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Towards the Development of the NOS Nowcast/Forecast System for Delaware River and Bay

Richard A. Schmalz, Jr.[1], F. ASCE

Abstract

The National Oceanic and Atmospheric Administration (NOAA) is in the process of developing the nowcast/forecast system for Delaware River and Bay from the head of tide at Trenton, NJ extending through the Bay entrance out onto the continental shelf to supplement its Physical Oceanographic Real Time System (PORTS), which was installed in 2003 to provide water surface elevation, temperature, salinity, and meteorological information. In conjunction with this effort, a Model Evaluation Environment (MEE) has been developed, which involves the comparison of both structured and unstructured three-dimensional hydrodynamic model results versus the National Ocean Service (NOS) Delaware River and Bay 1984 Circulation Survey measurements of water surface elevation, currents, salinity, and temperature during the 21 March through 7 September 1984 evaluation period. The MEE provides additional validation data particularly for currents and density that are not available within the PORTS. Initial MEE results are presented and additional simulations over two shorter 15-day periods using the Princeton Ocean Model (POM), one of the structured grid models, are used to further guide the development of the Delaware River and Bay Nowcast/Forecast System. The effects of a spatially varying bottom friction, subtidal water level forcings at the Chesapeake and Delaware (C&D) Canal boundary, and navigation channel bathymetry and upriver storage areas on water level and current response are studied. POM is also used to examine the need for a revised bottom friction treatment and flood/dry capability. In conclusion, plans for further development and testing are presented.

Introduction

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 at the locations shown in Figure 1. To complement the PORTS, a nowcast/forecast system is being developed within the Coastal Ocean Modeling Framework (COMF; Gross et al., 2006) as discussed by Aikman et al. (this volume). In conjunction with this effort, a Model Evaluation Environment (MEE) as described by Patchen (this volume) was constructed for the

1 Oceanographer, National Oceanic and Atmospheric Administration, National Ocean Service, Coast Survey Development Laboratory, Marine Modeling and Analysis Programs, 1315 East-West Highway, Rm 7824, Silver Spring, Maryland 20910. (301)-713-2809 x104; e-mail: Richard.Schmalz@noaa.gov.

Delaware River and Bay based on the NOS 1984-1985 Circulation Data Survey (Klavans et al., 1986). The purpose of the MEE is to provide for a consistent comparison of hydrodynamic models using the same geometrical, forcing, and validation data. In the context of the Delaware River and Bay Nowcast/Forecast System, the MEE 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 development of the Delaware River and Bay Nowcast/Forecast System. Here we first describe and present the results from the MEE. For additional information on the development of the common open boundary conditions refer to Feyen and Yang (this volume). For individual model applications refer to Myers (this volume), Zhang and Wei (this volume), and Lanerolle (this volume). To seek further improvement, we consider two separate 15 day periods embedded within the MEE. POM simulation results are presented in turn for each of these periods in an effort to lead toward improvements in all the models. To conclude the paper, we outline further development and testing.

Model Evaluation Experiment Description and Results

The initial effort was to 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 with respect to CTD refer to Loeper (2006) and for CT and current see Richardson and Schmalz (2006).

The horizontal computational grid for POM which is 150 (E-W) x 550 (N-S) is shown for the upper Delaware River in Figure 2 and for the Delaware Bay in Figure 3 with the finest grid resolutions approximately 50 m . Fifteen sigma coordinate levels are used in the vertical with uniform spacings below the surface level.

Initial salinity and temperature conditions were developed from the NOS 1984-1985 circulation dataset. Salinity and temperature lateral boundary conditions were specified based on 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 on a 32 km grid (NCEP, www.ncep.noaa.gov/mmb/rrean/index.html) with meteorological observations at NOAA buoys, C-Man stations and airports. River discharge and temperature were obtained from the USGS. Water levels and currents at the open-ocean lateral boundaries were obtained from the ADCIRC model for the Western Atlantic Ocean on the East Coast 1995 grid (Mukai et al., 2001) forced with the blended National Centers for Environmental Prediction (NCEP) reanalysis wind product with available meteorological observations, and verified tidal constituents developed by Myers (2007; personal communication) along the open-ocean boundary at 60^{o} W.

The following models were evaluated based on the four experiments described by Patchen (this volume):

1. Regional Ocean Modeling System (ROMS) as described in Shchepetkin and McWilliams (2005) and Haidvogel et al. (submitted).

On the Internet at: 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 (submitted).
   On the Internet at: www.ccalmr.ogi.edu/corie/modeling

Here we focus on the 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 1 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 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 3. 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 4. 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.

<u>MEE Assessment and Nowcast/Forecast System Development</u>

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). To this end two15-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. 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

Table 1. MEE Water Level Skill Assessment Results.
Note stations proceed from the coast (Figure 2) up estuary to head of tide (Figure 3) and the NOS target is CF(15 cm) ≥ 90 %.

	RMSE (m)				CF (15 cm)			
Station	ROMS	POM	FVCOM	SELFE	ROMS	POM	FVCOM	SELFE
Atlantic City, NJ	0.115	0.115	0.108	0.108	80.7	80.9	83.5	83.6
Ocean City Pier, MD	0.131	0.136	0.134	0.134	72.9	71.7	72.2	72.2
Chesapeake City, MD	0.182	0.135	0.132	0.192	60.2	75.1	75.7	51.8
Lewes, Ft. Miles, DE	0.119	0.133	0.107	0.123	80.7	75.8	85.0	84.5
Cape May Canal, NJ	0.121	0.130	0.113	0.135	82.5	79.6	81.7	73.4
Brandywine Shoal Light, DE	0.117	0.127	0.103	0.138	85.4	81.8	85.4	73.4
Reedy Point, DE	0.291	0.244	0.135	0.208	35.6	48.5	77.7	67.7
Philadelphia, PA	0.369	0.363	0.213	0.369	39.7	39.1	50.5	43.2
Trenton Marine Terminal, NJ	0.589	0.502	0.474	0.576	21.3	28.7	17.9	24.5

Table 2. MEE Current Skill Assessment Results.
Note stations proceed from the coast (Figure 2) up estuary to head of tide (Figure 3) and the NOS target is CF(26 cm/s) ≥ 90%.

			RMSE (m/s)				CF (26 cm/s)			
Station No.	Water Depth (m)	Obs Depth (m)	ROMS	POM	FVCOM	SELFE	ROMS	POM	FVCOM	SELFE
1	22.9	3.7	0.254	0.245	0.194	0.244	66.6	67.9	81.9	71.0
17	30.5	7.6	0.119	0.088	0.122	0.098	97.5	99.2	96.1	99.4
23	11.6	3.7	0.151	0.157	0.237	0.214	91.3	89.9	73.7	78.9
33	14.6	3.7	0.290	0.261	0.154	0.318	57.7	64.3	90.8	46.9
39	12.8	4.3	0.230	0.408	0.177	0.344	72.8	36.4	82.4	49.8
42	10.1	4.9	0.368	0.286	0.189	0.273	51.4	61.5	84.0	61.7
47	13.1	4.6	0.377	0.369	0.192	0.298	36.9	32.6	82.1	49.6
50	15.2	7.3	0.335	0.297	0.282	0.325	47.7	50.2	63.4	47.6
51	13.7	5.2	0.336	0.337	0.219	0.341	44.2	40.1	76.6	45.2
52	10.4	6.1	0.225	0.216	0.198	0.232	74.5	77.4	80.5	74.9
54	11.0	4.6	0.113	0.094	0.083	0.091	98.0	99.4	100.0	99.6

Table 3. MEE Salinity Skill Assessment Results.
Note station water depth and observation depth are as given in Table 2.
Stations proceed from the coast (Figure 2) up estuary to the head of tide (Figure 3) and the NOS target is CF(3.5 PSU) ≥ 90%.

	RMSE (PSU)				CF (3.5 PSU)			
Station No.	ROMS	POM	FVCOM	SELFE	ROMS	POM	FVCOM	SELFE
1	4.136	4.042	1.503	11.418	48.0	54.3	97.3	0.0
17	1.483	1.470	1.483	2.015	100.0	100.0	100.0	94.2
23	6.321	5.540	3.160	10.815	4.3	40.7	73.8	0.9
33	11.489	9.212	4.767	11.278	1.7	22.5	48.4	2.5
39	6.119	3.198	1.784	3.510	43.2	67.5	96.6	61.6
42	4.164	0.349	2.543	0.409	60.3	100.0	100.0	100.0
47	0.011	0.011	1.715	0.011	100.0	100.0	100.0	100.0
50	0.000	0.000	2.168	0.004	100.0	100.0	100.0	100.0
51	0.024	0.027	1.566	0.024	100.0	100.0	100.0	100.0
52	0.030	0.029	2.296	0.033	100.0	100.0	100.0	100.0
54	0.101	0.096	1.190	0.101	100.0	100.0	100.0	100.0

Table 4. MEE Water Temperature Skill Assessment Results.
Note station water depth and observation depth are as given in Table 2.
Stations proceed from the coast (Figure 2) up estuary to the head of tide (Figure 3) and the NOS target is CF(3.0 ^{o}C) ≥ 90%.

	RMSE (^{o}C)				CF (3.0 ^{o}C)			
Station No.	ROMS	POM	FVCOM	SELFE	ROMS	POM	FVCOM	SELFE
1	2.454	2.309	1.694	3.457	78.0	83.9	94.5	53.4
17	2.001	2.644	1.569	4.405	89.8	76.4	92.3	47.2
23	3.294	3.380	2.226	5.995	67.7	54.1	84.2	16.7
33	1.545	2.180	1.630	5.308	97.8	84.6	92.0	20.8
39	0.351	0.924	6.763	6.617	100.0	100.0	0.0	0.0
42	0.719	2.217	5.688	4.704	100.0	91.3	6.8	21.3
50	1.054	0.792	1.986	1.478	100.0	100.0	84.6	100.0
51	3.024	4.663	2.972	2.831	64.3	61.5	63.6	58.9
52	1.064	0.887	2.032	1.504	100.0	100.0	84.9	100.0
54	1.655	1.744	1.793	1.718	100.0	99.2	97.8	98.3

astronomic tides and allowed for an assessment of the tidal response. Since the author was the POM lead modeler, this model was used to seek further improvements. It was expected that what was learned in improving POM would be helpful to the other models.

To move toward a more standard nowcast/forecast system set-up, 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 (see 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 interpolation from meteorological data at 10 stations (including 2 offshore NBDC buoys) to provide the wind and sea-level atmospheric pressure fields. Note the subtidal water level signal at Cape May, NJ was applied to the entire ocean open boundary. Note 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).

Using the above methods, a POM baseline simulation was performed over the period 27 March – 5 April, 1984. 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. In the MEE the water level residual at the head of the C&D canal was considered zero. Here, the water level residual 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 water level residual 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 5 with RMSEs increasing from 14 cm at the Bay entrance to 23 cm at Philadelphia, PA with a maximum near the head of tide at Trenton, NJ of 47 cm as shown in Figure 4 top panel. 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 Willmott et al. (1985) dimensionless (0-1) relative error, with zero representing perfect agreement. Note for the time series plots (Figures 4-7) the indicator of agreement (IND AGMT) equal to one minus the relative error is given.

Table 5. Water Surface Elevation-MLLW (m) High Flow Hindcasts:
Baseline March 27 - April 5, 1984 Results / Revised March 27 – April 10, 1984 Results

Station	RMS Error (cm)	Relative Error (-)	Model Mean (cm)	Observed Mean (cm)
Lewes, DE	14/13	0.02/0.02	91/86	86
Cape May, NJ	14/13	0.01/0.01	98/93	93
Indian River, DE	23/22	0.07/0.08	68/62	63
Phila. Pier 11, PA	23/22	0.04/0.03	135/145	133
Trenton, NJ	47/37	0.09/0.04	180/204	191

Current speed and direction are compared against observations in Tables 6 and 7, 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.

Table 6. Current Speed (cm/s) High Flow Hindcasts:
Baseline March 27 - April 5, 1984 Results / Revised March 27 – April 10, 1984 Results

Station Model Level	RMS Error (cm/s)	Relative Error (-)	Model Mean (cm/s)	Observed Mean (cm/s)
16 Level 6	13.65/12.76	0.46/0.48	9.98/9.82	15.33
17 Level 11	13.45/12.73	0.55/0.59	13.56/14.06	13.34
23 Level 4	14.57/15.28	0.11/0.14	42.71/42.40	40.54
33 Level 4	25.74/19.46	0.22/0.12	43.58/52.19	58.17
50 Level 9	29.87/27.83	0.36/0.38	39.73/46.72	61.78
52 Level 9	21.54/17.99	0.34/0.26	30.97/38.65	47.17

The simulated salinity at the corresponding model sigma level (K=1, 15 with 1 representing the near surface) are compared with observations in Table 8. One notes as shown in Figure 5 top panel 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 9. With the SST specification, the RMSEs are within order 2 ^{o}C.

Table 7. Current Direction (^{o}T) High Flow Hindcasts:
Baseline March 27 - April 5, 1984 Results / Revised March 27 – April 10, 1984 Results

Station Model Level	RMS Error (°T)	Relative Error (-)	Model Mean (°T)	Observed Mean (°T)
16 Level 6	89.75/86.25	0.85/0.78	186.29/194.21	228.85
17 Level 11	136.62/137.58	0.83/0.83	174.72/178.02	215.01
23 Level 4	26.40/31.54	0.02/0.03	243.53/239.16	254.61
33 Level 4	35.83/29.10	0.04/0.02	226.99/219.72	226.66
50 Level 9	30.15/36.06	0.03/0.04	167.41/170.13	176.83
52 Level 9	26.56/30.48	0.02/0.03	148.05/153.85	148.01

Table 8. Salinity (PSU) High Flow Hindcasts:
Baseline March 27 - April 5, 1984 Results / Revised March 27 – April 10, 1984 Results

Station Model Level	RMS Error (PSU)	Relative Error (-)	Model Mean (PSU)	Observed Mean (PSU)
16 Level 12	0.95/1.05	0.73/0.65	31.66/31.62	32.58
16 Level 8	0.67/0.69	0.71/0.60	31.66/31.60	32.19
16 Level 6	0.83/0.78	0.70/0.59	31.63/31.58	32.28
17 Level 11	1.12/1.01	0.92/0.89	32.71/32.79	33.78
23 Level 4	1.23/1.49	0.57/0.45	25.81/25.33	25.58
33 Level 4	6.48/2.72	0.67/0.17	20.01/12.61	13.14

Table 9. Temperature (°C) High Flow Hindcasts:
Baseline March 27 - April 5, 1984 Results / Revised March 27 – April 10, 1984 Results

Station Model Level	RMS Error (°C)	Relative Error (-)	Model Mean (°C)	Observed Mean (°C)
16 Level 12	2.07/1.86	0.84/0.69	6.78/6.81	5.01
16 Level 8	2.05/1.82	0.82/0.67	6.80/6.82	5.06
16 Level 6	1.99/1.74	0.79/0.65	6.83/6.83	5.17
17 Level 11	1.98/2.02	0.87/0.85	7.40/7.51	5.51
23 Level 4	0.65/0.73	0.55/0.99	6.43/6.43	6.43
33 Level 4	0.73/1.40	0.57/0.51	5.69/5.71	6.71

Revised High Flow Simulation

To seek further improvements the following revisions to both input data and hydrodynamic model were made:

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 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) 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.