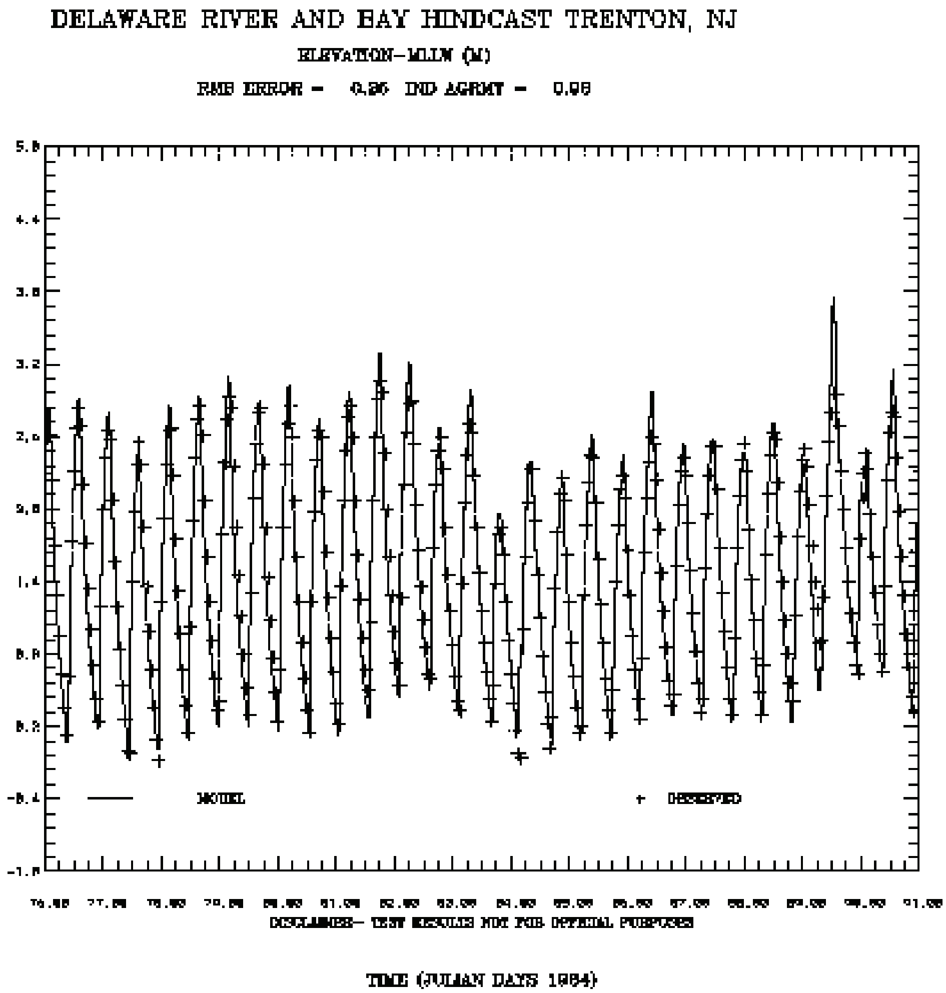


Figure 6.13. DBOFS Version 1.1 Water Surface Elevation JD 70-91, 1984 at Trenton, NJ. Observations are at one hour intervals.

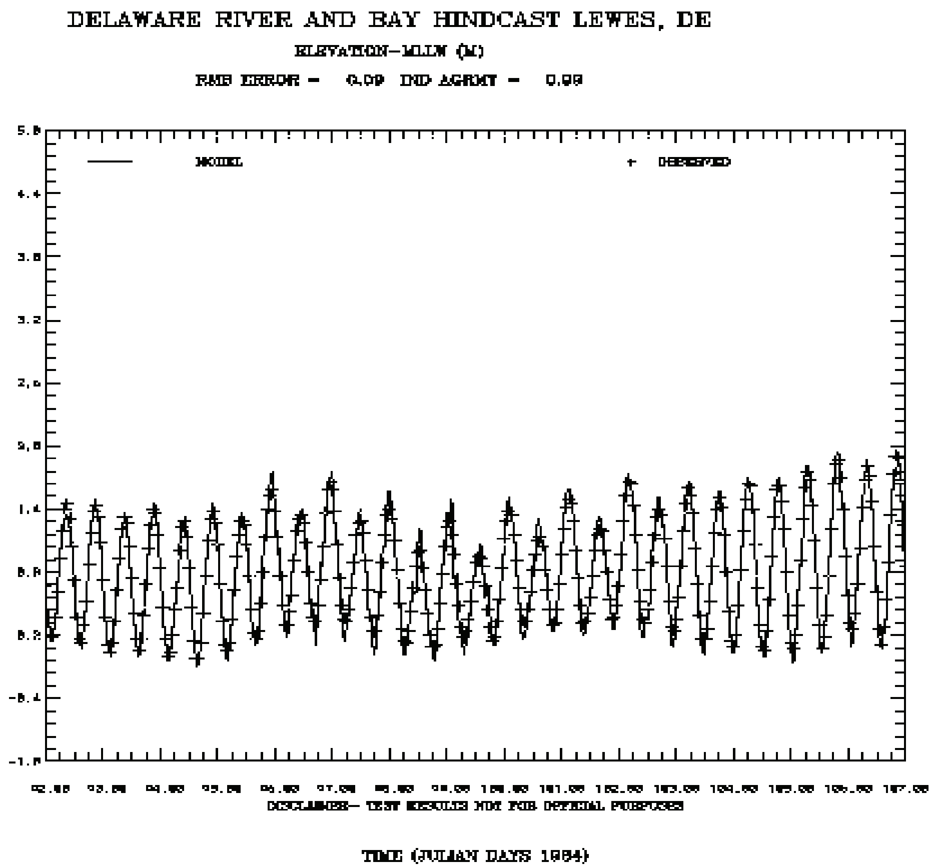


Figure 6.14. DBOFS Version 1.1 Water Surface Elevation JD 92-107, 1984 at Lewes, DE. Observations are at one hour intervals.

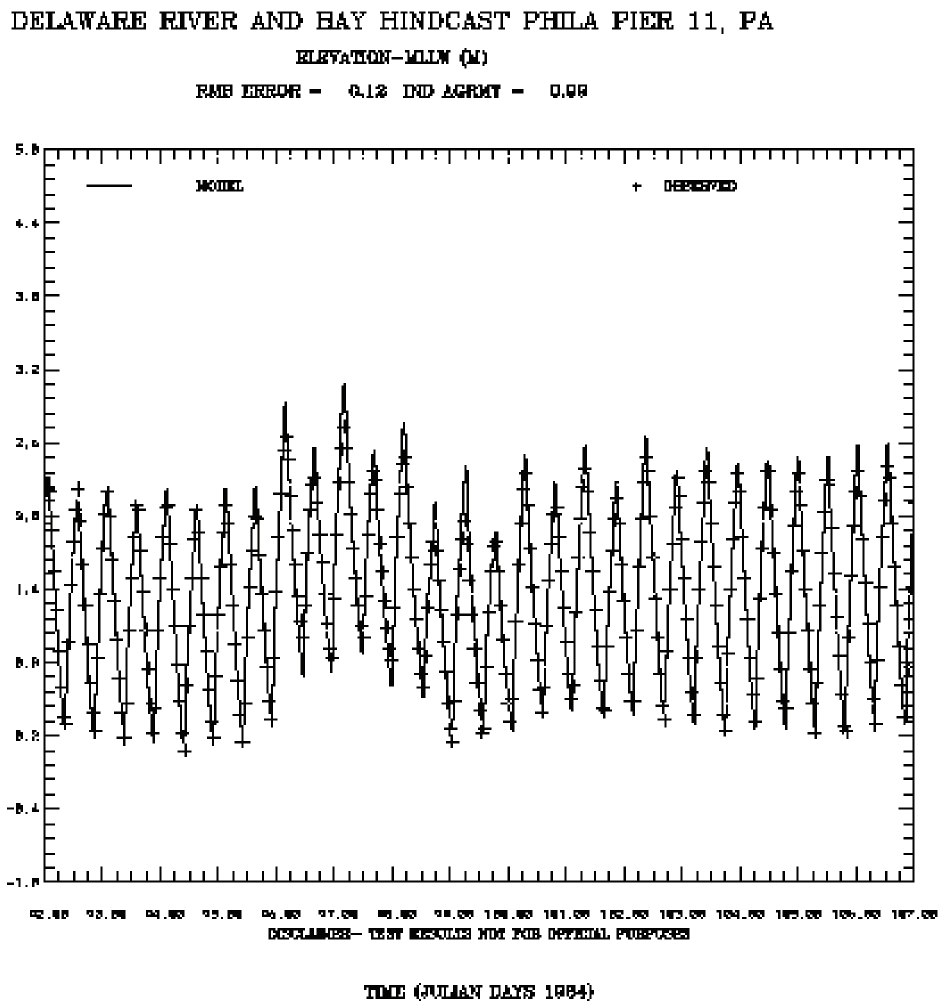


Figure 6.15. DBOFS Version 1.1 Water Surface Elevation JD 92-107, 1984 at Philadelphia, PA. Observations are at one hour intervals.

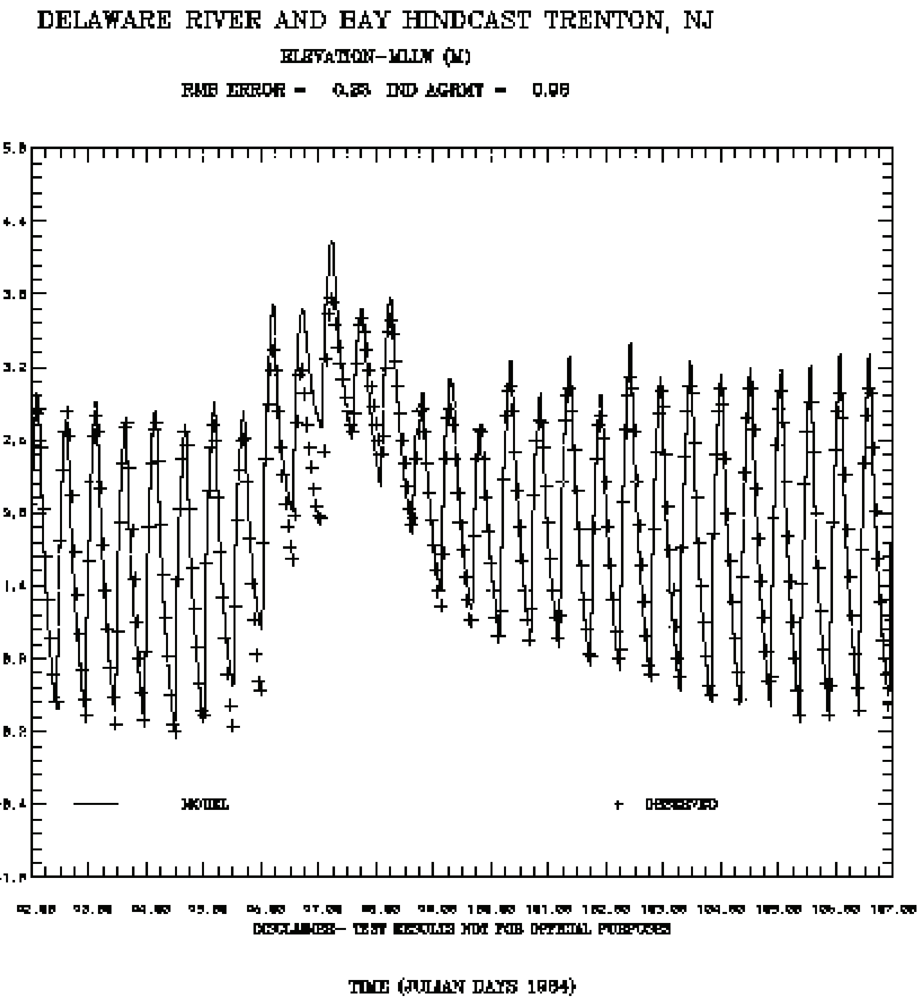


Figure 6.16. DBOFS Version 1.1 Water Surface Elevation JD 92-107, 1984 at Trenton, NJ. Observations are at one hour intervals.

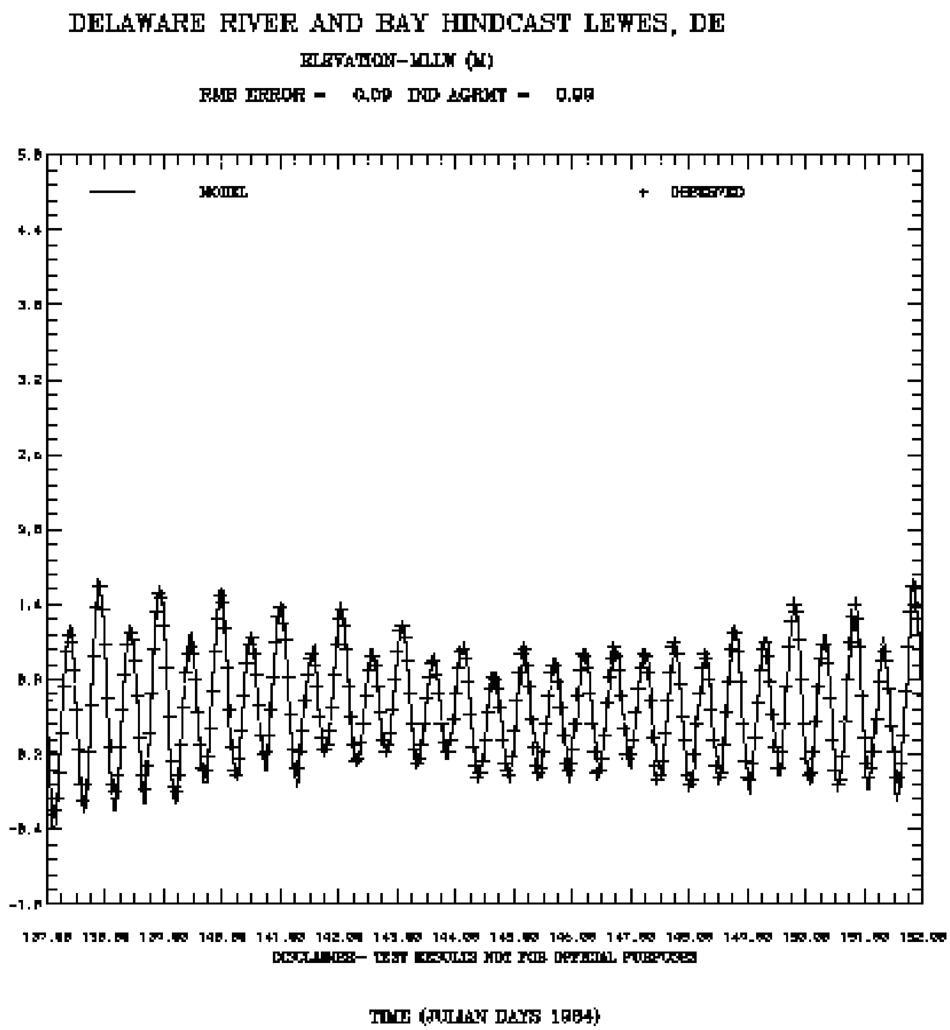


Figure 6.17. DBOFS Version 1.1 Water Surface Elevation JD 137-152, 1984 at Lewes, DE. Observations are at one hour intervals.

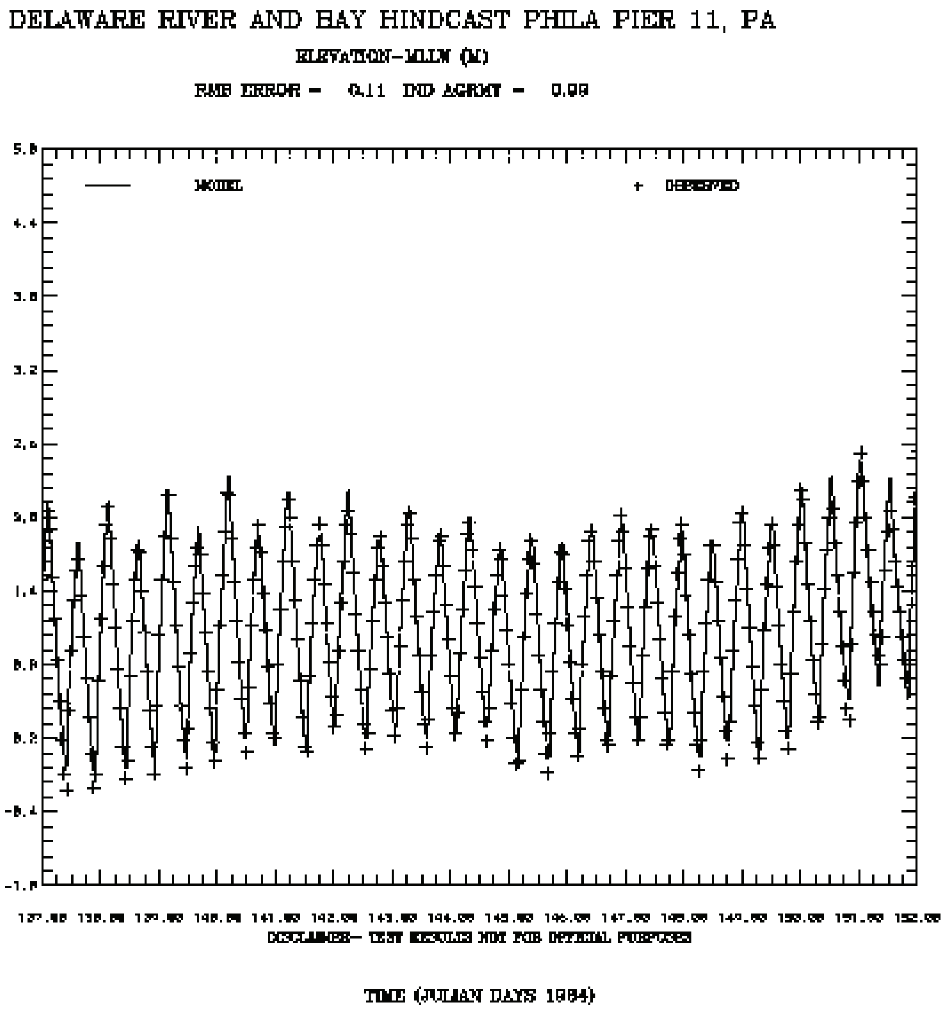


Figure 6.18. DBOFS Version 1.1 Water Surface Elevation JD 137-152, 1984 at Philadelphia, PA. Observations are at one hour intervals.

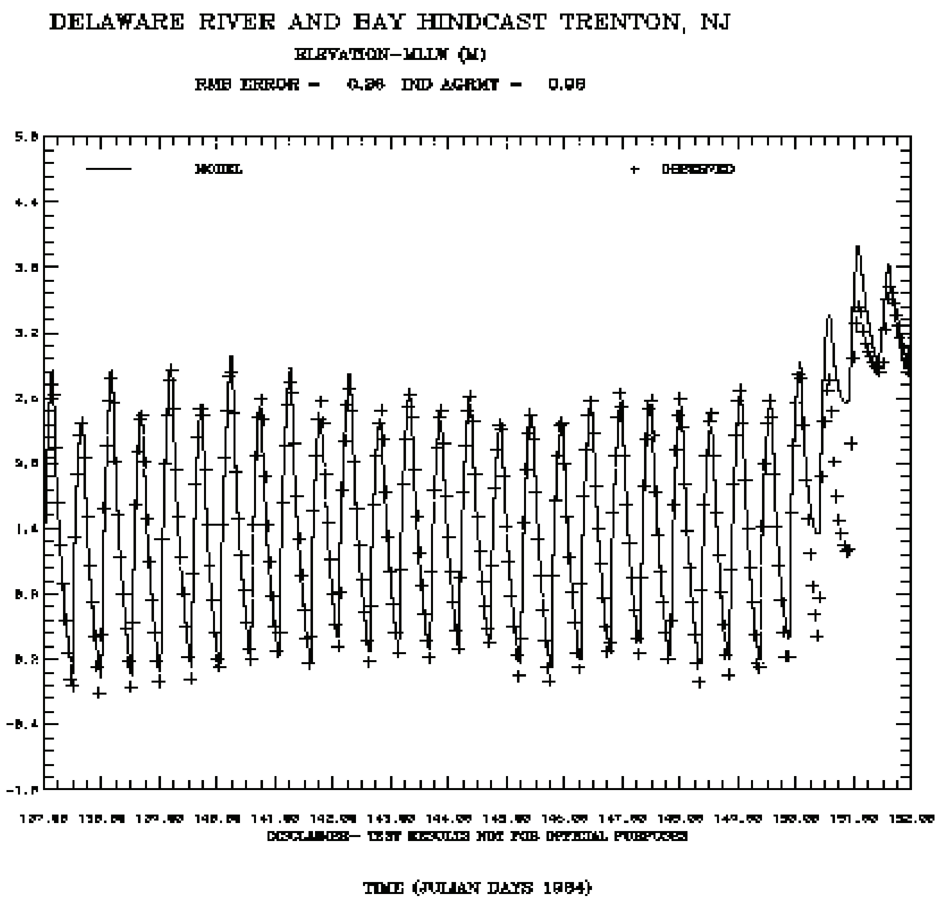


Figure 6.19. DBOFS Version 1.1 Water Surface Elevation JD 137-152, 1984 at Trenton, NJ. Observations are at one hour intervals.

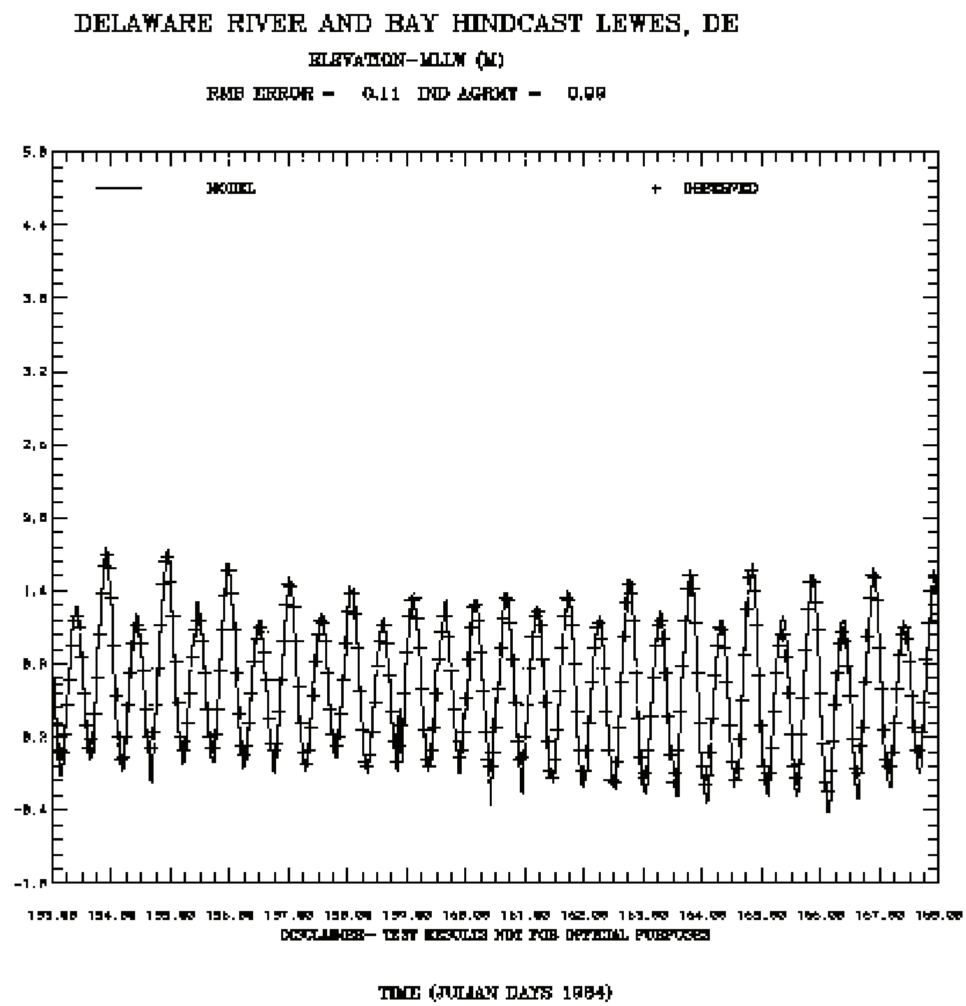


Figure 6.20. DBOFS Version 1.1 Water Surface Elevation JD 153-168, 1984 at Lewes, DE. Observations are at one hour intervals.

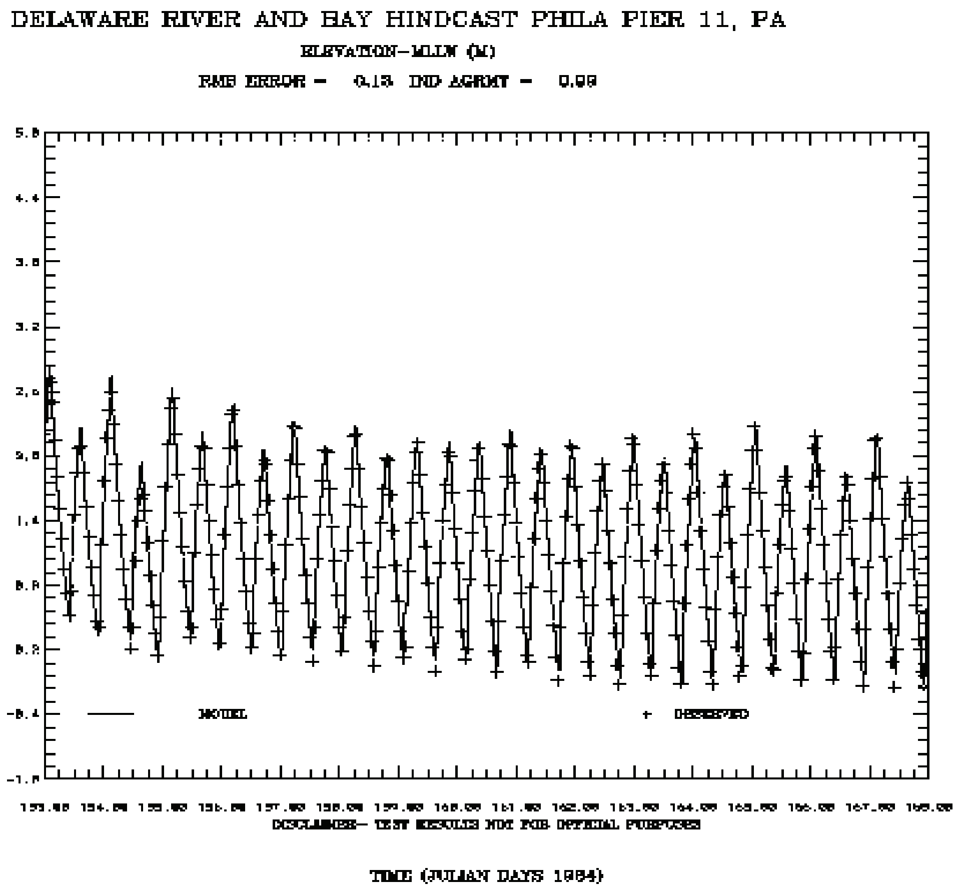


Figure 6.21. DBOFS Version 1.1 Water Surface Elevation JD 153-168, 1984 at Philadelphia, PA. Observations are at one hour intervals.

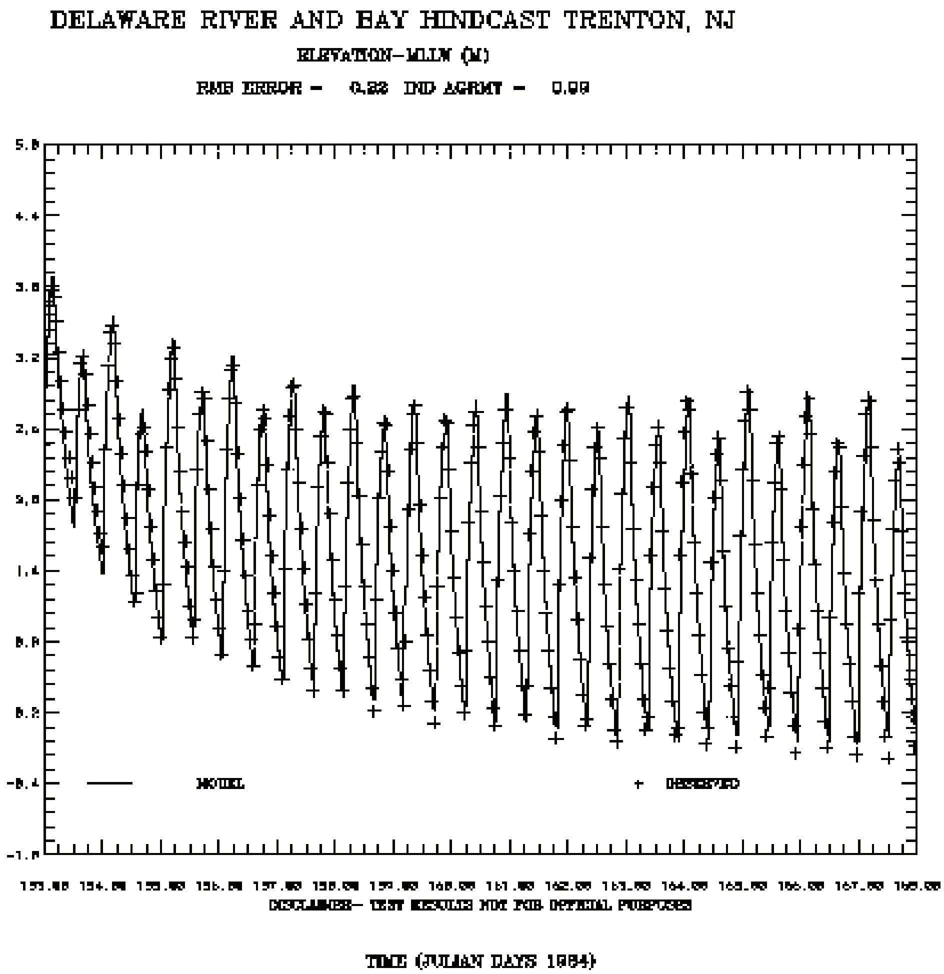


Figure 6.22. DBOFS Version 1.1 Water Surface Elevation JD 153-168, 1984 at Trenton, NJ. Observations are at one hour intervals.

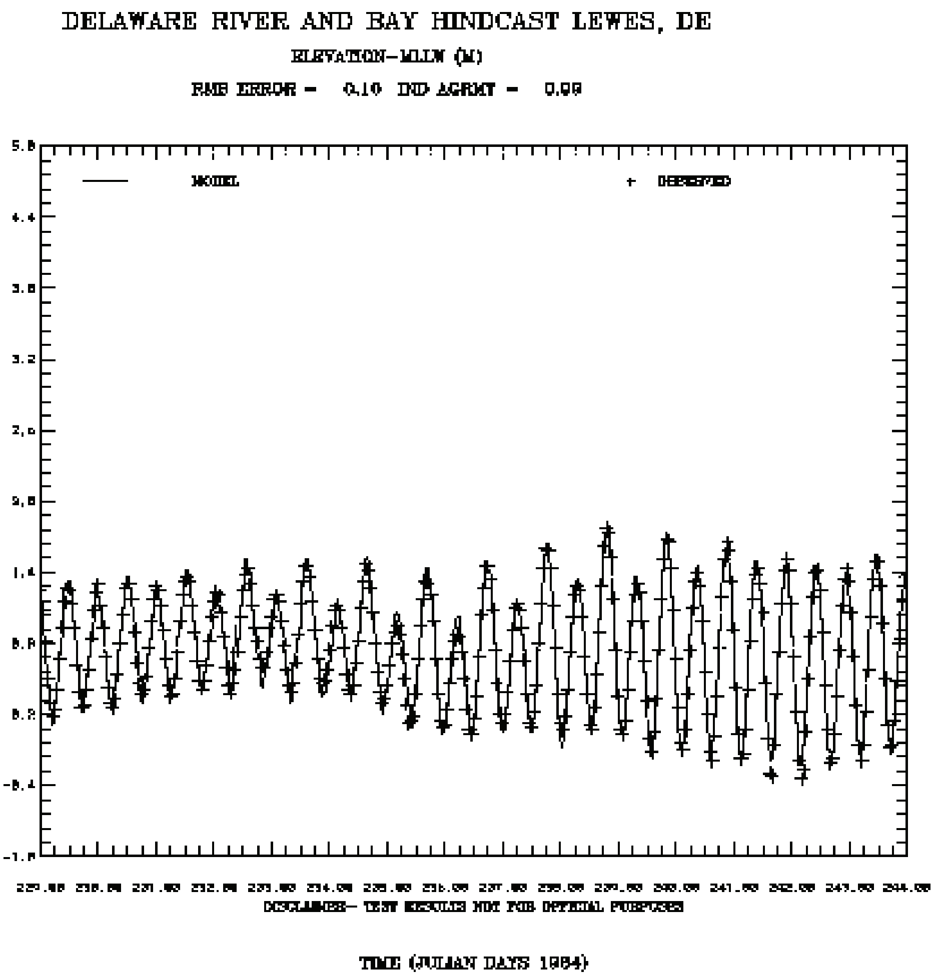


Figure 6.23. DBOFS Version 1.1 Water Surface Elevation JD 229-244, 1984 at Lewes, DE. Observations are at one hour intervals.

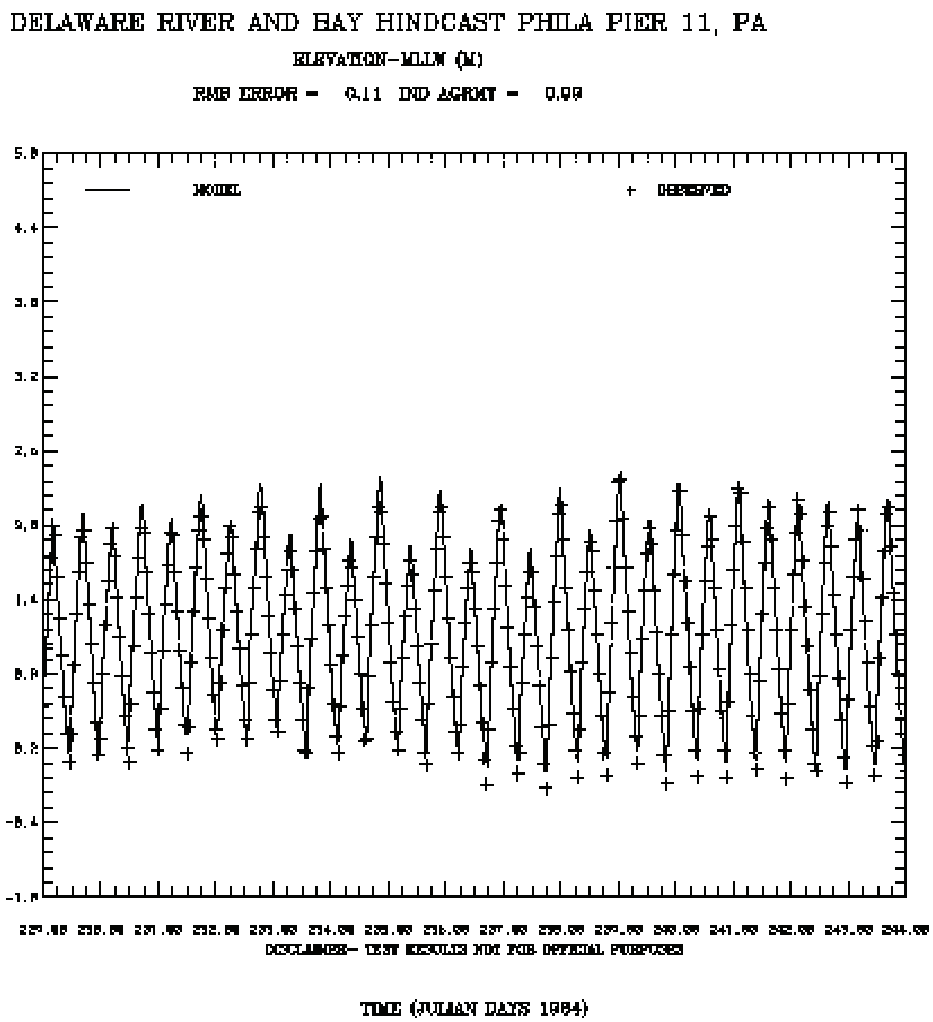


Figure 6.24. DBOFS Version 1.1 Water Surface Elevation JD 229-244, 1984 at Philadelphia, PA. Observations are at one hour intervals.

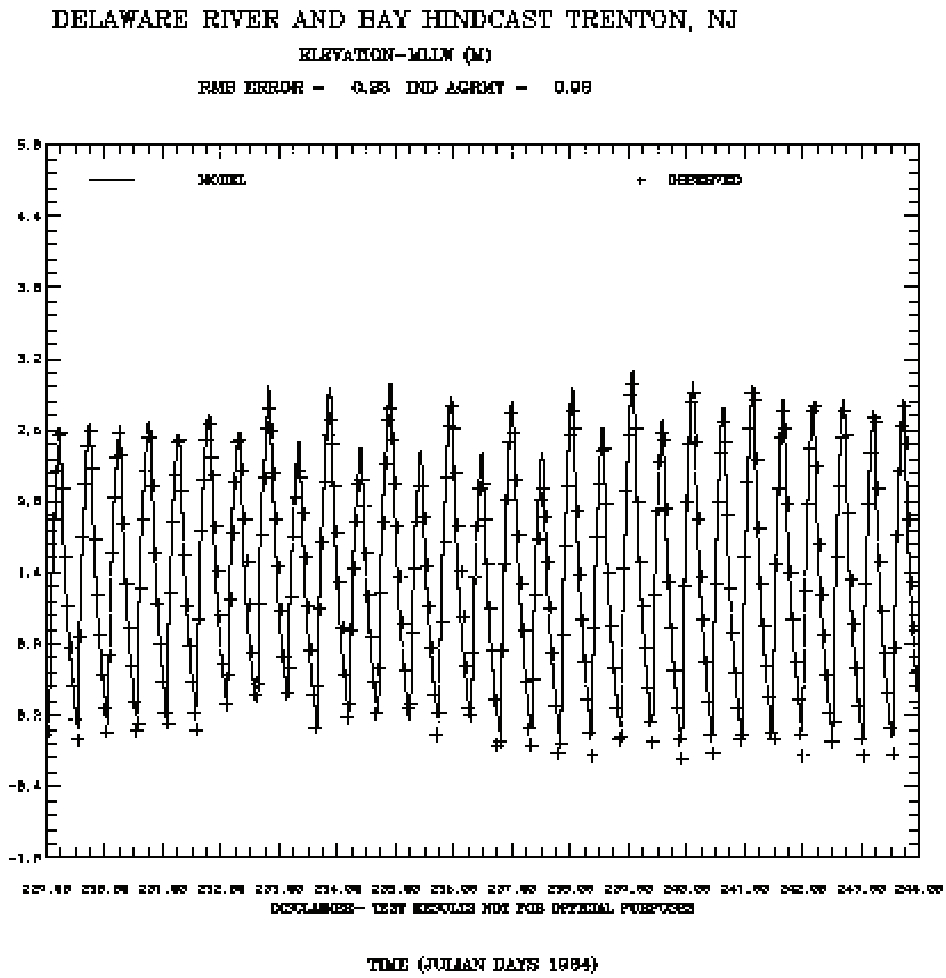


Figure 6.25. DBOFS Version 1.1 Water Surface Elevation JD 229-244, 1984 at Trenton, NJ. Observations are at one hour intervals.

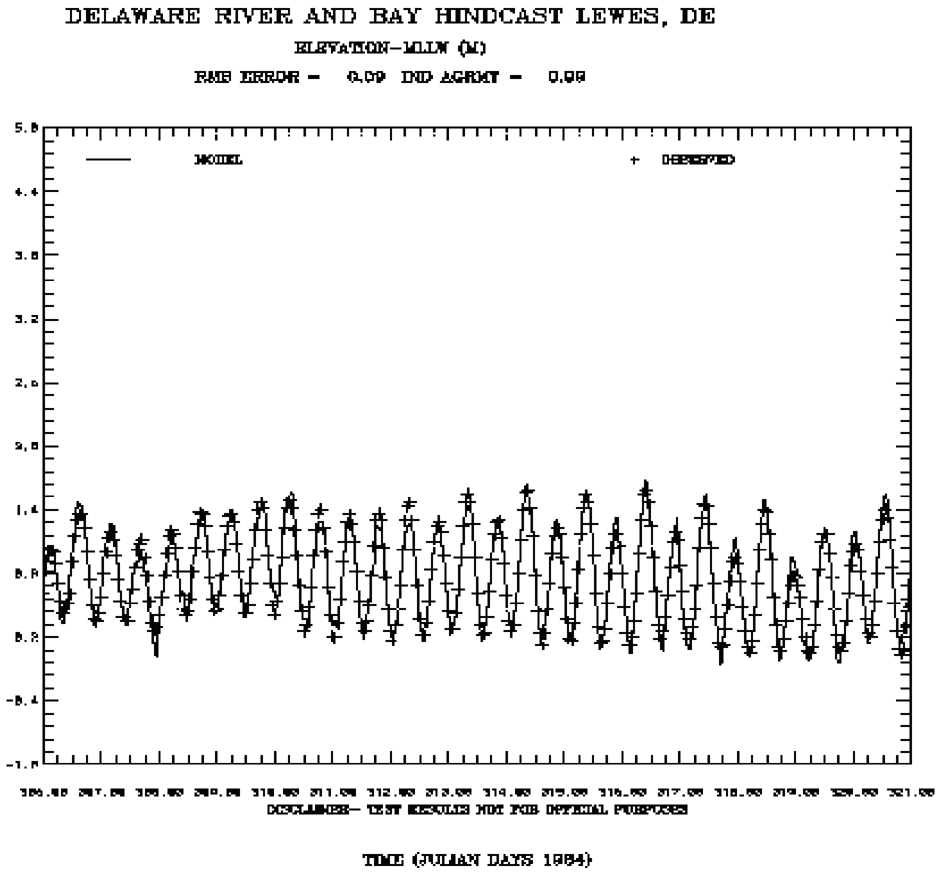


Figure 6.26. DBOFS Version 1.1 Water Surface Elevation JD 306-321, 1984 at Lewes, DE. Observations are at one hour intervals.

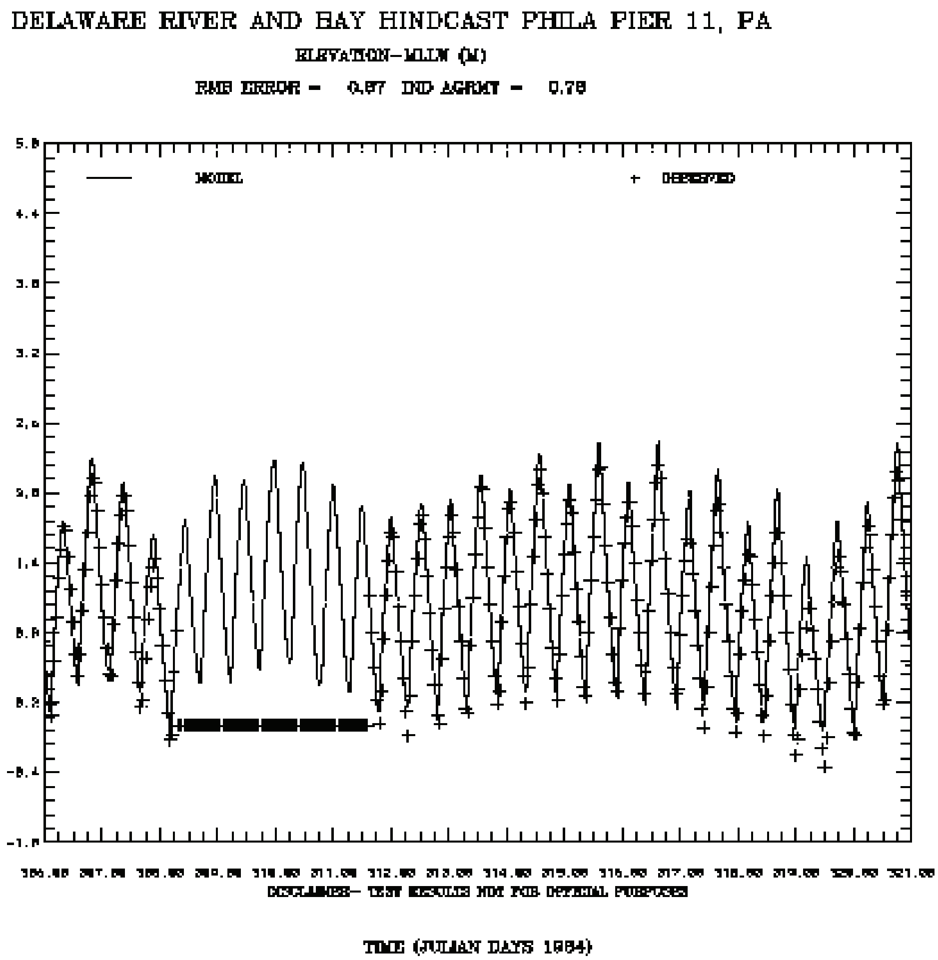


Figure 6.27. DBOFS Version 1.1 Water Surface Elevation JD 306-321, 1984 at Philadelphia, PA. Observations are at one hour intervals.

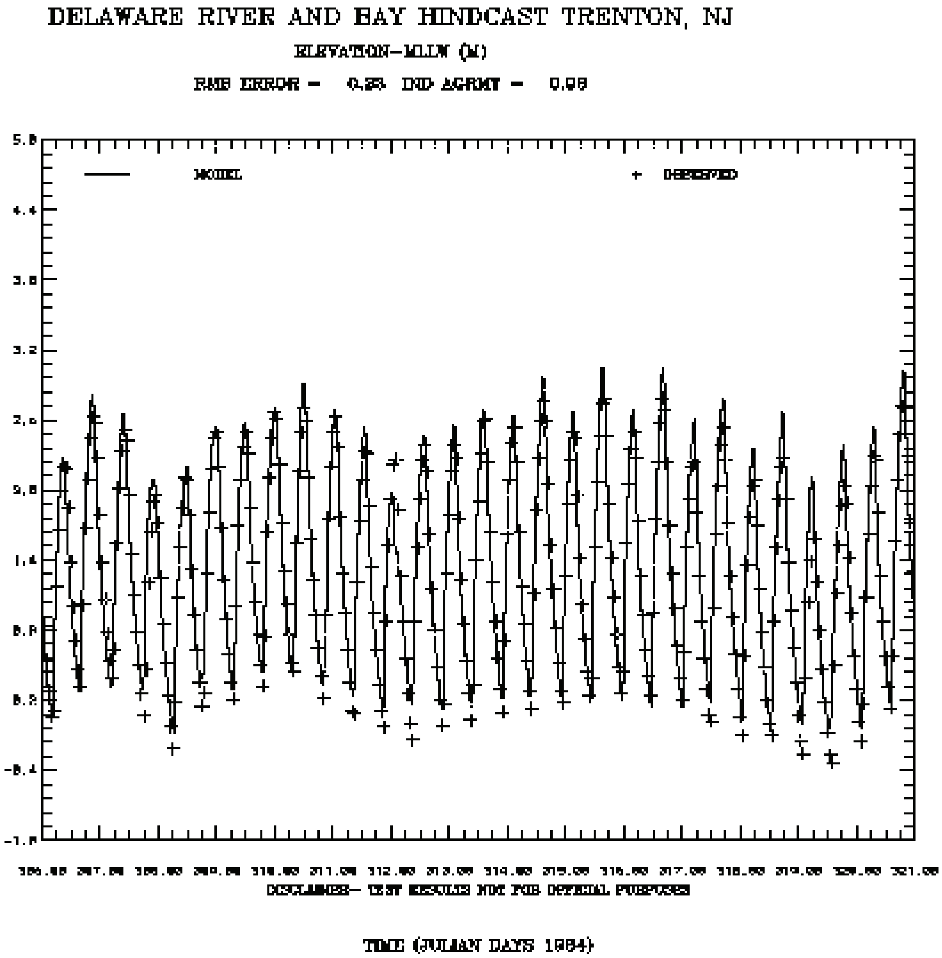


Figure 6.28. DBOFS Version 1.1 Water Surface Elevation JD 306-321, 1984 at Trenton, NJ. Observations are at one hour intervals.

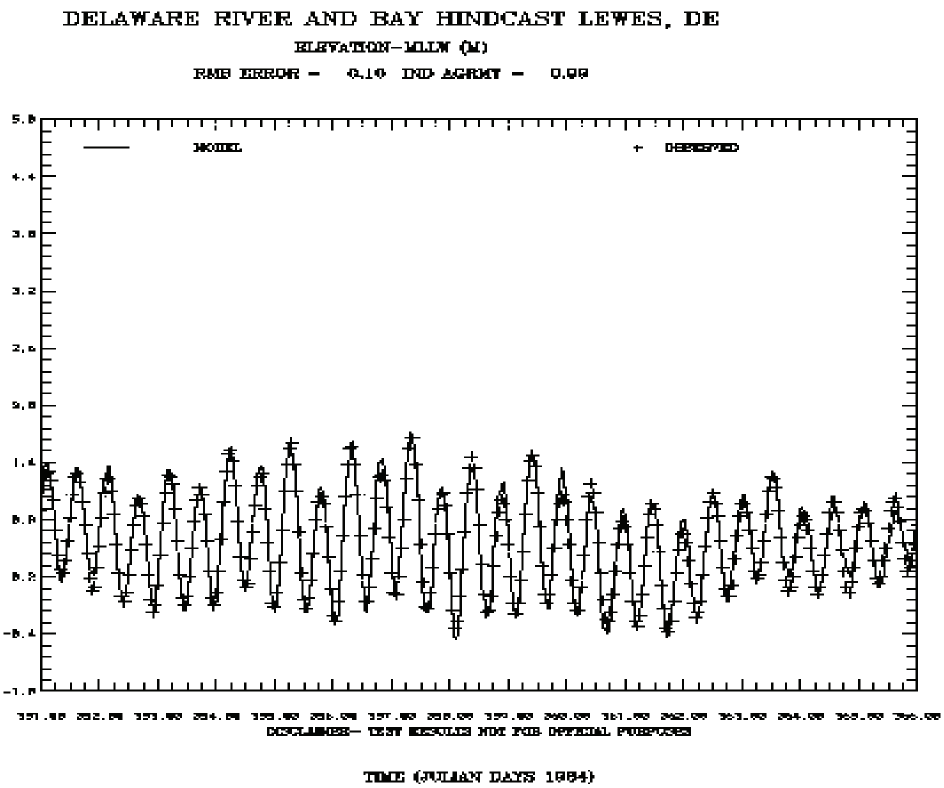


Figure 6.29. DBOFS Version 1.1 Water Surface Elevation JD 351-366, 1984 at Lewes, DE. Observations are at one hour intervals.

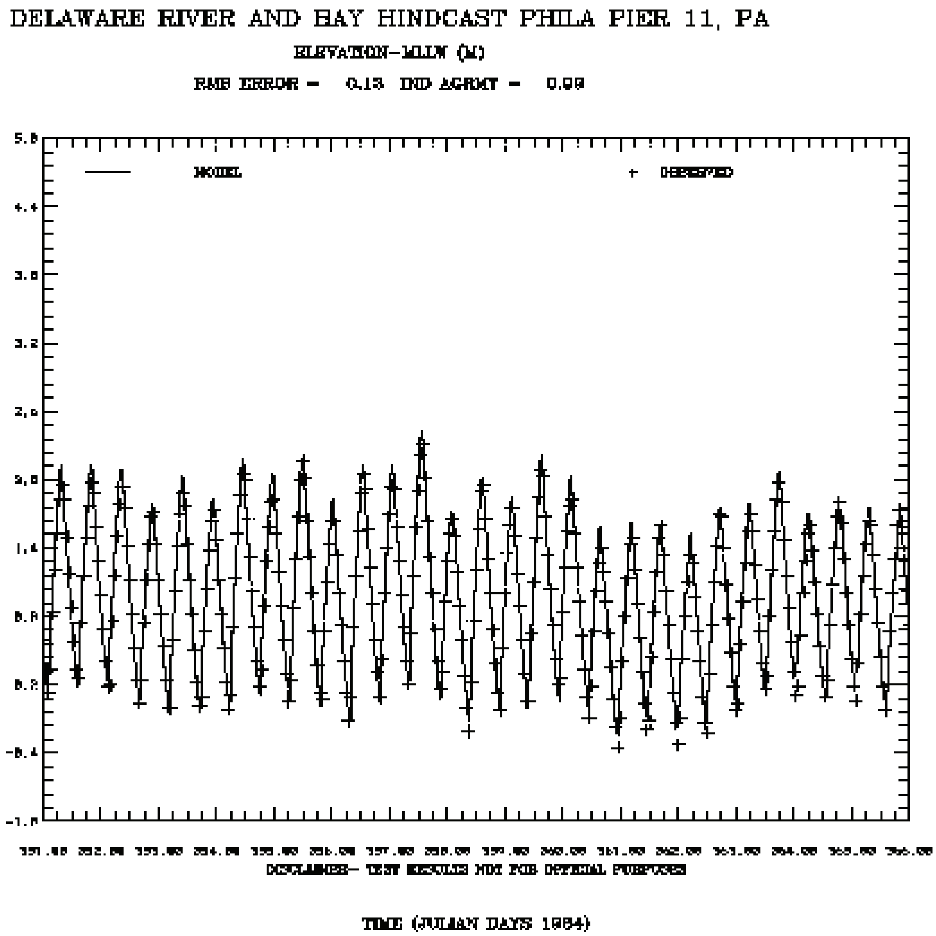


Figure 6.30. DBOFS Version 1.1 Water Surface Elevation JD 351-366, 1984 at Philadelphia, PA. Observations are at one hour intervals.

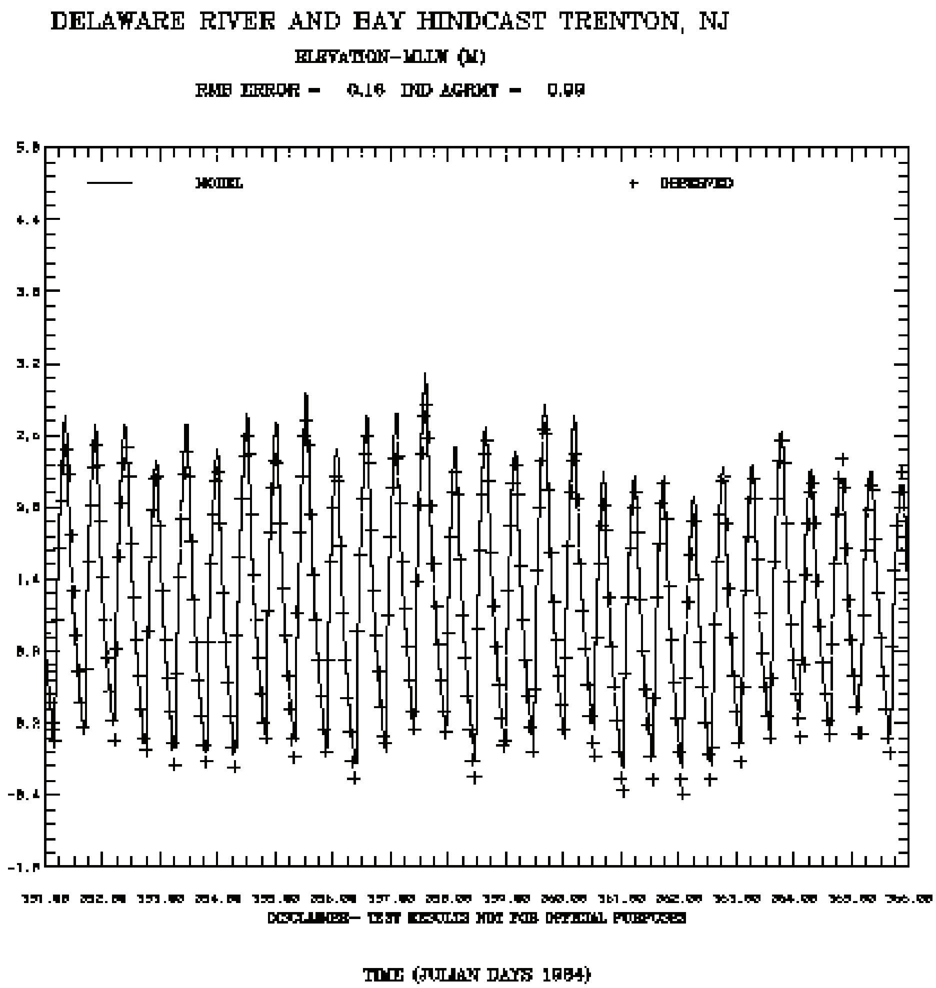


Figure 6.31. DBOFS Version 1.1 Water Surface Elevation JD 351-366, 1984 at Trenton, NJ. Observations are at one hour intervals.

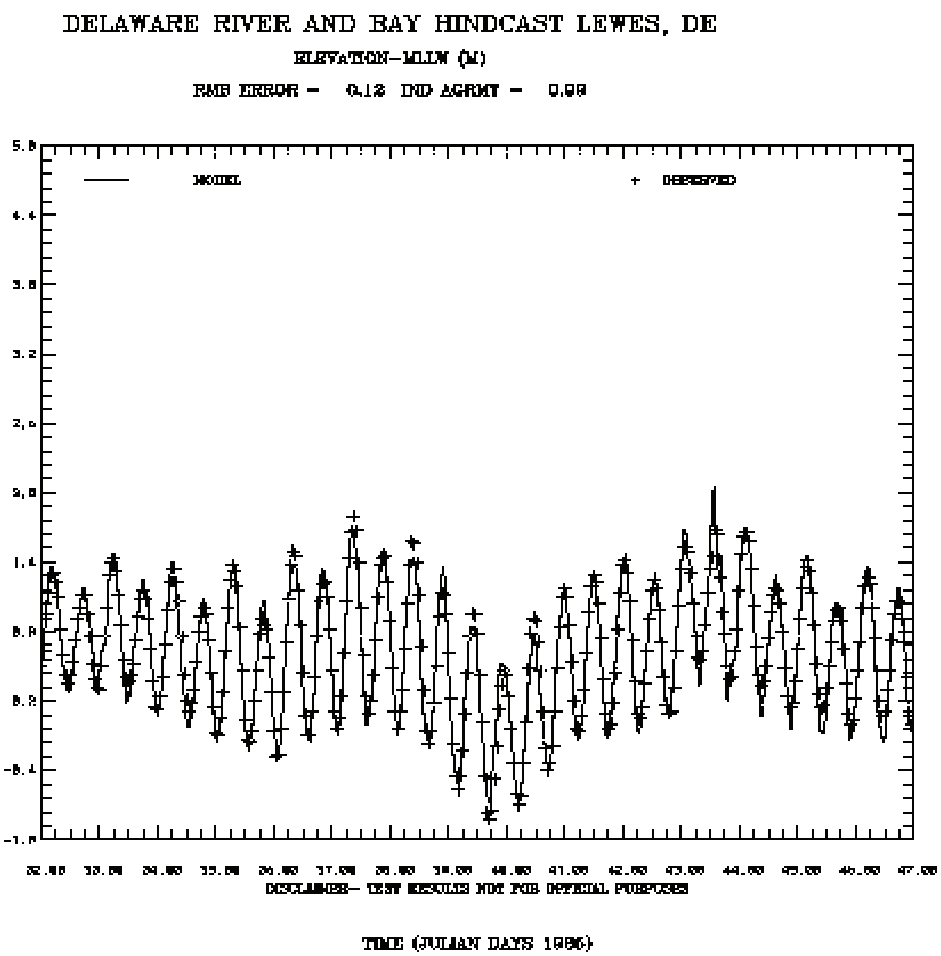


Figure 6.32. DBOFS Version 1.1 Water Surface Elevation JD 32-47, 1985 at Lewes, DE. Observations are at one hour intervals.

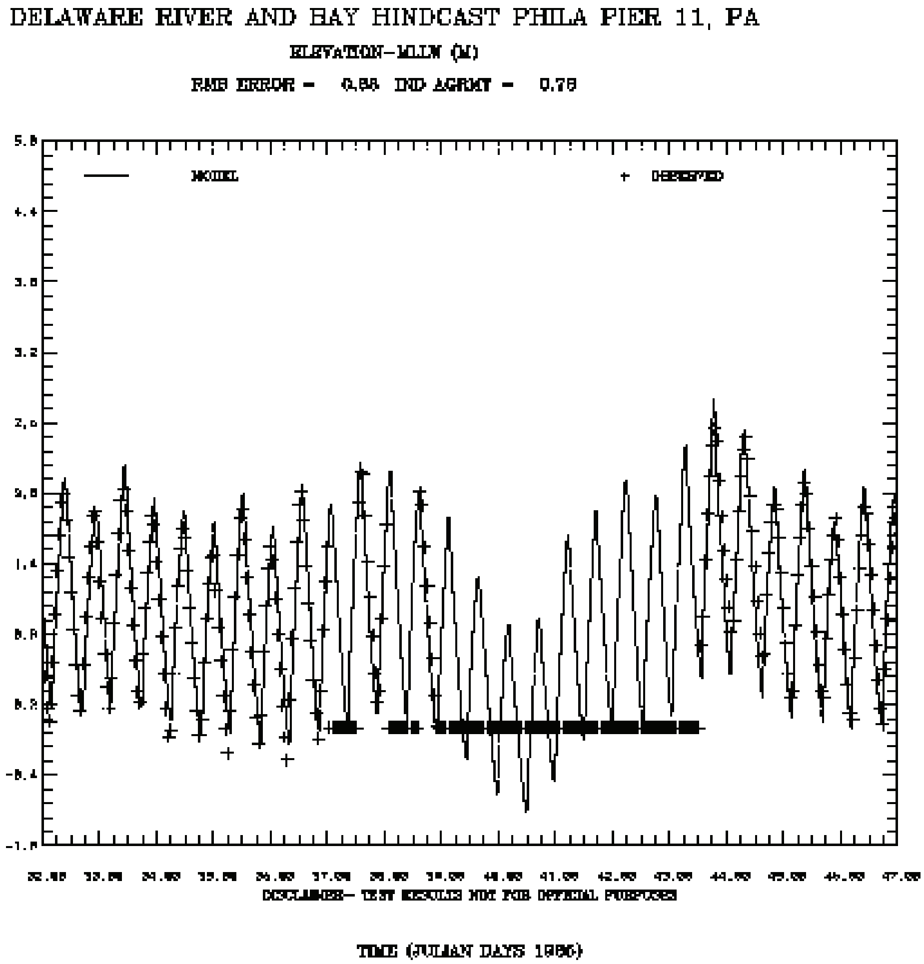


Figure 6.33. DBOFS Version 1.1 Water Surface Elevation JD 32-47, 1985 at Philadelphia, PA. Observations are at one hour intervals.

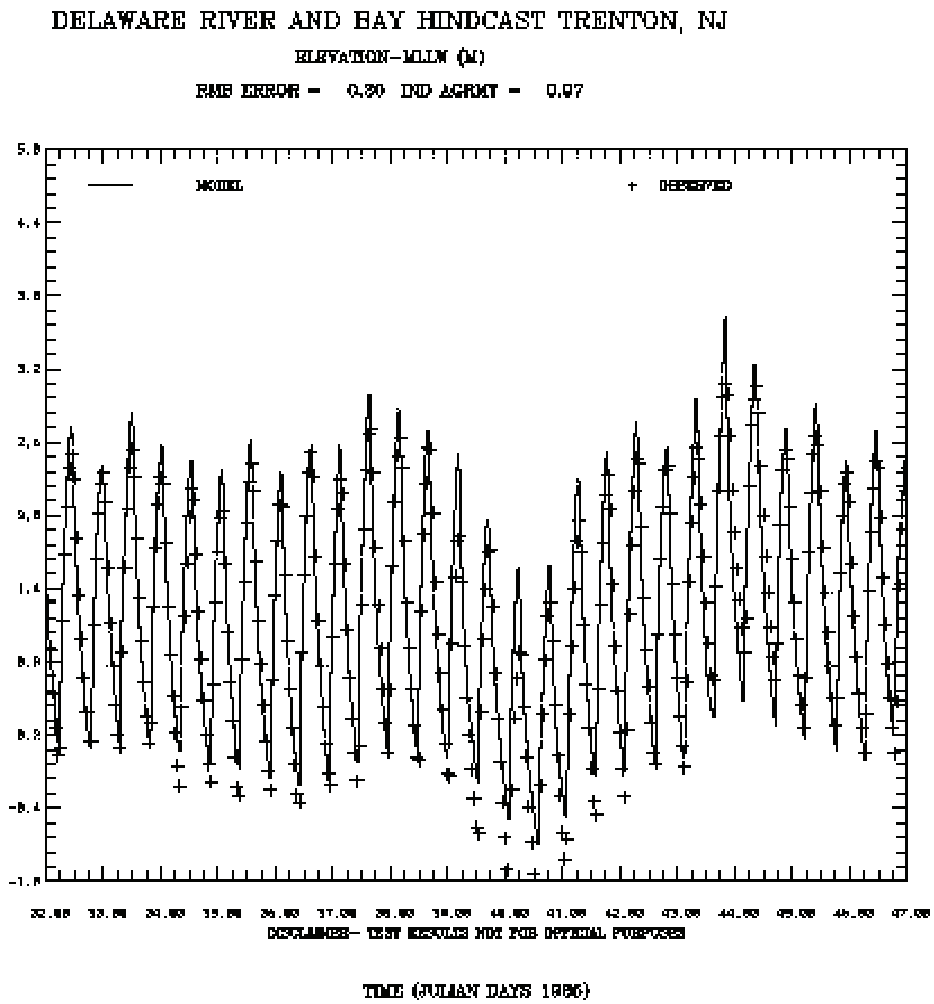


Figure 6.34. DBOFS Version 1.1 Water Surface Elevation JD 32-47, 1985 at Trenton, NJ. Observations are at one hour intervals.

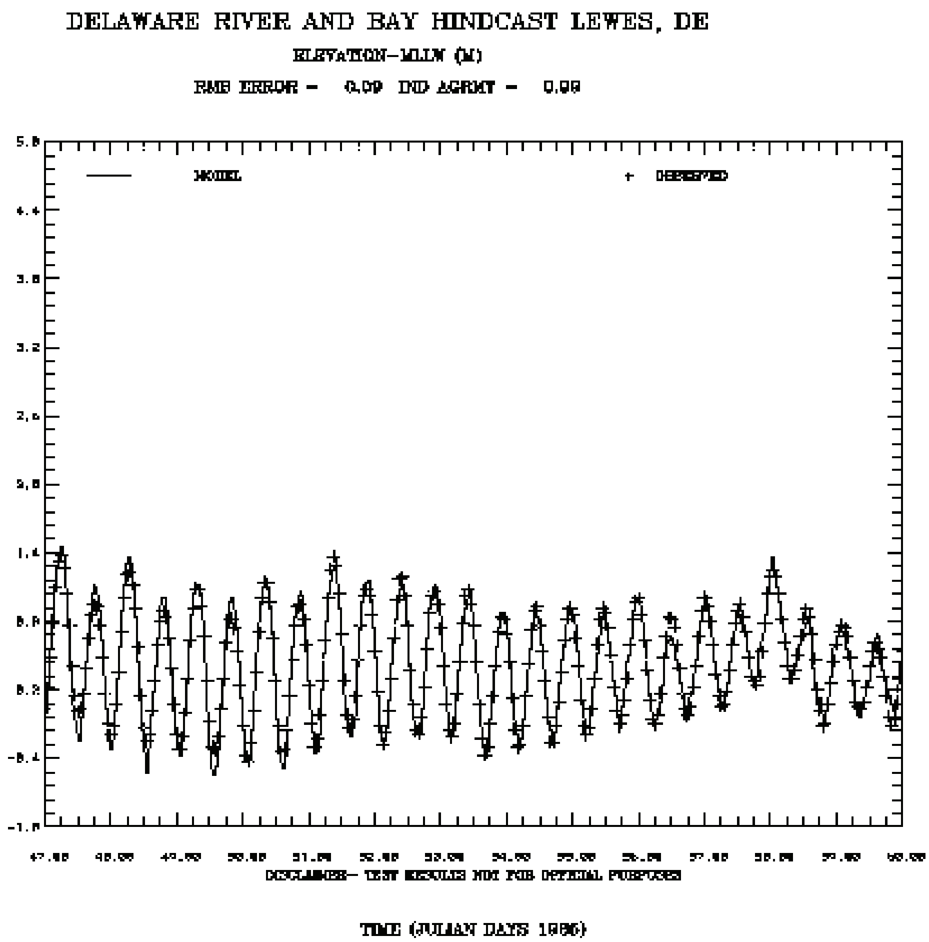


Figure 6.35. DBOFS Version 1.1 Water Surface Elevation JD 47-60, 1985 at Lewes, DE. Observations are at one hour intervals.

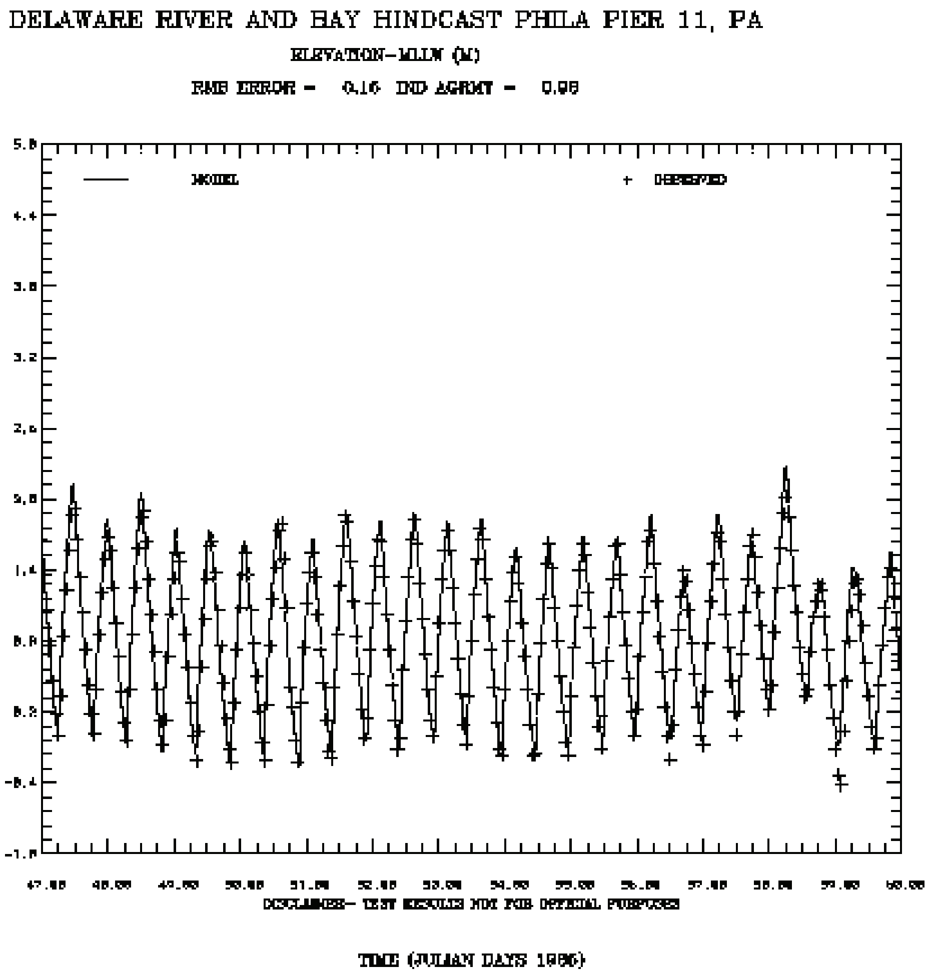


Figure 6.36. DBOFS Version 1.1 Water Surface Elevation JD 47-60, 1985 at Philadelphia, PA. Observations are at one hour intervals.

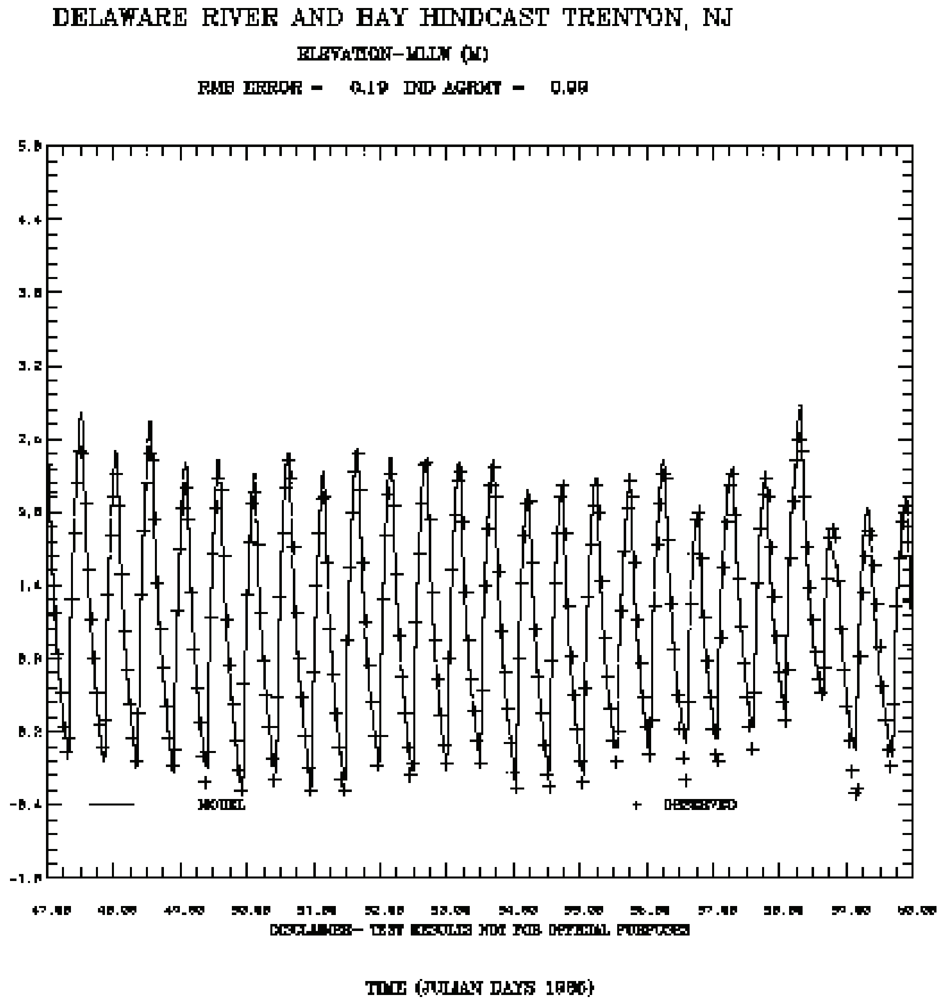


Figure 6.37. DBOFS Version 1.1 Water Surface Elevation JD 47-60, 1985 at Trenton, NJ. Observations are at one hour intervals.

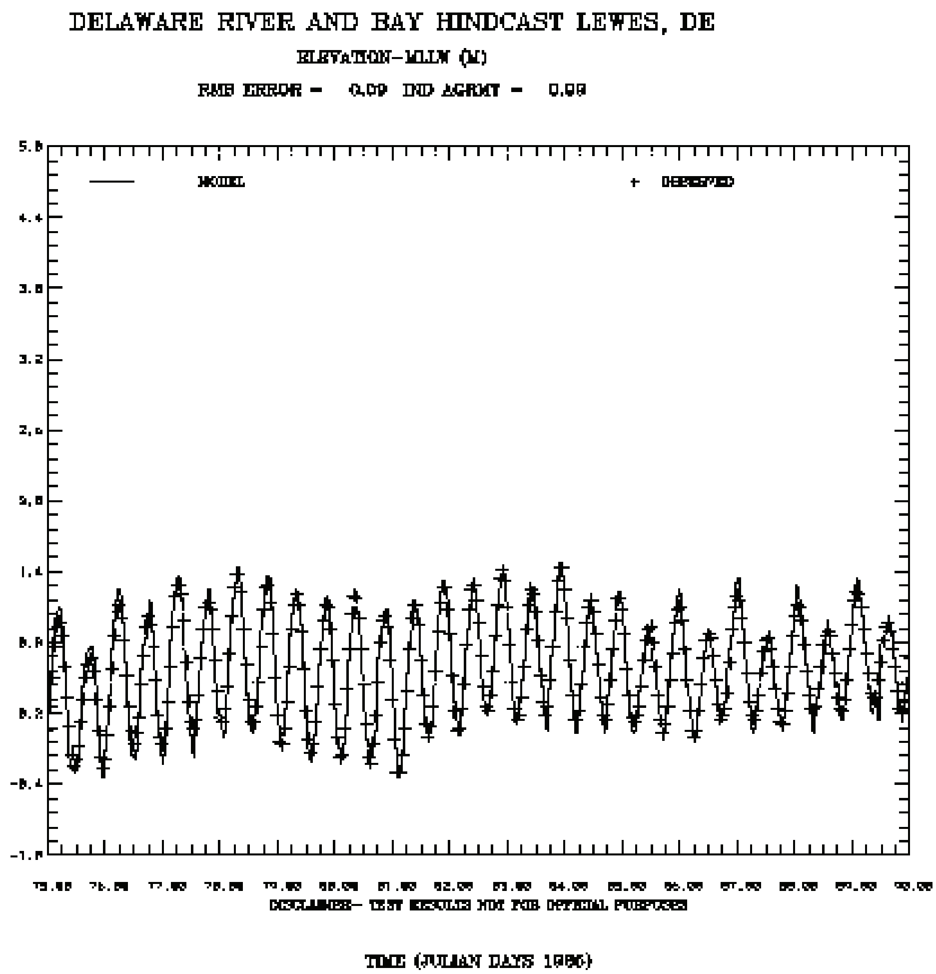


Figure 6.38. DBOFS Version 1.1 Water Surface Elevation JD 75-90, 1985 at Lewes, DE. Observations are at one hour intervals.

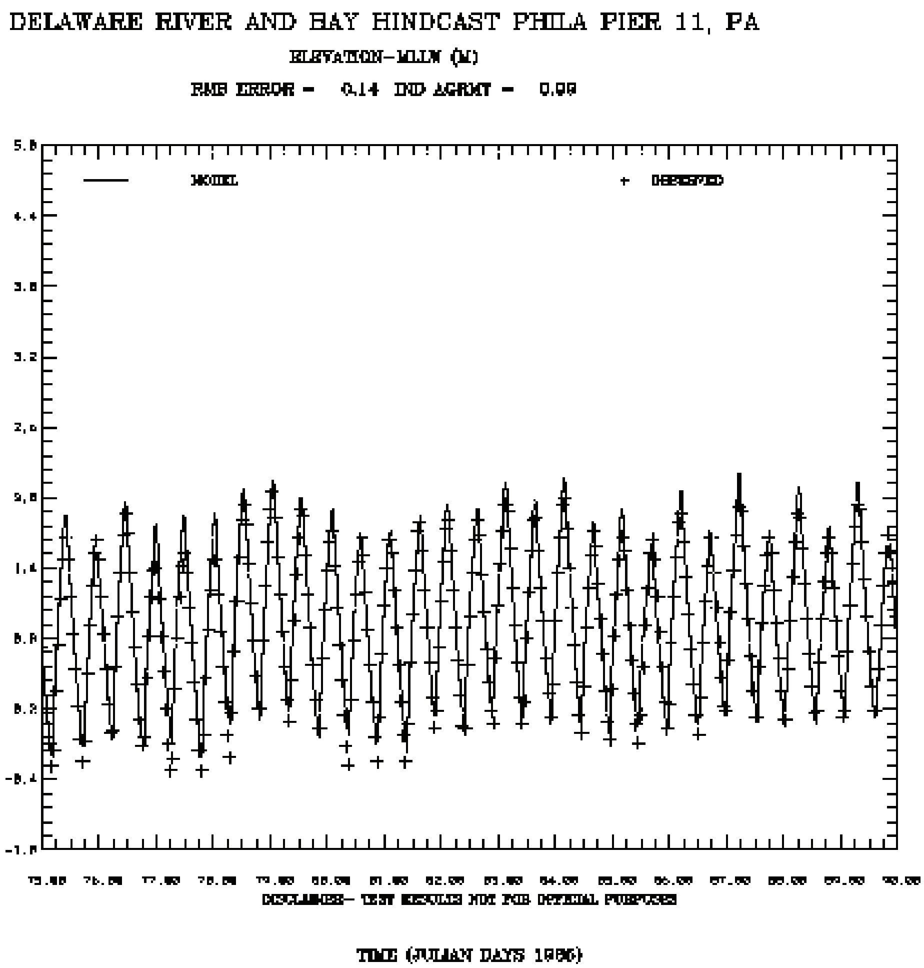


Figure 6.39. DBOFS Version 1.1 Water Surface Elevation JD 75-90, 1985 at Philadelphia, PA. Observations are at one hour intervals.

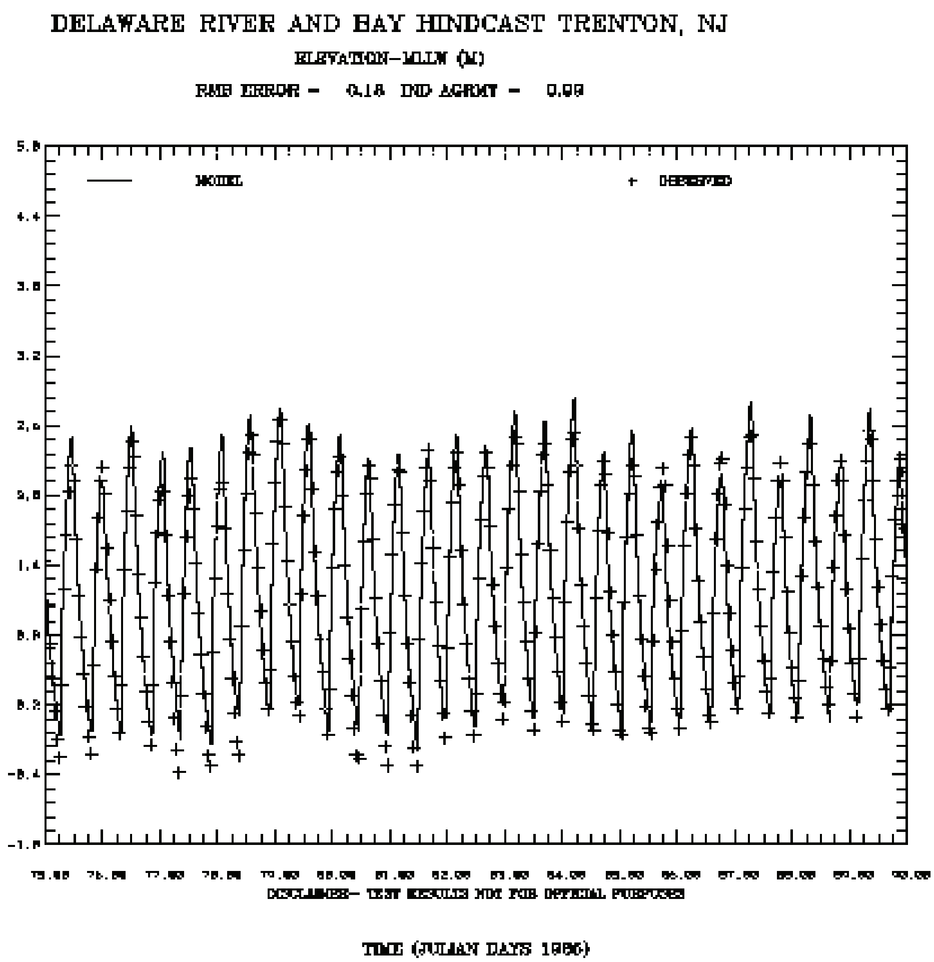


Figure 6.40. DBOFS Version 1.1 Water Surface Elevation JD 75-90, 1985 at Trenton, NJ. Observations are at one hour intervals.

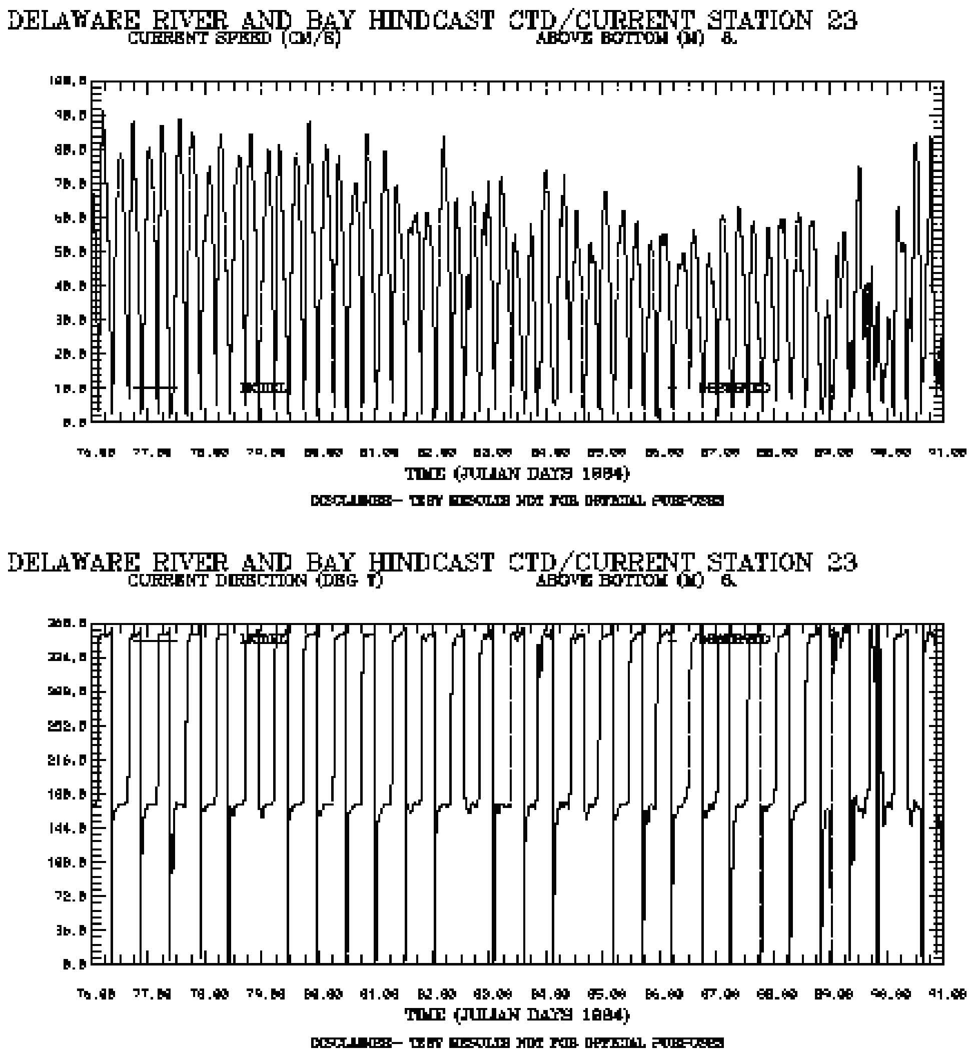


Figure 6.41. DBOFS Version 1.1 Current JD 76-91, 1984 at Station 23.

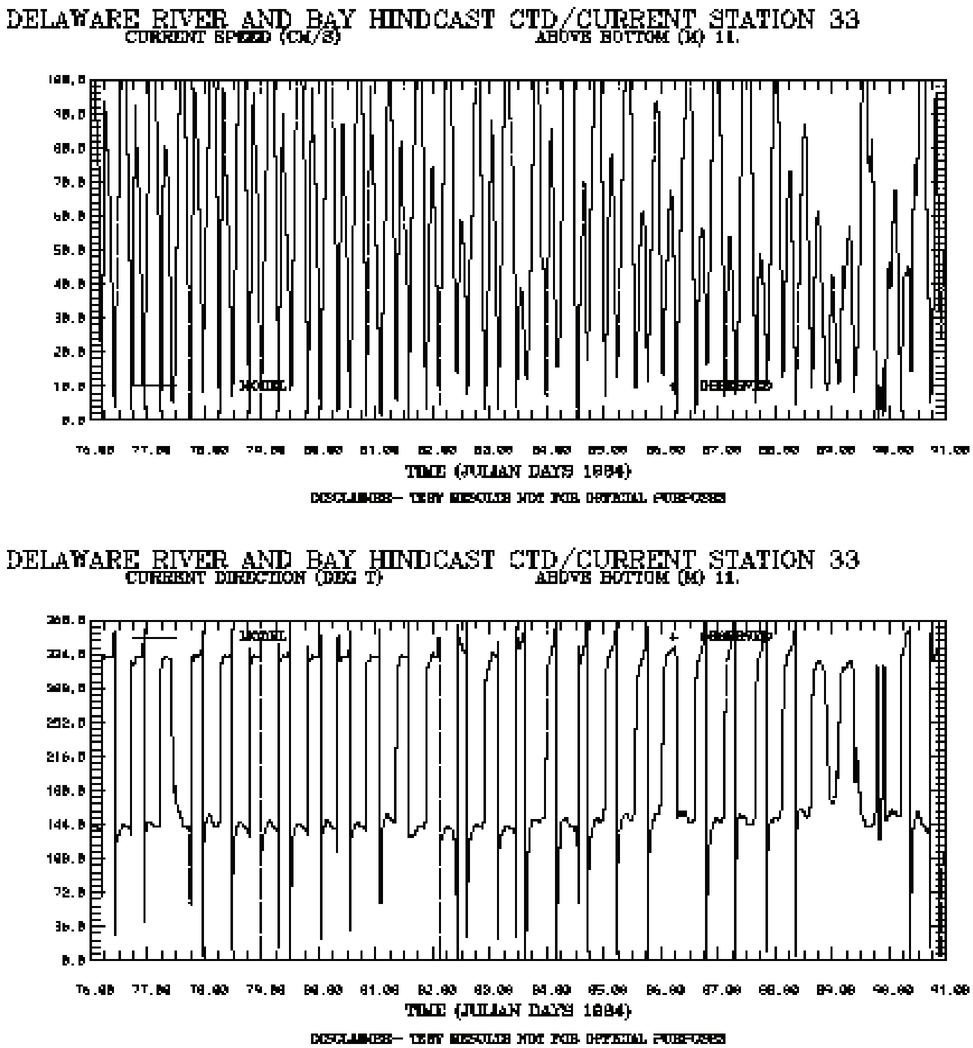


Figure 6.42. DBOFS Version 1.1 Current JD 76-91, 1984 at Station 33.

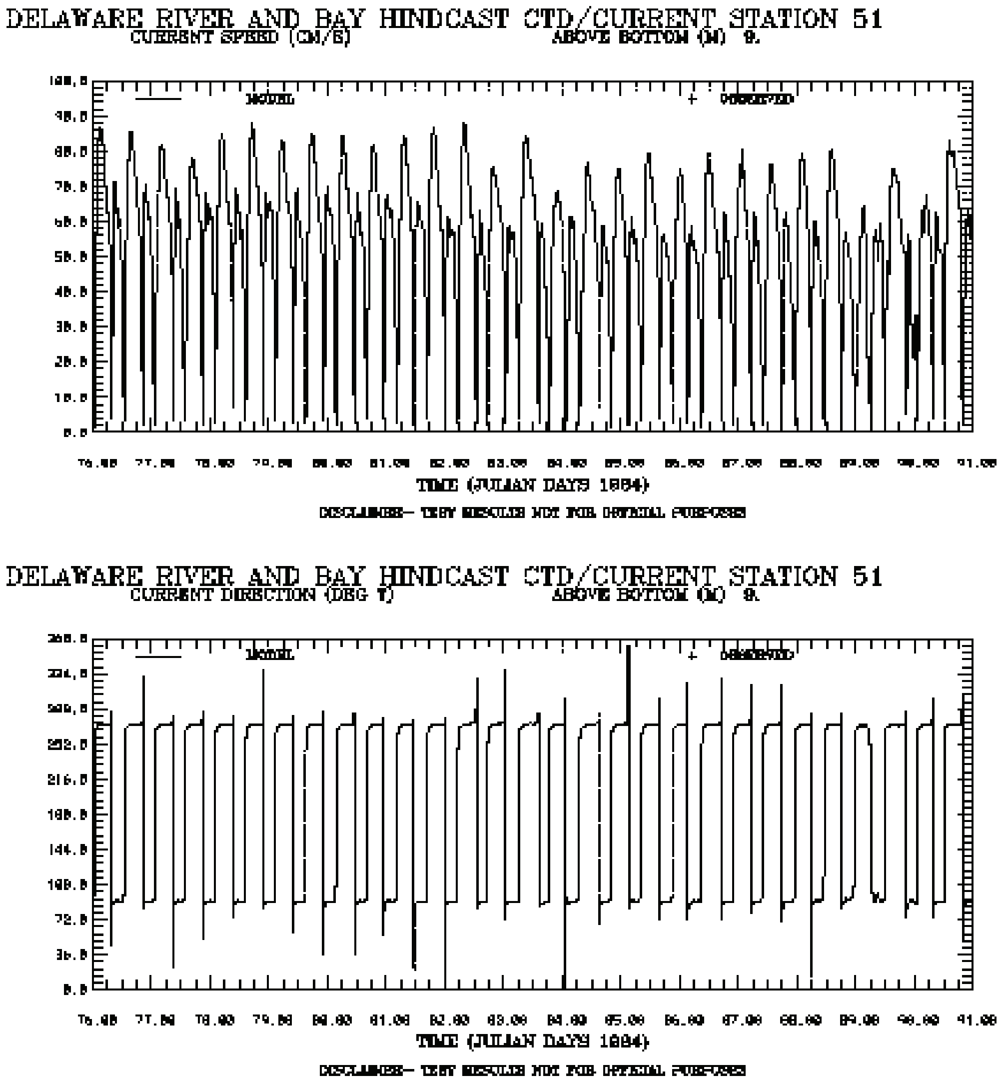


Figure 6.43. DBOFS Version 1.1 Current JD 76-91, 1984 at Station 51.

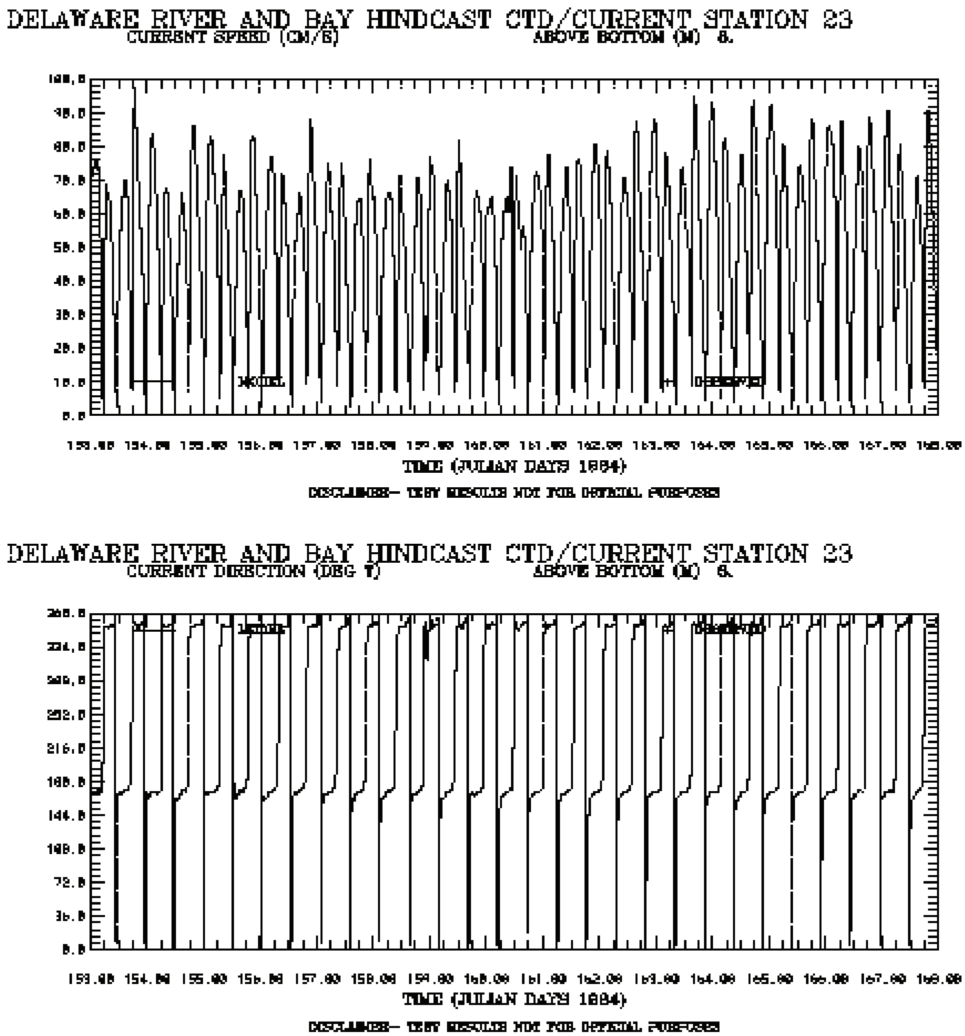


Figure 6.44. DBOFS Version 1.1 Current JD 153-168, 1984 at Station 23.

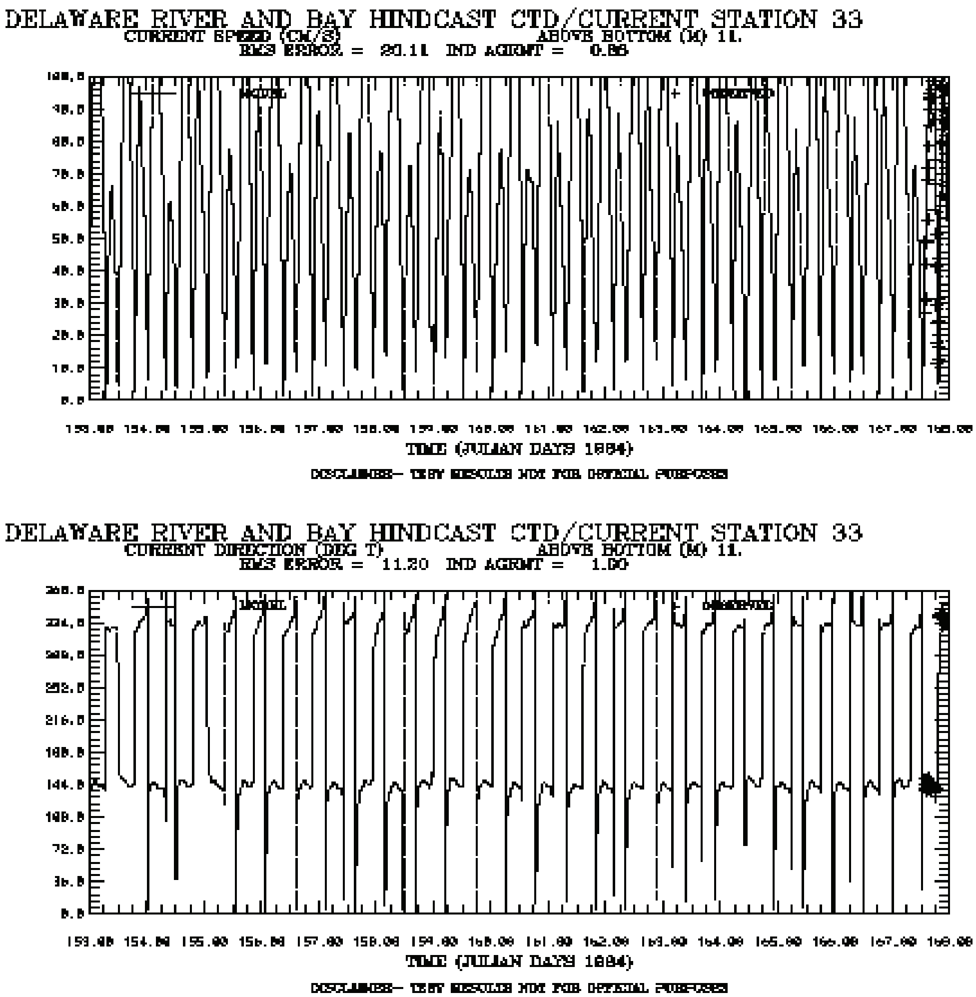


Figure 6.45. DBOFS Version 1.1 Current JD 153-168, 1984 at Station 33. Observations are at 10-minute intervals.

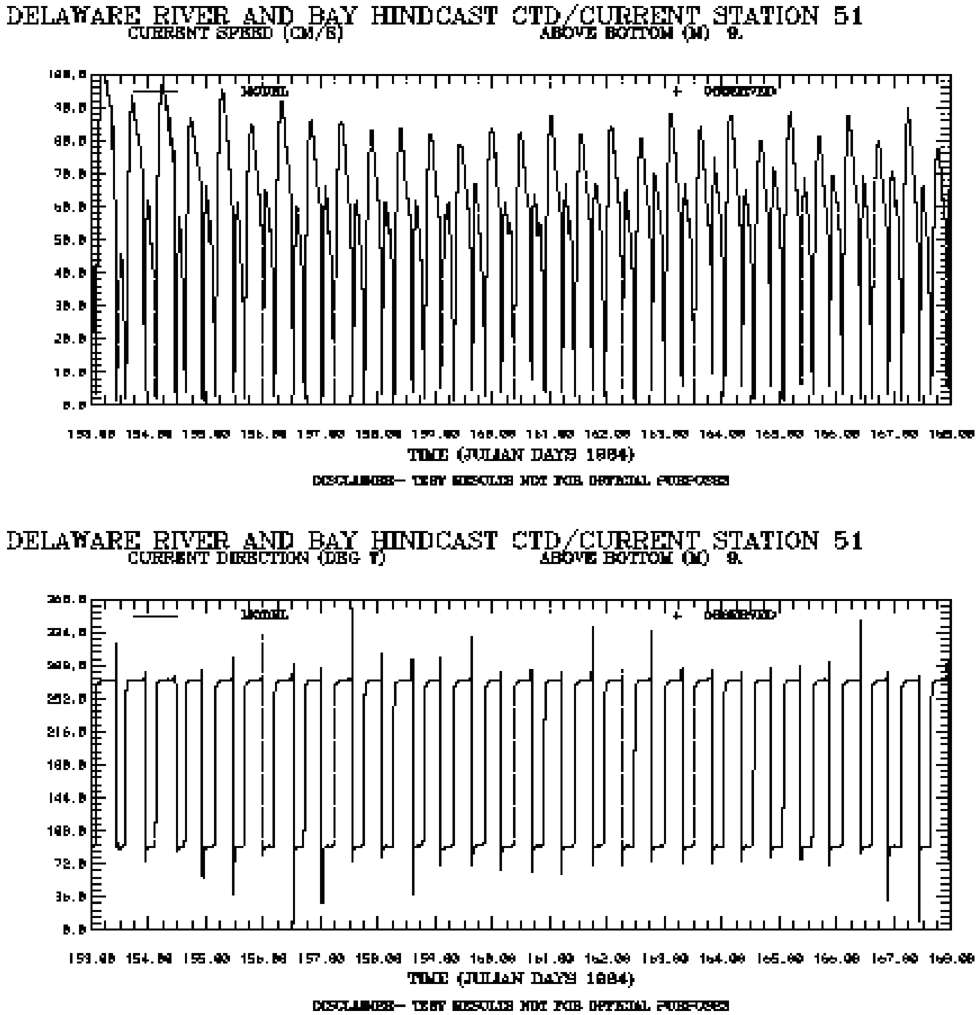


Figure 6.46. DBOFS Version 1.1 Current JD 153-168, 1984 at Station 51.

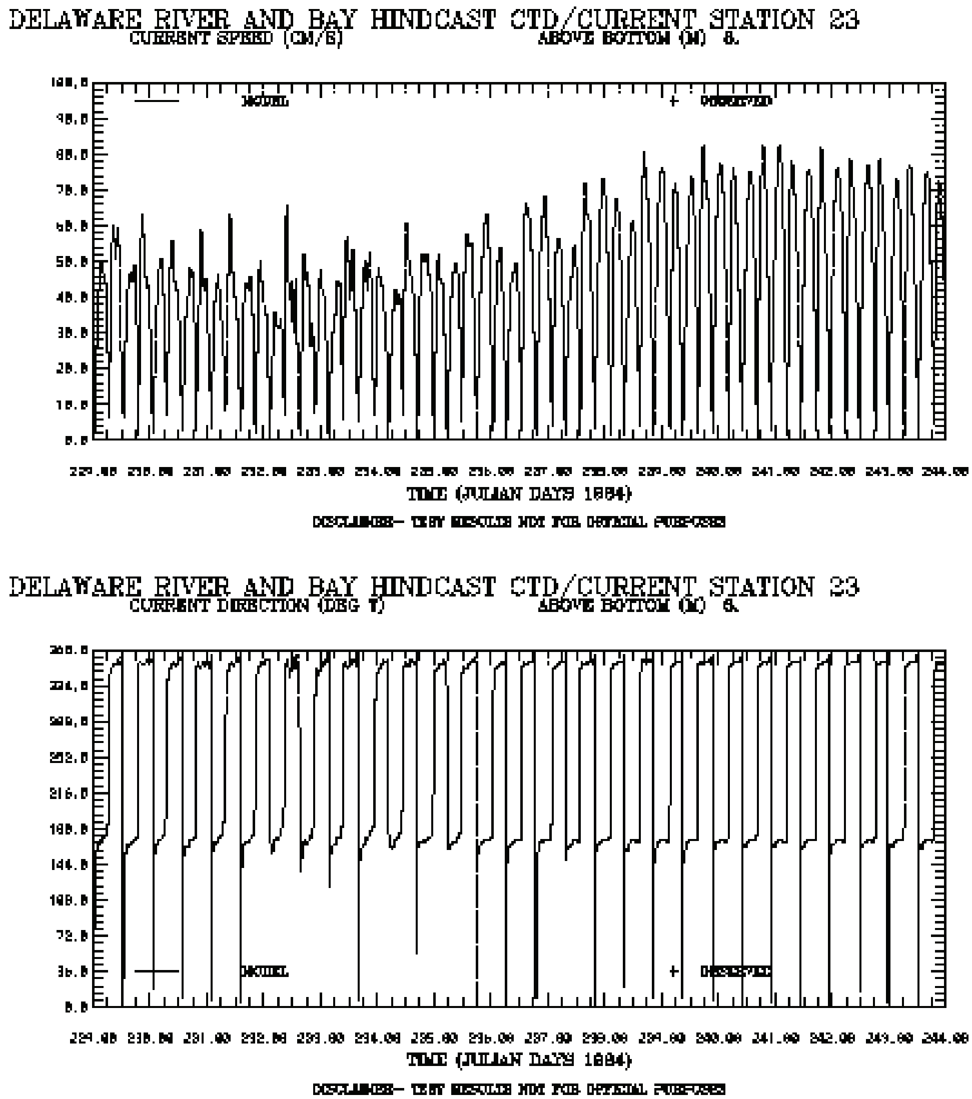


Figure 6.47. DBOFS Version 1.1 Current JD 229-254, 1984 at Station 23.

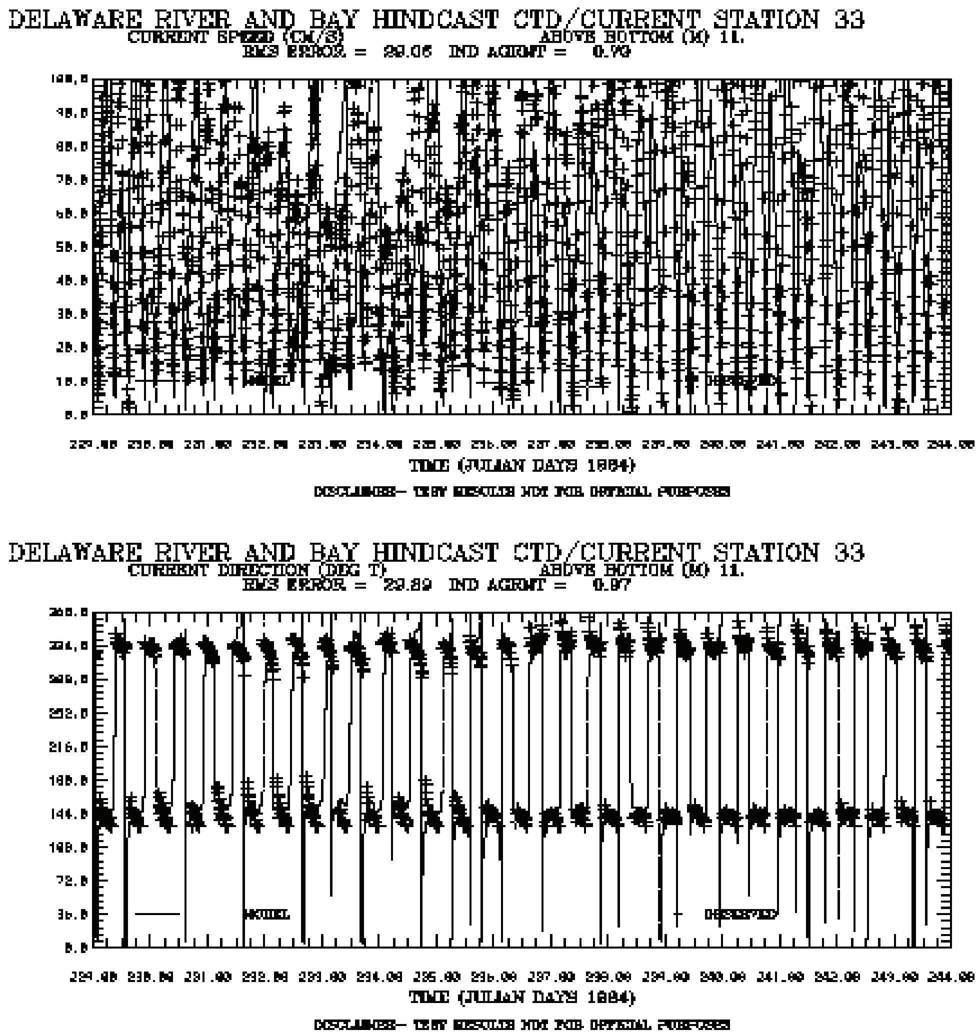


Figure 6.48. DBOFS Version 1.1 Current JD 229-254, 1984 at Station 33. Observations are at 10-minute intervals.

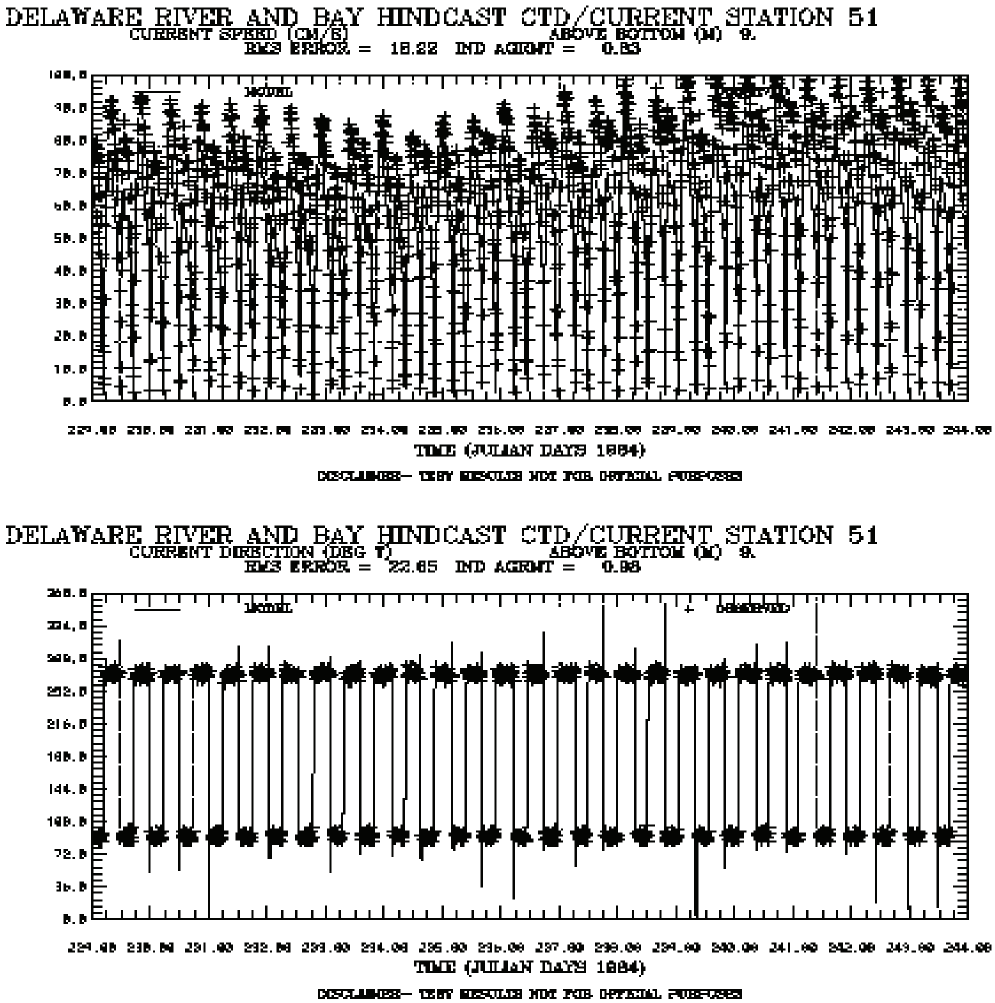


Figure 6.49. DBOFS Version 1.1 Current JD 229-254, 1984 at Station 51. Observations are at 10-minute intervals.

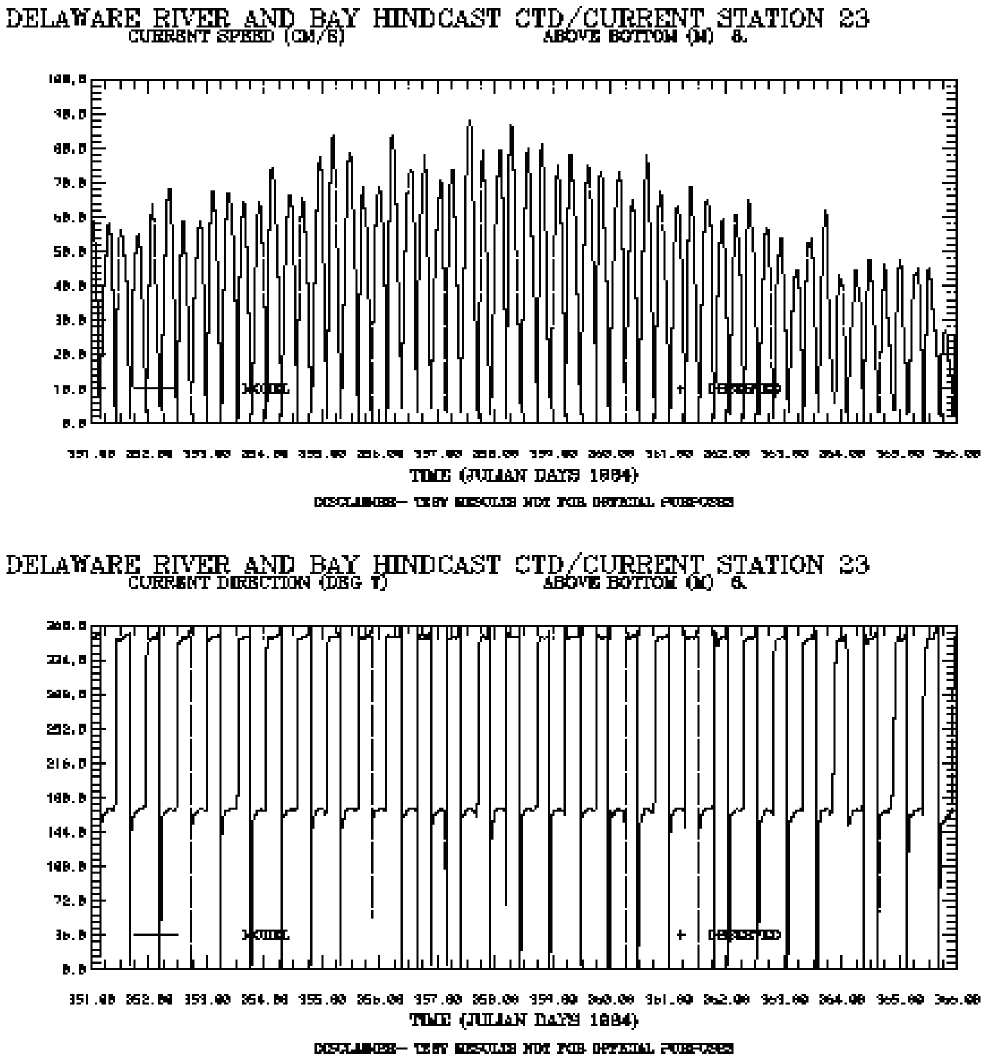


Figure 6.50. DBOFS Version 1.1 Current JD 351-366, 1984 at Station 23.

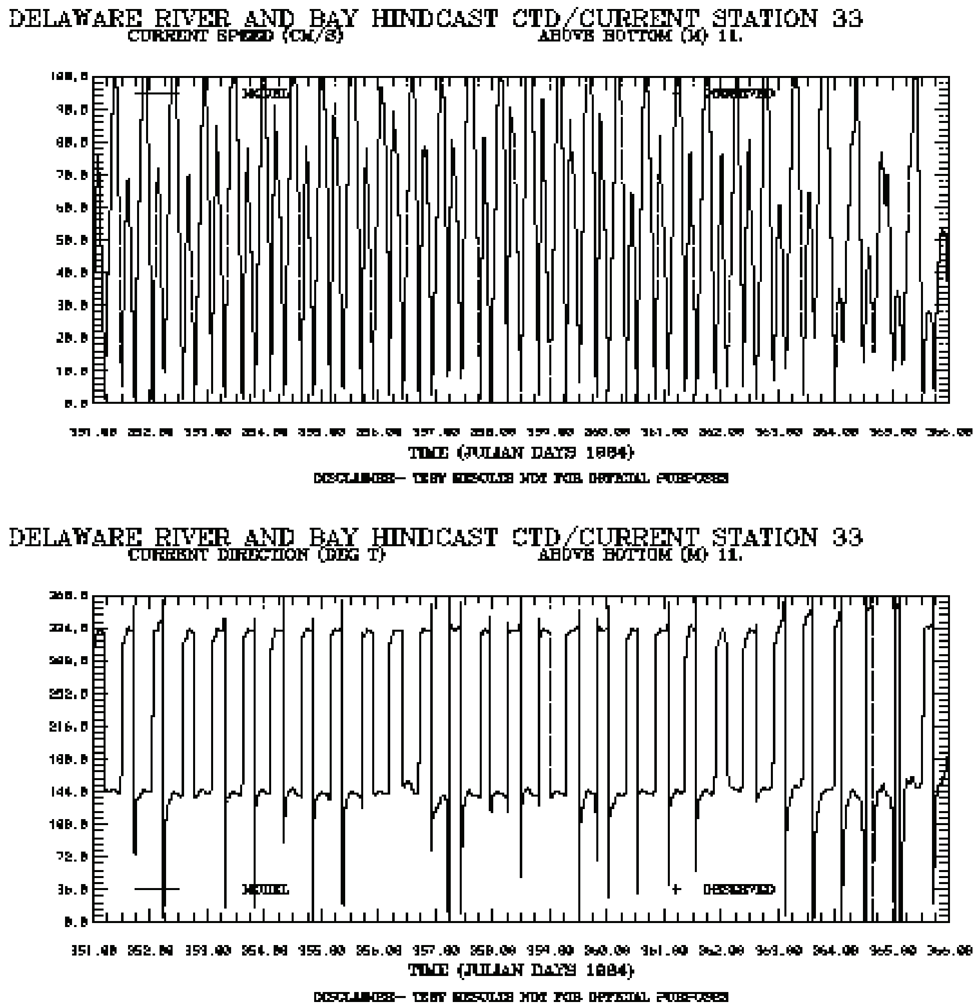


Figure 6.51. DBOFS Version 1.1 Current JD 351-366, 1984 at Station 33.

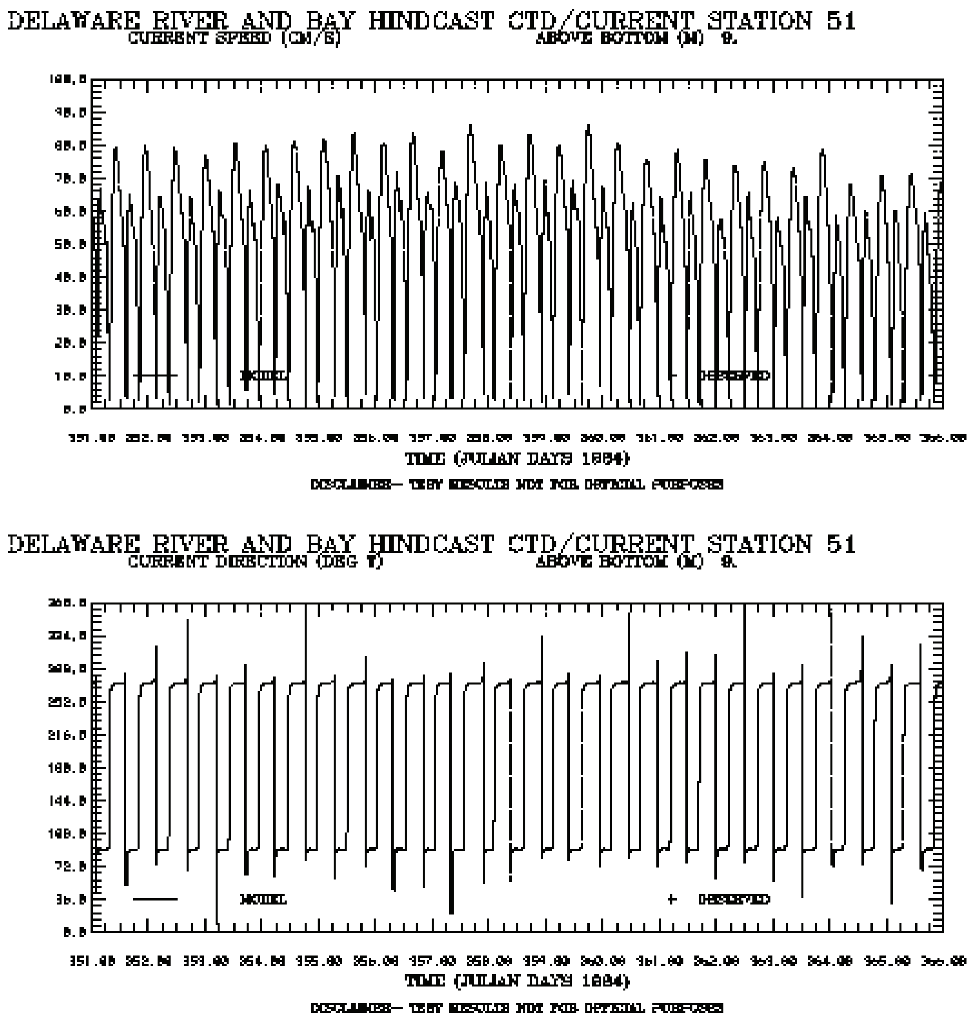


Figure 6.52. DBOFS Version 1.1 Current JD 351-366, 1984 at Station 51.

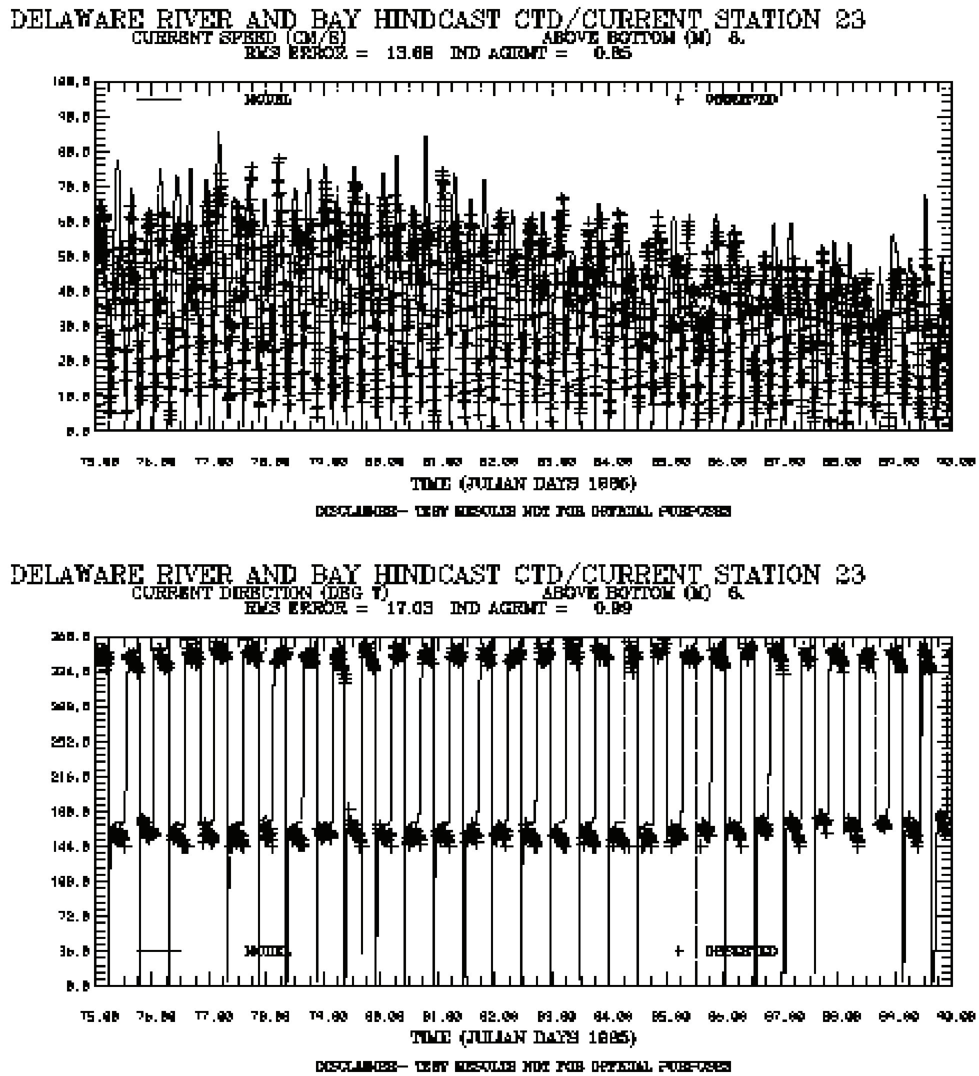


Figure 6.53. DBOFS Version 1.1 Current JD 75-90, 1985 at Station 23. Observations are at 10-minute intervals.

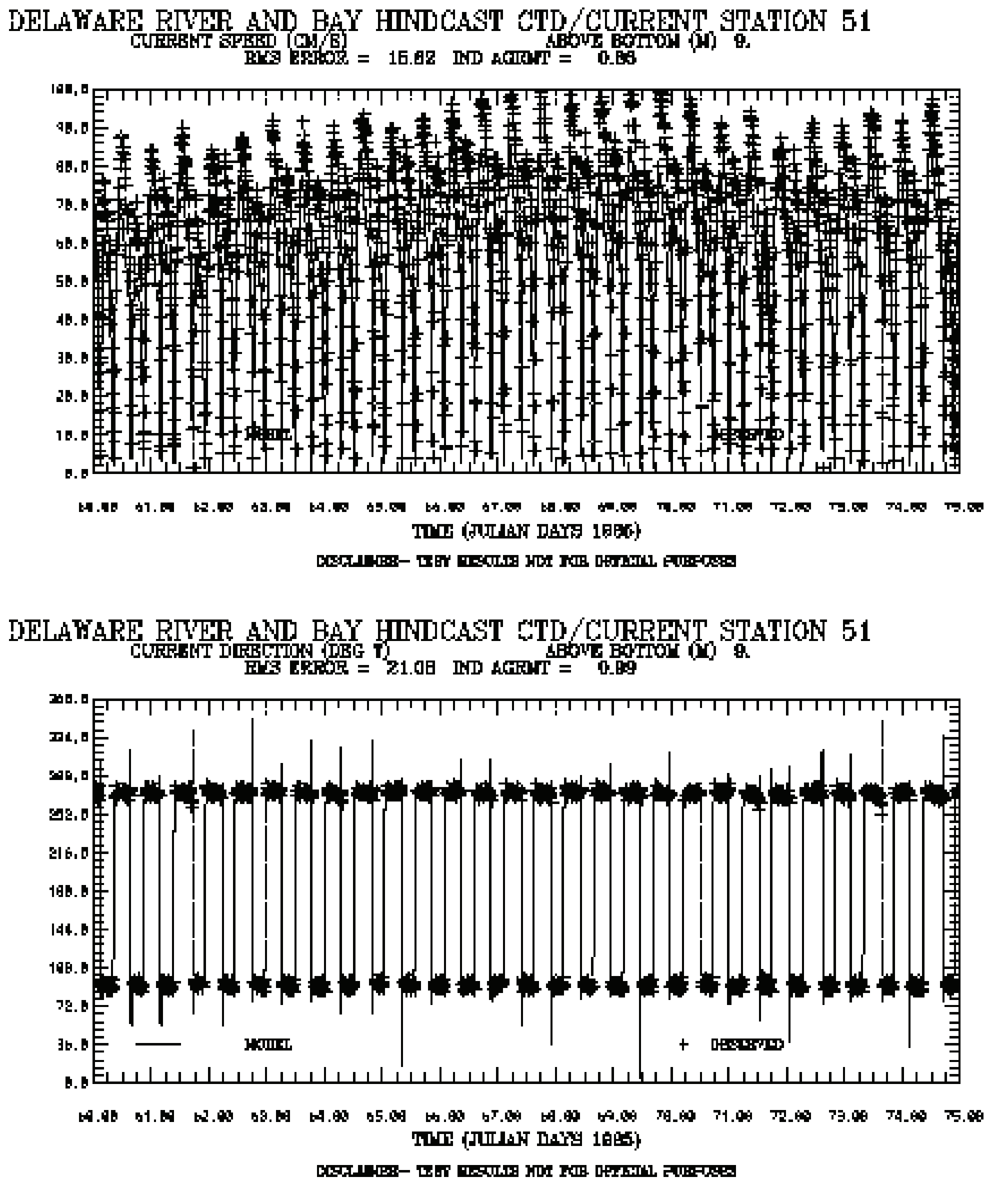


Figure 6.54. DBOFS Version 1.1 Current JD 75-90, 1985 at Station 51. Observations are at 10-minute intervals.

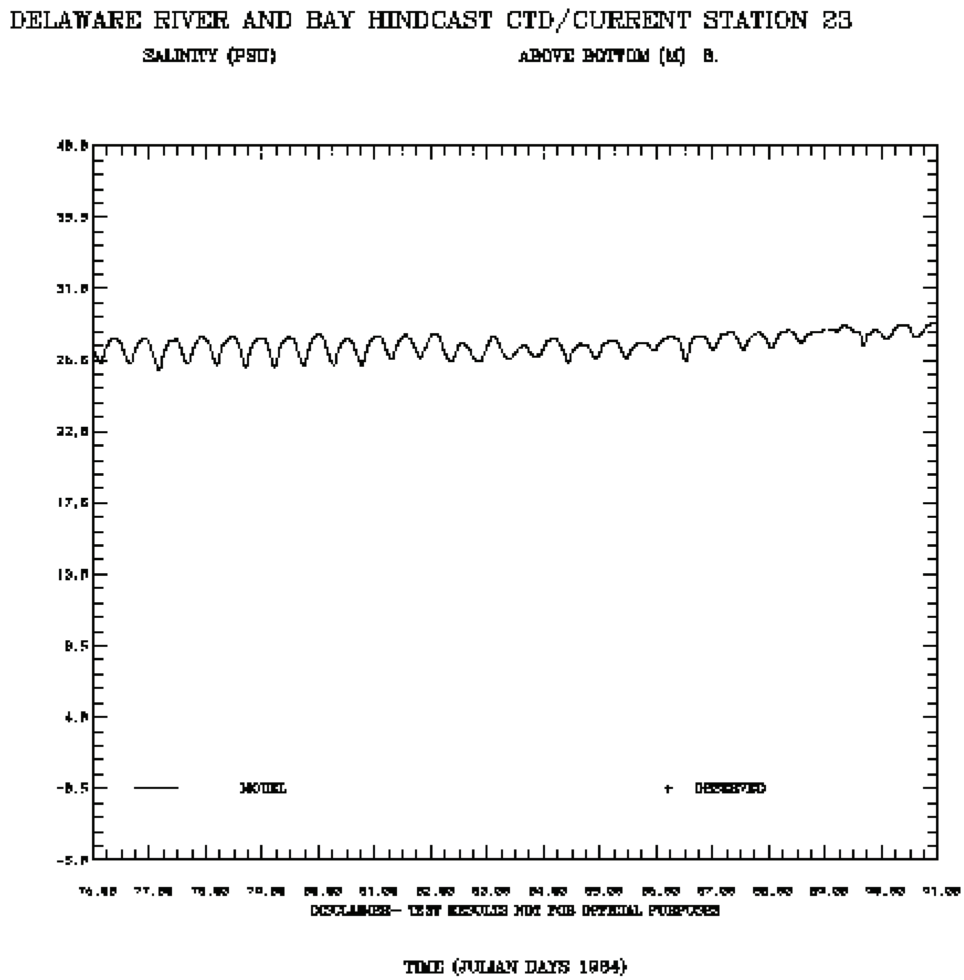


Figure 6.55. DBOFS Version 1.1 Salinity JD 76-91, 1984 at Station 23.

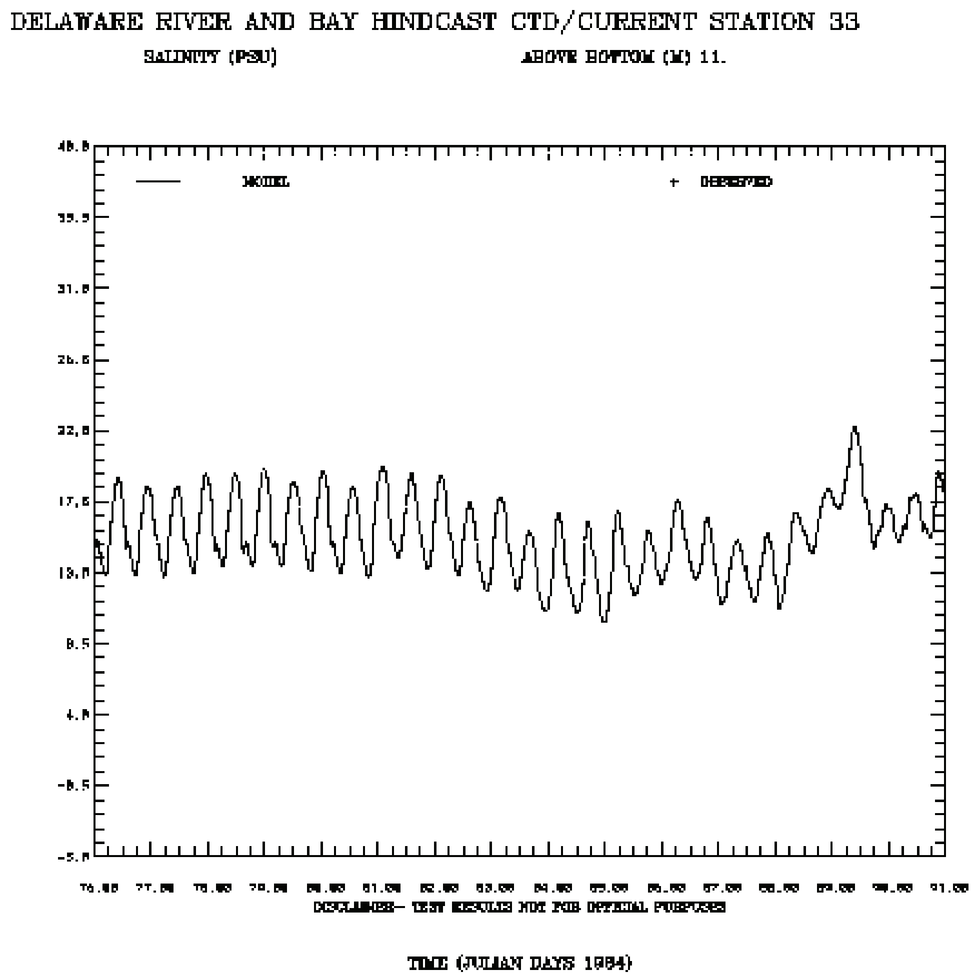


Figure 6.56. DBOFS Version 1.1 Salinity JD 76-91, 1984 at Station 33.

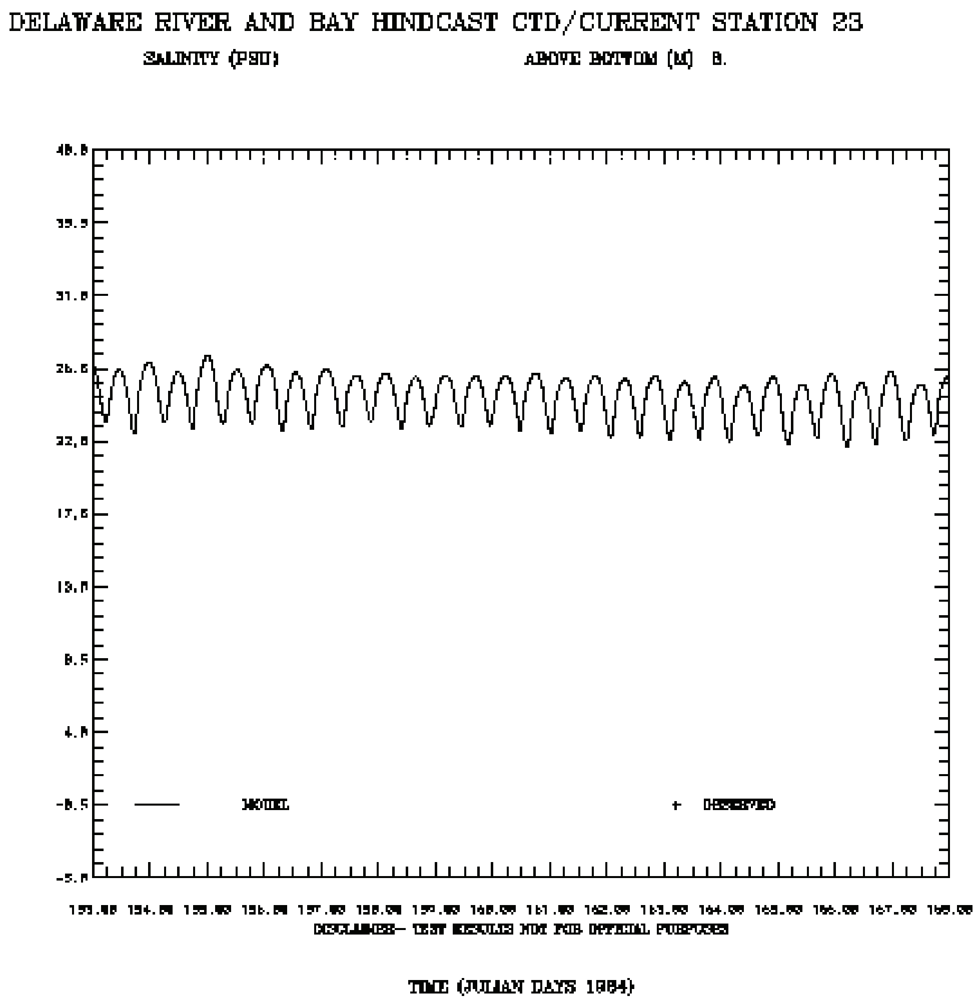


Figure 6.57. DBOFS Version 1.1 Salinity JD 153-168, 1984 at Station 23.

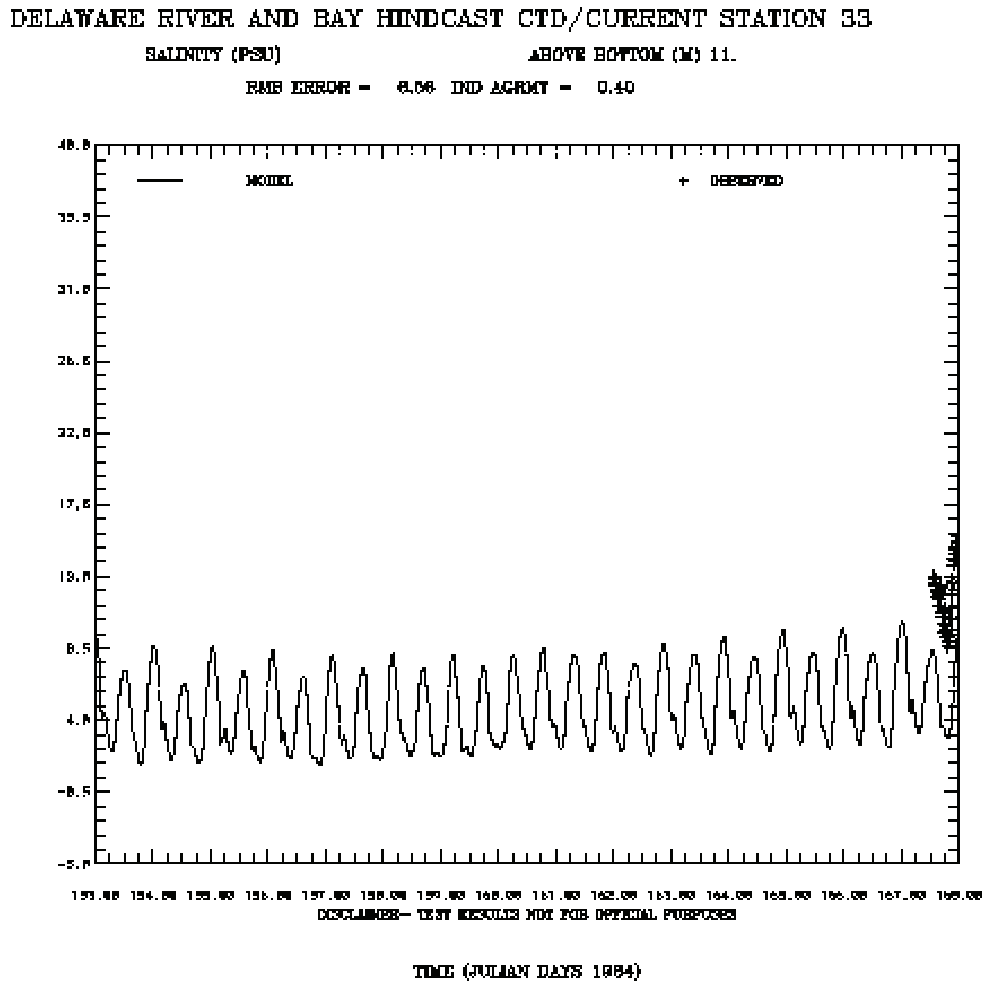


Figure 6.58. DBOFS Version 1.1 Salinity JD 153-168, 1984 at Station 33. Observations are at 10-minute intervals.

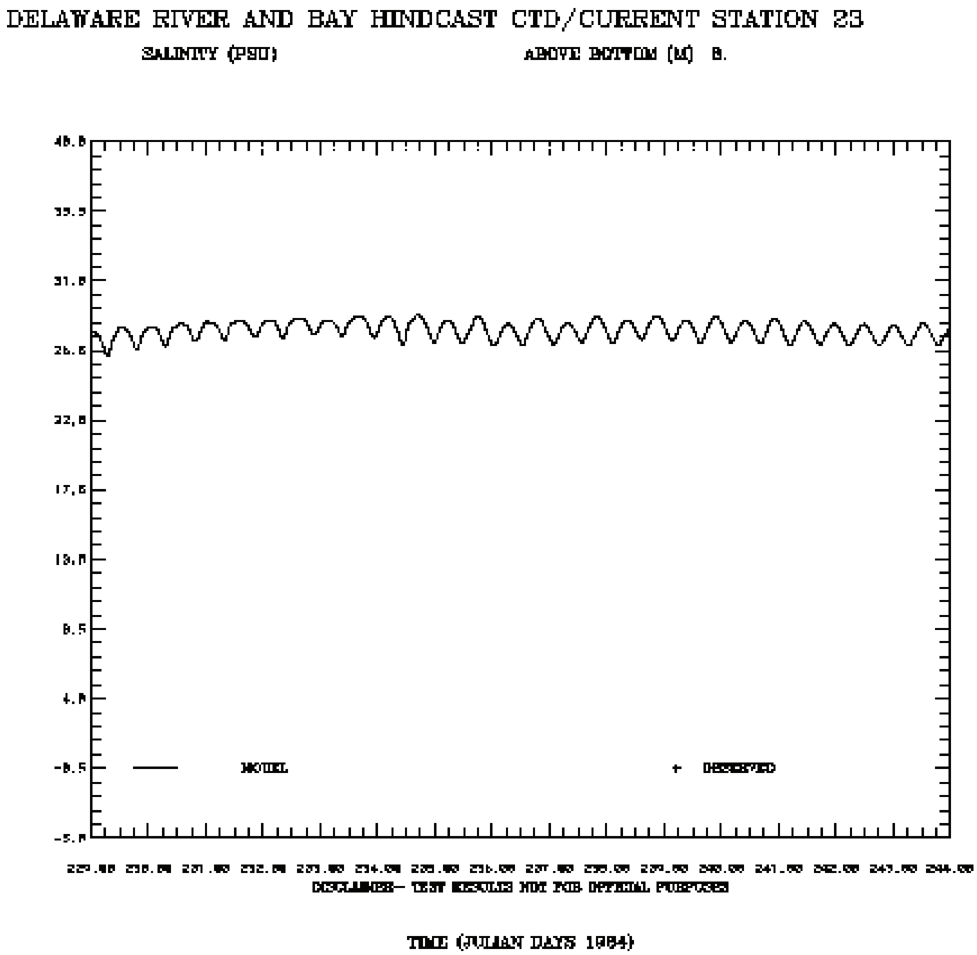


Figure 6.59. DBOFS Version 1.1 Salinity JD 229-244, 1984 at Station 23.

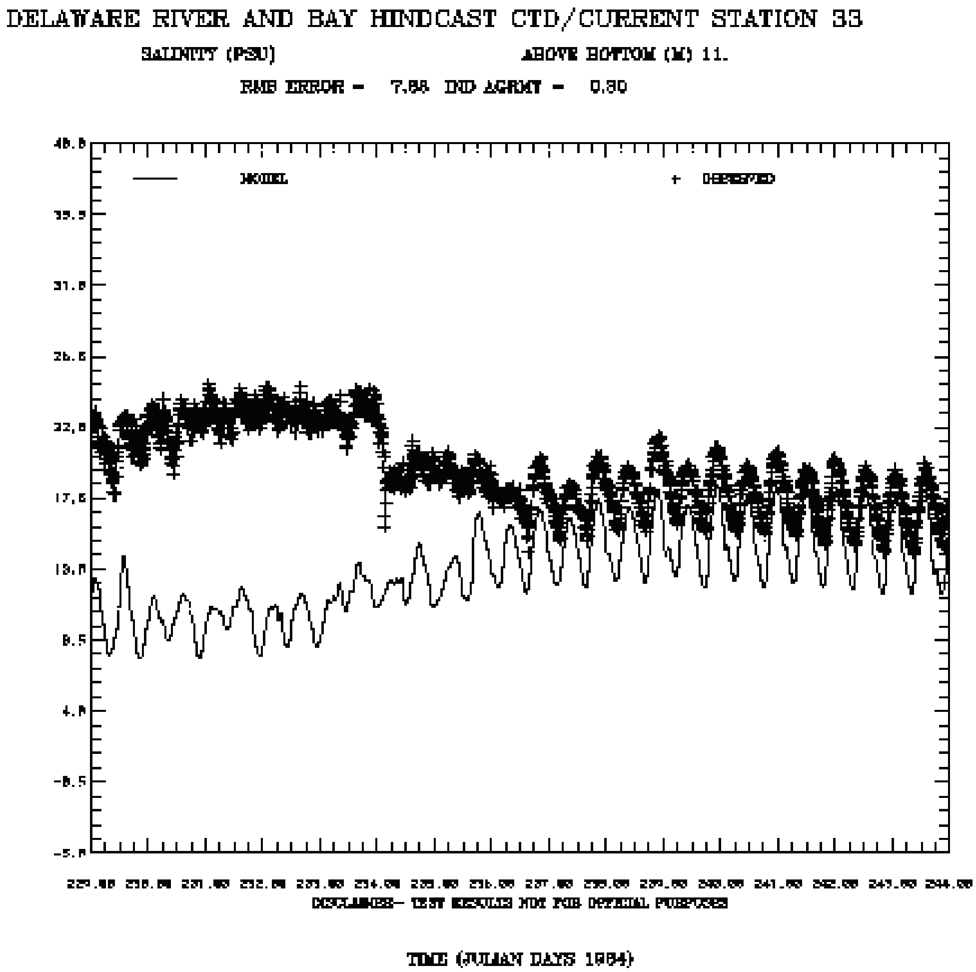


Figure 6.60. DBOFS Version 1.1 Salinity JD 229-244, 1984 at Station 33. Observations are at 10-minute intervals.

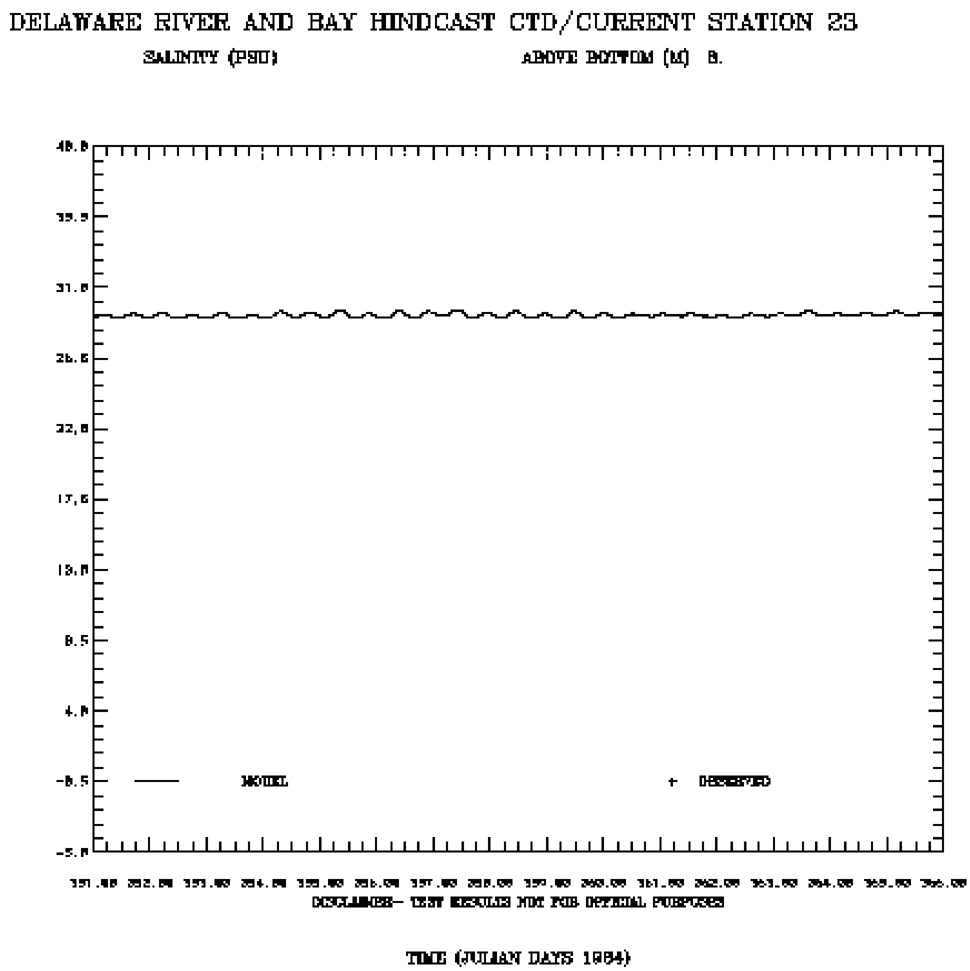


Figure 6.61. DBOFS Version 1.1 Salinity JD 351-366, 1984 at Station 23.

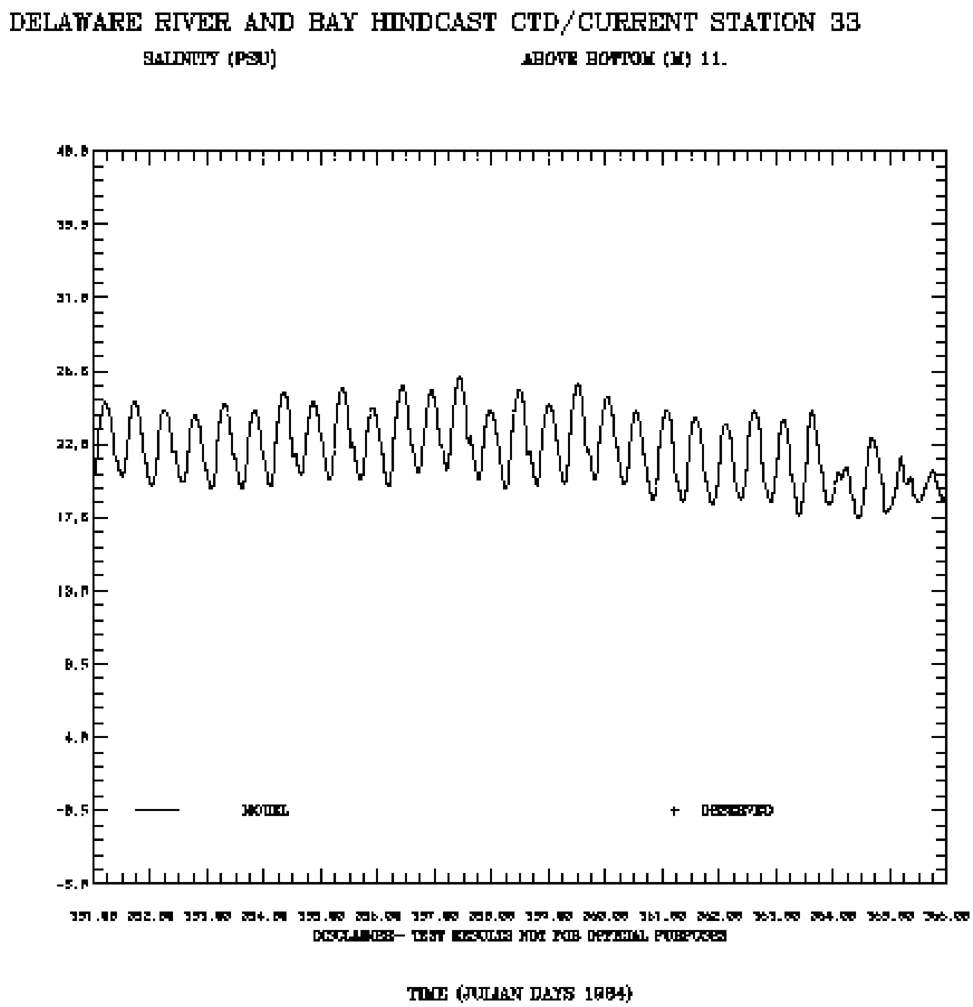


Figure 6.62. DBOFS Version 1.1 Salinity JD 351-366, 1984 at Station 33.

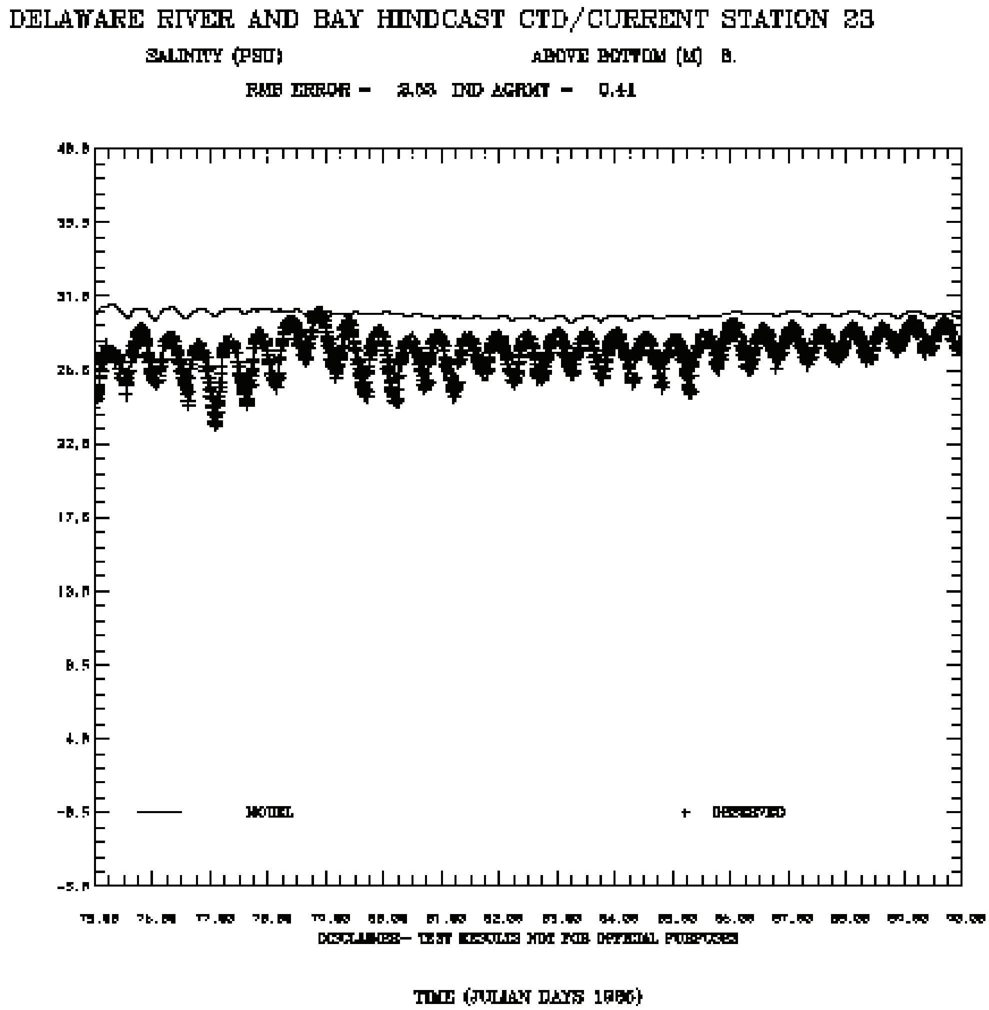


Figure 6.63. DBOFS Version 1.1 Salinity JD 75-90, 1985 at Station 23. Observations are at 10-minute intervals.

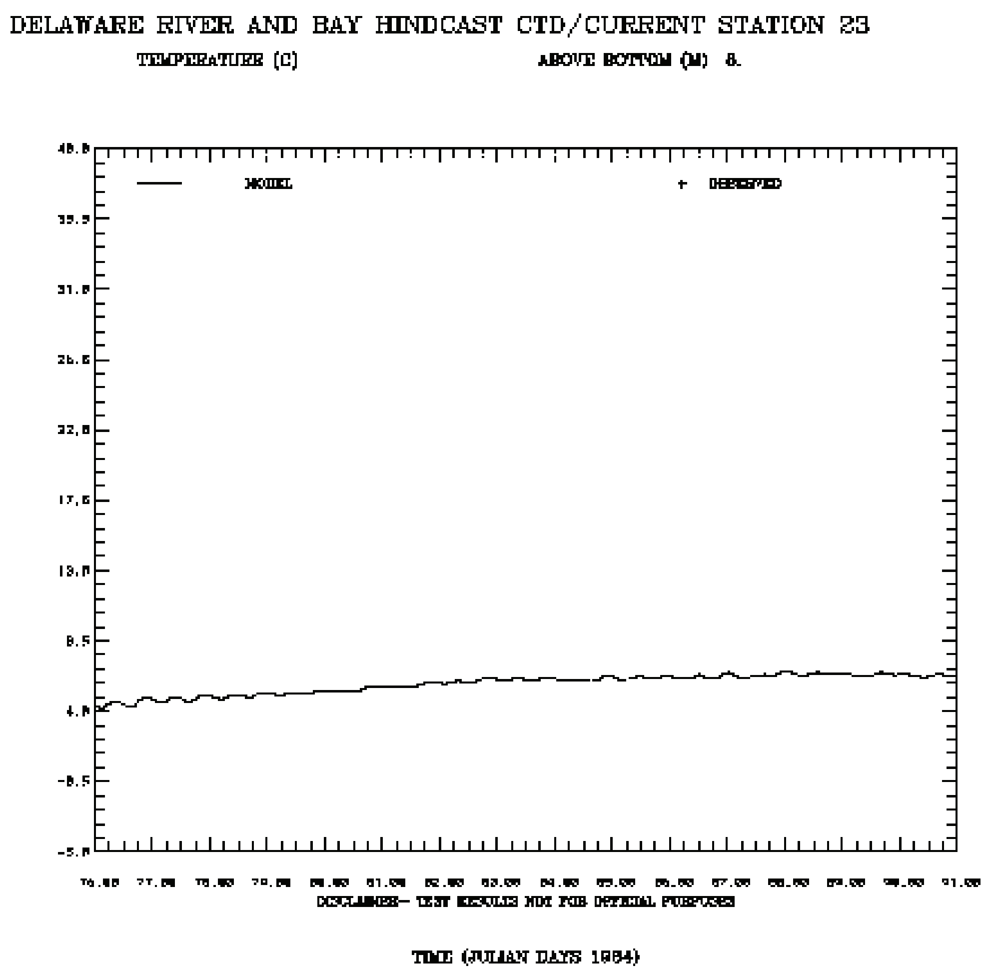


Figure 6.64. DBOFS Version 1.1 Temperature JD 76-91, 1984 at Station 23.

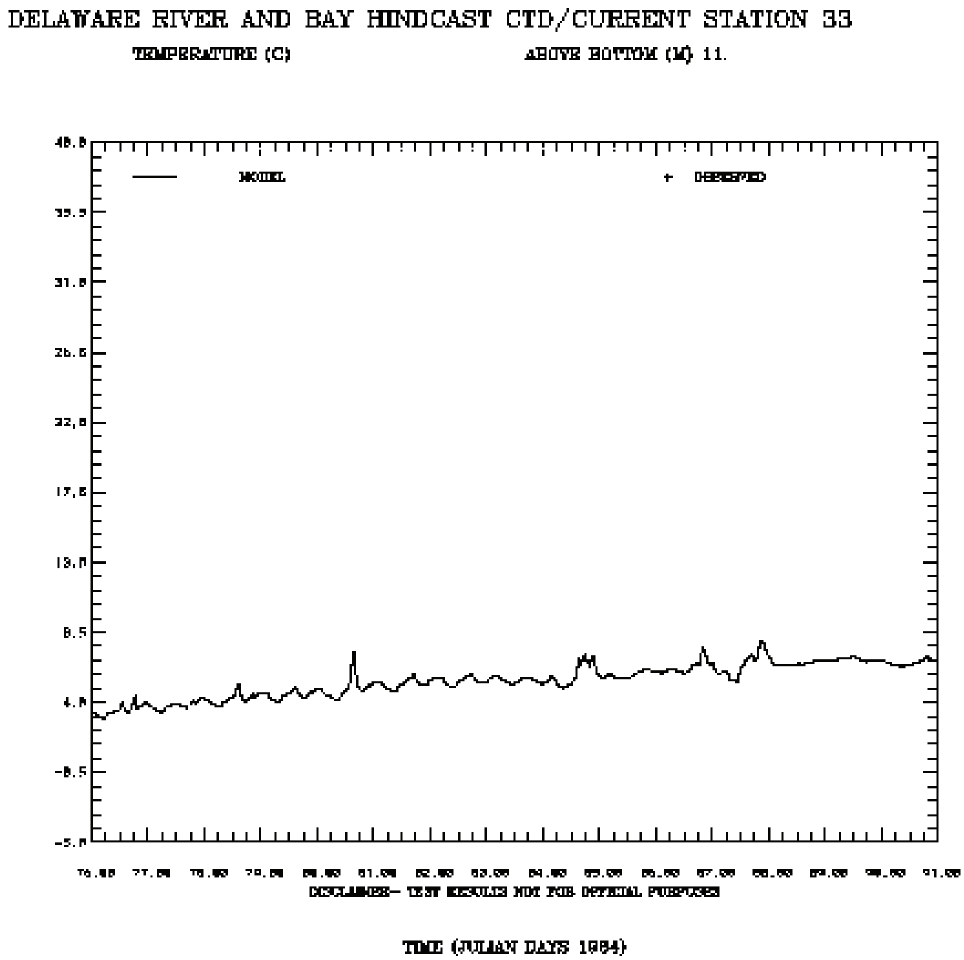


Figure 6.65. DBOFS Version 1.1 Temperature JD 76-91, 1984 at Station 33.

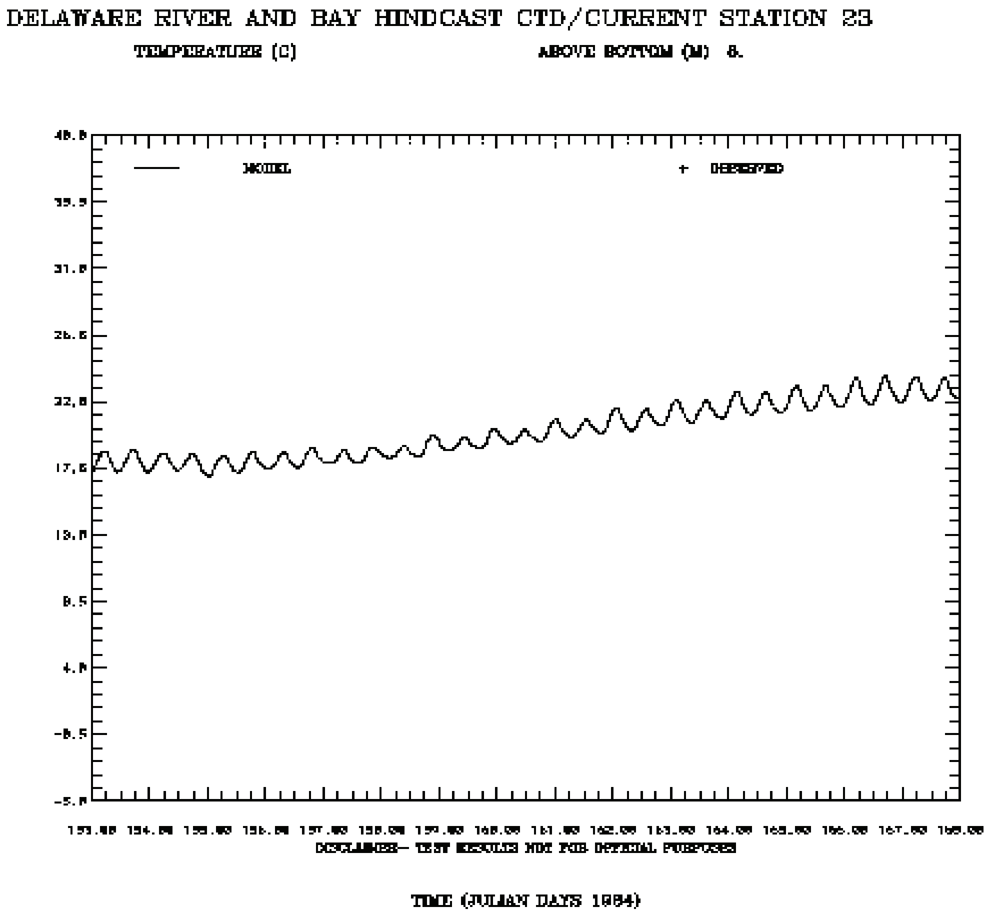


Figure 6.66. DBOFS Version 1.1 Temperature JD 153-168, 1984 at Station 23.

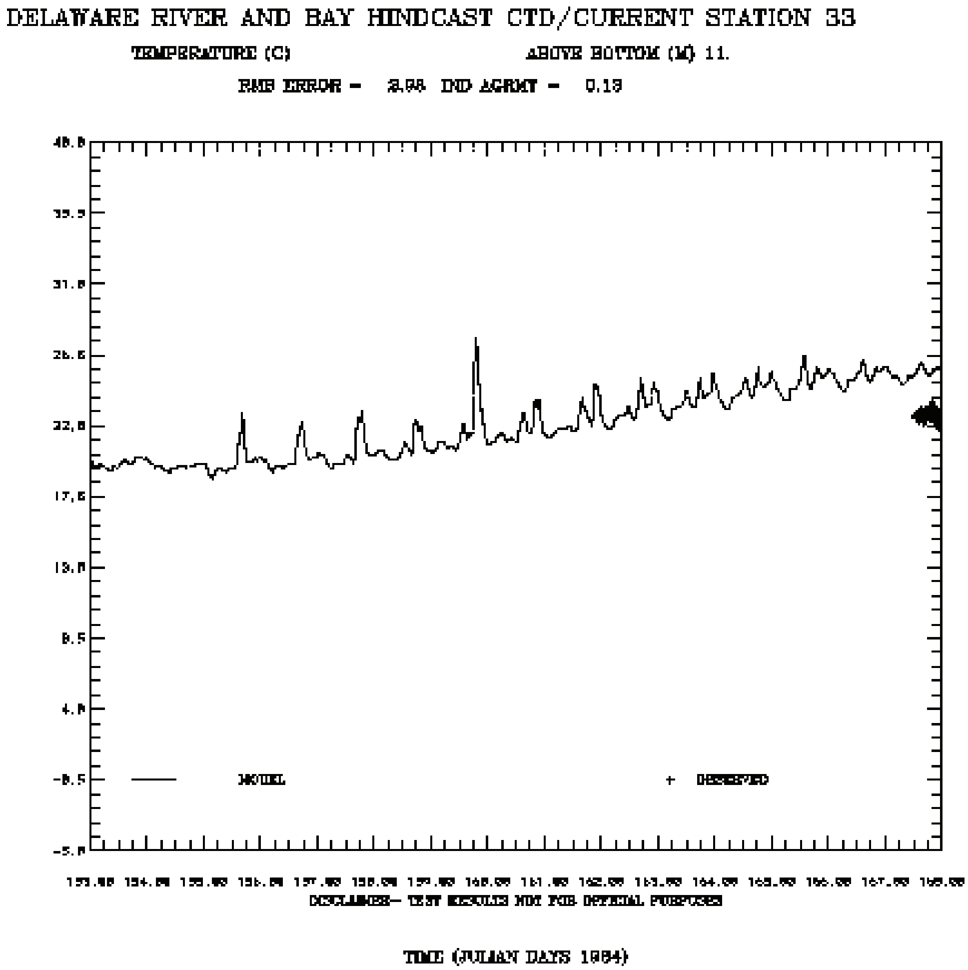


Figure 6.67. DBOFS Version 1.1 Temperature JD 153-168, 1984 at Station 33. Observations are at 10-minute intervals.

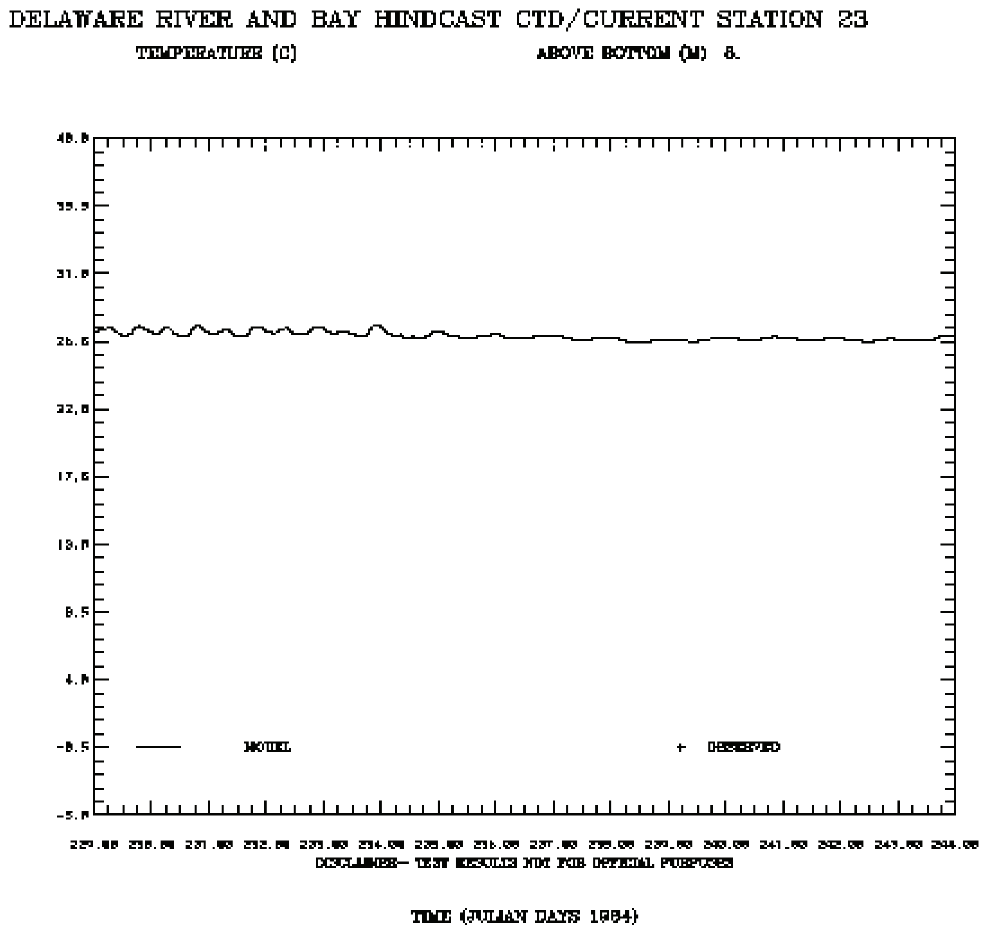


Figure 6.68. DBOFS Version 1.1 Temperature JD 229-244, 1984 at Station 23.

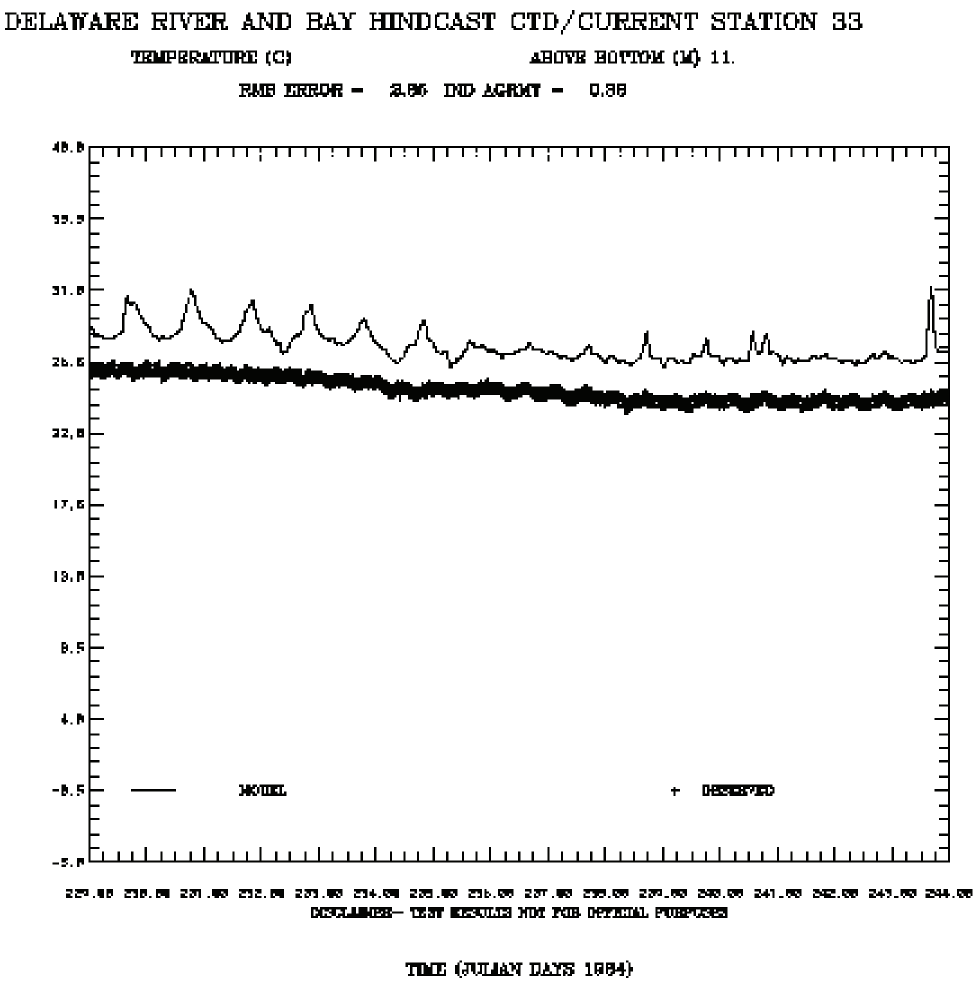


Figure 6.69. DBOFS Version 1.1 Temperature JD 229-244, 1984 at Station 33. Observations are at 10-minute intervals.

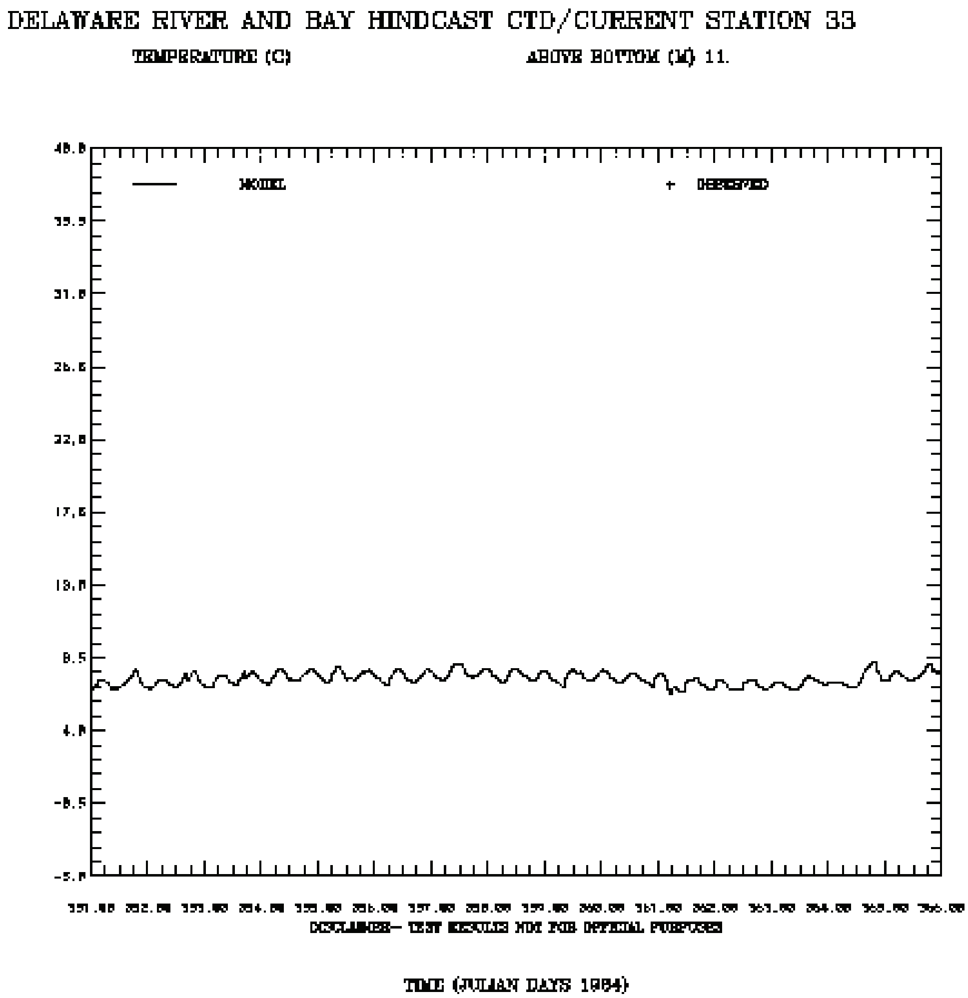


Figure 6.70. DBOFS Version 1.1 Temperature JD 351-366, 1984 at Station 33.

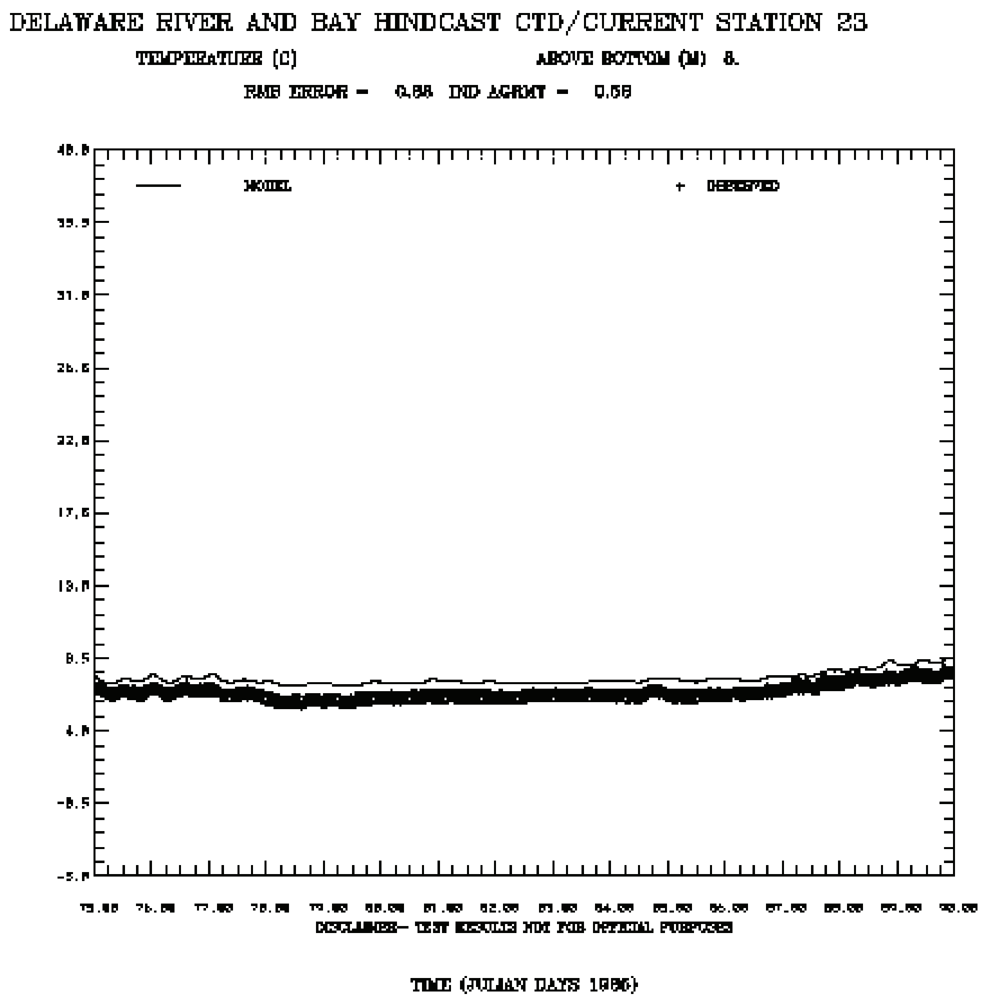


Figure 6.71. DBOFS Version 1.1 Temperature JD 75-90, 1985 at Station 23. Observations are at 10-minute intervals.

6.5. Summary and Additional Considerations

The optimized offshore tidal water level constituents and bottom roughness coefficient sets obtained for the April 1984 tidal simulation, lead to much improved model responses in both the 13-month tidal and hindcast simulations. Due to the fact that the offshore boundary extends to the continental shelf break, it is necessary during the optimization process to perform harmonic analysis of the tidal simulations to further refine the tidal water level harmonic constants obtained from the ADCIRC Western North Atlantic tidal inversion. This approach was not necessary for the previous generation forecast systems, whose offshore boundaries did not extend substantially on to the shelf and therefore their tidal water level harmonic constants could be obtained by an adjustment of nearby coastal water level station values. Sufficient accuracies in these revised model predictions were obtained to justify the development of the semi-operational nowcast/forecast system at NCEP.

7. SEMI-OPERATIONAL NOWCAST/FORECAST SYSTEM CONSTRUCTION

To develop a semi-operational nowcast/forecast system, it was necessary to revise the COMF used at CO-OPS for implementation at NCEP. In this effort, it was necessary to standardize the initial condition, boundary condition, and forcing files for the operational nowcast forecast systems to be run at NCEP. To support this effort several templates were developed to aid in the development of the appropriate fixed files.

7.1 River Template

To specify the lateral (river) boundary conditions the template given in Table 7.1 was developed for DBOFS.

Table 7.1. Template of River Control File for DBOFS.

```
Section 1:  USGS real-time streamflow gages

NO      USGS_ID    NWS_ID min(cfs) max(cfs) mean(cfs)   Name
1       01411500            20.    5260.      253.   Maurice River, Norma, NJ
2       01412800             5.    2150.       56.   Cohansey River, Seeley, NJ
3       01463500          1240.  279000.    11850.   Delaware River, Trenton, NJ
4       01465500             3.   27300.      302.   Neshaminy Creek, Langhorne, PA
5       01467087             1.    3140.       41.   Frankford Creek, Philadelphia,
PA
6       01474500             1.   93400.     2773.   Schuylkill River, Philadelphia,
PA
7       01477120             3.    1260.       40.   Racoon Creek, Swedesboro, NJ
8       01478650            35.   14200.       45.   Brandywine Creek, Wilmington, DE
9       01482500             0.    4460.       20.   Salem River, Woodstown, NJ
10      01484525             0.    1260.       95.   Millsboro Pond, Millsboro, DE
11      01477000             6.    6510.       92.   Chester Creek, PA

Section 2: ROMS river discharge inputs
GRID_ID  I/Xpos  J/Ypos  DIR FLAG DQ_USGS_ID DQ_Scale TS_USGS_ID TS_SCALE River_Basin_Name
   1       94     92      0   3   01411500    1.0     01474500    1.0        MAURICE RIVER
   2       88    128      0   3   01412800    1.0     01474500    1.0        COHANSEY RIVER
   3       77    730      1   3   01463500   0.33     01463500    1.0        DELAWARE RIVER
   4       78    730      1   3   01463500   0.34     01463500    1.0        DELAWARE RIVER
   5       79    730      1   3   01463500   0.33     01463500    1.0        DELAWARE RIVER
   6       73    608      0   3   01465500    1.0     01467087    1.0        NESHAMINY CREEK
   7       76    542      0   3   01467087    1.0     01467087    1.0        FRANKFORD CREEK
   8       73    426      0   3   01474500    1.0     01474500    1.0        SCHUYLKILL RIVER
   9       86    341      0   3   01477120   -1.0     01474500    1.0        RACCOON CREEK
  10       73    283      0   3   01478650    1.2     01474500    1.0        BRANDYWINE CREEK
  11       87    206      0   3   01482500   -1.0     01474500    1.0        SALEM RIVER
  12       65     52      0   3   01484525    1.0     01474500    1.0        MILLSBORO POND
  13       73    349      0   3   01477000    1.0     01474500    1.0        CHESTER CREEK
  14       67     96      0   3   01484525   0.25     01474500    1.0        ROACH MARSH


Note min, max, and mean flows are in cfs. Note DQ_SCALE is negative for Raccoon Creek
and Salem River to note the flow is in the direction of decreasing coordinate values.
```

7.2 Open Boundary Condition Template

For the open boundary condition, the template given in Table 7.2 was constructed, which seeks to use secondary and backup water level gages for subtidal water level. In general the A and B coefficients would need to be determined via linear regression of at least one month of subtidal water levels.

Table 7.2. Template of Open Boundary Condition Control File for DBOFS.

```
Section 1:  OBC Boundary Signal Information
NO      NOS_ID     SEC_WL_ID  As  Bs  BKP_WL_ID Ab    Bb    PORTS_SIG_ID  Clim_SIG_ID        Name
1       853-4720         2    1.  0.      4      1.0  0.        0              0    Atlantic City, NJ
2       857-0283         1    1.  0.      4      1.0  0.        0              0 Ocean City Inlet, MD
3       857-3927         5    1.  0.     99      1.0  0.        1              1  Chesapeake City, MD
4       853-6110        99    1.  0.     99      1.0  0.       99             99          Cape May, NJ
5       857-9999        99    1.  0.     99      1.0  0.       99             99        Baltimore, MD

Note for subtidal water level: SEC_WL_ID is the secondary water level station
id and BKP_WL is the backup water level station id.

A(s,b) and B(s,b) are used to estimate the water level at the NOS_ID as
follows:
WL(NOS_ID)= As*WL(SEC_WL_ID) + Bs, and WL(NOS_ID)= Ab*WL(BKP_WL_ID) + Bb.

Note ids equal to 99 indicate no stations for secondary or backup water level.

Note for T and S: PORTS_SIG_ID and CLIM_SIG_ID equal zero corresponds to
Levitus. If PORTS_SIG_ID is not
zero, specify PORTS signal information in Section 2. If CLIM_SIG_ID is not
zero then you must provide
T and S information in Section 3 as follows. Note ids equal to 99 indicate no
stations for PORTS or climatology, these are water level backup stations only.

Section 2: PORTS Signal Information
NO    PORTS Station     BKP_PORTS_ID  Tadj    Sadj
1     DBOFS-Chesapeake        2       0.      -5.
2     CBOFS-Baltimore        99       0.       0.
Note Tajd and Sadj are temperature and salinity adjustments in deg C and PSU,
respectively,
which are added to the CBOFS-Baltimore station values used to backup
Chesapeake City, MD.
If CBOFS-Baltimore is not available than one uses the climatological values in
Section 3.

Section 3: Interior Boundary Signal T/S Climatology
NO   T/S Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
1         3   3   8  12  15  18  19  22   24  18 12  7   --Temperature (Deg C)
          8   6   4   4   3  7   10  10    9   5  7  8   --Salinity (PSU)

Section 4: ROMS grid control information
Section #   IROMS_L  IROMS_U  JROMS_L  JROMS_U Bdy_ID_1 Bdy_ID_2 Scale_1  Scale_2  P_ID    C_ID
      1      60       69        1         1       2        1         1.      0.      0       0
      2      70      119        1         1       2        2         0.      0.      0       0
      3       1        1      210       211       3        3         1.      0.      1       1
      4     119      119        2        59       1        1         0.      0.      0       0
      5     119      119       60        69       1        2         1.      0.      0       0

Note L_U denotes lower and upper bounds of grid cell indicies. Note Bdy_IDs and
Scales used for subtidal water level signal determination. PORTS and Clim_Sig_IDs
```

```
used for T and S. If PORTS (P_ID) and Climatology(C_ID)Signal IDS are 0 use
Levitus. If P_ID is not zero attempt to use PORTS data in Section 2, if not
available use climatological information in section 3.
```

In addition, the specification of the subtidal water level was generalized based the previous operational forecast systems in New York (NYOFS), Chesapeake Bay (CBOFS), and Galveston Bay (GBOFS) using the following approach. During the nowcast, consider water level observations, *wlobs(T-nΔt)*, where *T* is the forecast start time and *n=0,….,24* with *Δt=1* hr. Note one could also use 6 minute data. The coastal water level station is near the offshore model boundary intersection with the coast. During the nowcast, consider Extratropical Storm Surge (ETSS) model predictions *wlmod(T-nΔt)*, at this same coastal water level station with the *T* and *nΔt* as defined above. One then forms corrections, *δ(T-nΔt)=wlobs(T-nΔt) – wlmod(T-nΔt)*.

Consider

$$df(T,T-24\Delta t) = \sum_{n=-24}^{0} \delta(T-n\Delta t)/25 \tag{7.1}$$

and

$$\varepsilon(T-n\Delta t) = \delta(T-n\Delta t) - df(T,T-24\Delta t) \tag{7.2}$$

During the Nowcast:

$$OBC_N(T-n\Delta t)= wlmod(T-n\Delta t) + df(T,T-24\Delta t) + \varepsilon(T-n\Delta t),\ n=0,\dots,24 \tag{7.3}$$

At each *Δt* during the nowcast period, one may scale the correction, *δ(T - nΔt*), which is equal to *df(T,T - 24Δt) + δ(T - nΔt)*, on a e-folding scale based on increasing distance from the shore point.

During the forecast:

$$OBC_F(T + n\Delta t)= wlmod(T + n\Delta t) + F_1 df(T,T - 24\Delta t) + F_2\varepsilon(T),\ n=0,\dots,24 \tag{7.4}$$

where $F_1=max(0.,1-n\Delta t/TR_1)$ and $F_2=max(0.,1-n\Delta t/TR_2)$.

At each *Δt* during the forecast period, one may scale the correction, $F_1 df(T,T - 24\Delta t) + F_2\varepsilon(T)$, on a e-folding scale based on increasing distance from the shore point. One notes the specification of TR1 and TR2 are as follows for the previous operational forecast systems.

Chesapeake Bay Operational Forecast System (CBOFS): $TR_1=\infty$, $TR_2 = 6$
New York Harbor Operational Forecast System (NYOFS): $TR_1= 6$, $TR_2=6$
Galveston Bay Operational Forecast System (GBOFS): $TR_1=\infty$, $TR_2=\infty$

To standardize the specification of the tidal boundary conditions at each open boundary cell, a harmonic constituent netCDF file for water level amplitude and phase and East and North vertically integrated horizontal current amplitudes and phases was constructed, such that all phases are in GMT. The HPC-COMF software at NCEP access this netCDF harmonic constituent file and for tidal currents computes the current ellipse parameters required by ROMS. The software also computes the node factors and equilibrium arguments and adjusts the harmonic constants.

7.3 Vertical Datum Considerations

Model datum specification is made to be consistent with the VDATUM Project utilizing the following approach. In GBOFS, the model datum was taken as equivalent to MTL and the MTL to MLLW field over the Galveston Bay grid was provided via VDATUM to enable specification of the water level forecast fields with respect to MLLW. In NYOFS and CBOFS, model datum is assumed equal to MSL and the VDATUM MSL to MLLW field is used to enable specification of the water level forecast fields with respect to MLLW. An alternative approach used here is to assume model datum equal to the North American Vertical Datum of 1988 (NAVD88) in the upper reaches of the Delaware Estuary in the river sections above Philadelphia, PA, but near the coast assume model datum equal to MSL. Therefore, an additional field, model datum minus mean sea level, was developed. For the majority of the coastal estuaries, the values in this file will be zero. For the Delaware Estuary, nonzero values were added as one proceeded up the Delaware River above Marcus Hook, PA to the head of tide at Trenton, NJ. As more gravity data become available the coastal geoid will be better determined; then these values can be further refined up the estuary. On the shelf, with advanced satellite altimeter observations, the tie to the mean sea level at the coast can be better determined as well.

A program was developed to access the VDATUM database for three separate VDATUM Projects with datum information to interpolate onto the high resolution DBOFS grid the following four datum fields: MLLW to MSL, MLW to MSL, MHHW to MSL, and MHW to MSL. The MLLW to MSL field is shown in Figure 7.1 and exhibits a smooth transition of contours out on to the continental shelf from the lower Bay region.

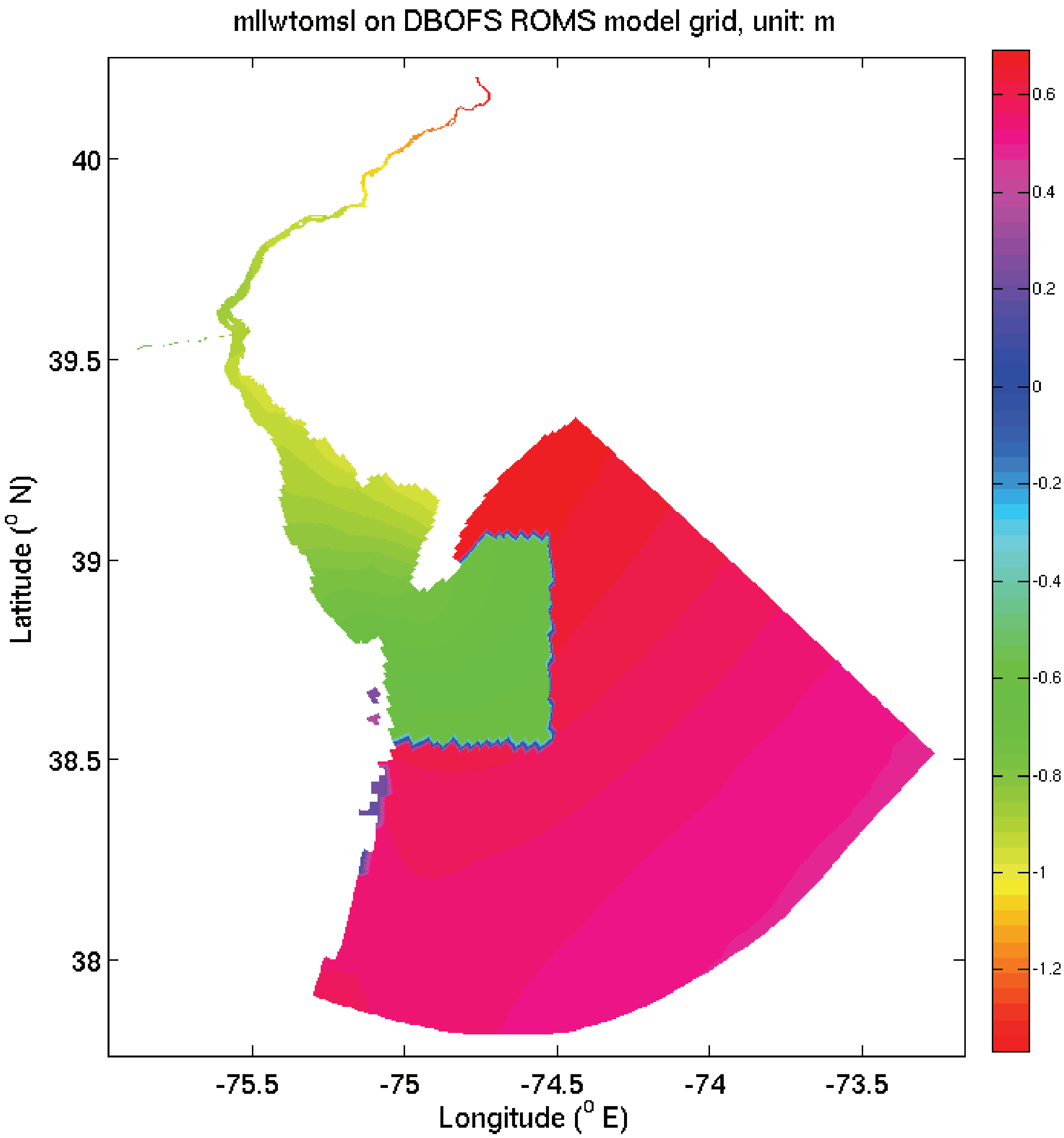


Figure 7.1 DBOFS MLLW to MSL Datum Conversion.

7.4 Operational Summary

In early June 2009, DBOFS Version 1.0 was provided to CO-OPS for implementation in the development mode at NCEP. The bathymetry was revised to increase the cutoff depth from 2 m to 5 m to overcome a stability problem. Since the revised bathymetry was used in late June 2009, the hydrodynamics have been very stable.

During the period June – December 2009, the work reported in Chapter 6 was conducted to further seek improvements and to develop DBOFS Version 1.1. In December 2009, DBOFS Version 1.1 was provided to CO-OPS and they implemented this version in January 2010 in parallel with version 1.0. The two versions are compared in Table 7.3 over the seven month period March-September 1984. One notes the substantial improvement gained by refining the open boundary tidal constituents and further adjusting the bottom roughness coefficients. The ten percent of water level range RMSE criteria is now satisfied at all stations up the estuary.

Table 7.3. Seven Month March-September 1984 Water Level RMSE (cm) Summary. The analyses are for 15 days, thus there are two entries for each month. PMTR denotes the RMSE expressed as a percentage of the mean tide range. First line denotes DBOFS Version 1.0 results, while DBOFS Version 1.1 results are given in line 2 and in line 3 for tide only.

Station	Mar	Apr	May	Jun	Jul	Aug	Sep	Seven Month RMSE	RMSE Range	PMRT
Trenton, NJ	33/26 25/25 22	33/25 23/16 20	39/34 17/26 20	42/35 22/20 21	33/39 25/20 24	35/34 20/23 25	28/39 18/18 25	34 23 23	17 8 5	13.7 9.3 9.3
Phila., PA	27/21 17/15 19	27/21 12/11 18	30/24 11/11 17	32/28 13/12 18	31/32 17/16 20	25/26 11/11 21	20/25 10/15 22	27 14 19	12 7 5	14.8 7.7 10.4
Lewes, DE	17/13 14/12 8	15/11 9/9 3	18/13 10/9 5	17/15 11/10 8	15/17 12/11 9	18/16 11/10 8	14/18 8/8 5	16 11 7	7 6 6	12.9 8.9 5.6
Cape May, NJ	21/14 15/11 7	20/15 9/10 4	21/15 9/9 5	18/16 10/11 8	16/18 10/11 9	14/19 10/8 8	15/20 7/8 6	17 10 7	7 8 5	11.4 6.7 4.7

8. CONCLUSIONS AND RECOMMENDATIONS

Following the Model Evaluation Experiment Project, two 15-day simulation periods one for high flow (April 1984) and one for low flow (September 1984) were used to compare POM with ROMS on the MEE Project medium resolution grid and to investigate the sensitivity of the water level response to the Walters (1992a; 1992b) bottom friction zones using different bottom friction coefficient sets. A high resolution grid using the DELFT3D RGFGRID package (Delft Hydraulics, 2004) was developed and the previous 15-day periods were used to further refine the bottom roughness and the open boundary condition conditions with the result being the construction of DBOFS version 1.0. An initial seven month hindcast was performed and evaluated for total water levels and tides for DBOFS Version 1.0, which was provided to CO-OPS in June 2009. To seek further improvements, an extensive set of 18 tidal simulations were used to further adjust the bottom roughness and open boundary water level specification via modification of the open water level boundary tidal constituents to develop DBOFS Version 1.1. Both 13-month simulations were performed using DBOFS Version 1.1 and informally skill assessed for water levels, currents, salinity, and temperature in terms of RMSE and Willmott et al. (1985) relative error. Improvements in water level RMSEs were significant over those in DBOFS Version 1.0 and met the informal ten percent range criteria at all stations. As a result, it is recommended that a formal skill assessment be performed over the 13-month period March 1984- March 1985 for both the hindcast and tidal simulations described in Chapter 6 for DBOFS Version. In addition, DBOFSVersion 1.1 implemented in the development mode at NCEP should be formally skill assessed and compared with the results for the 13-month hindcast and tidal simulations to insure proper implementation at NCEP.

In conjunction with the model development effort, the results of the 13-month hindcast suggest that further improvements can be made in the following areas:

The temperature response exhibited overheating during the summer and fall of 1984, thereby suggesting that the downward short wave radiation be attenuated. However, during the winter, the water temperatures in the upper Bay and lower river sections remained extremely cold with freezing indicated. This indicated that the attenuation in downward short wave radiation may need to be seasonally specified. Heat flux algorithm adjustments may need to be further considered in the coastal zone in conjunction with ice dynamics. The development of the cold water pool along the outer shelf also was a feature that needs a more refined open boundary condition than Levitus climatology.

The salinity response in the lower Bay was considerably fresher than the observations at Station 33, and suggests that the location of the salt wedge needs further study.The $\delta_x H/H$ criteria of under 0.25 is violated throughout the grid and may result in horizontal pressure gradient errors which tend to effect the salt wedge representation. It is recommended that additional levels in the vertical be considered as well as the $\delta_x \Delta H/H$ criteria. Additional data from the DRBC salt line dataset may be useful in further studying the salt wedge dynamics.

Bottom currents tend to be overestimated and there becomes a trade-off between water level representation, salt wedge location, and current dynamics. Additional ADCP data over vertical sections in the upper Bay would be useful to further adjust the hydrodynamics. Inclusion of the alongshore transport over the shelf should also be further investigated.

To extend the model prediction skill to major storm surge events (enumerated by Mark and Scheffner, 1994), accounting for the low lying marsh areas through the use of using wetting and drying techniques (see Schmalz, 2007) should be considered. In addition, the treatment of the change in cross-sectional area with discharge due to the low lying marsh areas is extremely difficult to accomplish. We note at the flood stage of 20 ft the corresponding flow is 137,000 cfs. At 330,000 cfs based on an average daily flow, which is the flood of record the stage would be 29 ft. One might estimate channel width changes as the flows increase by using a very simple method as follows. If the cross-section were approximately 300m wide by 5m in depth for 3900 m3/s (137,000 cfs), then the expected flow velocity would be order 2.6 m/s. Assuming the same flow speed of 2.6 m/s and an increase of 3 m in elevation the channel width (w) would can be approximated as 9430 m3/s (330,000 cfs) = 2.6m/s * w*(5+3m), which would imply w = 453m. This would be an increase of 153m assuming a constant depth of 8 m, which is somewhat under the 29 ft (8.84m) level. Another approach might be to assume a maximum flow speed of 3 m/s at 29 ft (8.84m) and then based on this uniform depth compute w= 355.6 m. Additional efforts may have to be made to adjust the bottom roughness as a function of Delaware River flow at Trenton, NJ to simulate frictional effects at higher flows.

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