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EVALUATION OF A THREE-DIMENSIONAL HYDRODYNAMIC MODEL APPLIED TO CHESAPEAKE BAY THROUGH LONG-TERM SIMULATION OF TRANSPORT PROCESSES[1]

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ABSTRACT: A numerical model, the Curvilinear Hydrodynamics in 3-Dimensions, Waterway Experiment Station version (CH3D-WES), was applied to represent transport processes of the Chesapeake Bay. Grid resolution and spatial coverage, tied with realistic bathymetry, ensured dynamic responses along the channel and near the shoreline. The model was run with the forcing ranges from high frequency astronomical tides to lower frequency meteorological forcing, given by surface wind and heat flux, as well as hydrological forcing given by fresh water inflows both from upstream and distributed sources along the shoreline. To validate the model, a long-term simulation over seven-year time period between 1994 and 2000 was performed. The model results were compared with existing observation data including water level time series, which spans over a wide spectrum of time scales, and long-term variations in salinity structures over varying parts of the Bay. The validated model is set to provide an appropriate transport mechanism to the water quality model through linkage, warranting that the model takes into account the complexity in time and spatial scales associated with the dynamic processes in the Chesapeake.

(KEY TERMS: estuaries; hydrodynamics; computational methods; simulation.)

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INTRODUCTION

Chesapeake Bay is a large estuary where physical and ecological processes are influenced by oceanic inputs as well as loading from the surrounding watersheds and airshed. Nichols and Biggs (1985) gave a comprehensive description of the geological and hydrodynamic settings of the Chesapeake Bay, described as an estuarine system created by inundation of a drowned river valley during sea level rise. The Bay is the estuary of the Susquehanna River, draining about 72,000 km^2, which comprises of over 40% of all the watersheds to the Bay. The total area of the Chesapeake watershed is approximately 166,000 km^2, and covers areas of six states including New York, Pennsylvania, Delaware, Maryland, Virginia, West Virginia, and the District of Columbia. The Bay is connected to Delaware Bay in the northeastern end through the Chesapeake and Delaware (C&D) Canal, which is characterized by net flux out of the Bay (Nichols and Biggs, 1985). The lower Bay is connected to the Atlantic Ocean. The shoreline of the Bay and its tidal tributaries extends over 18,500 km. The Bay is essentially a shallow pan, 5- to 50-km wide and 320-km long from the entrance

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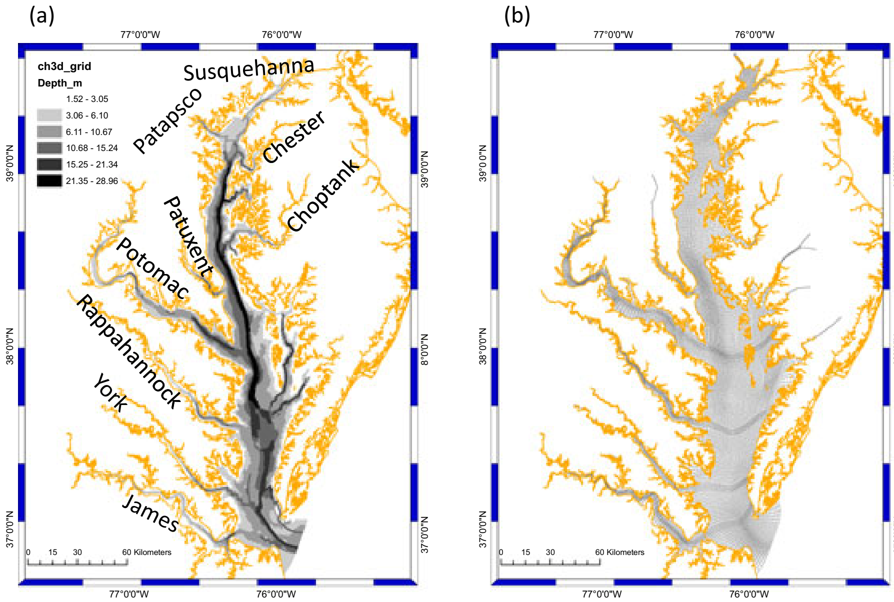

FIGURE 1. Location Map. (a) Model bathymetry (in gray scale varying between 1.5 and 30 m). The names listed are for major tributaries. (b) Model grid.

to the fall line. The lower Bay has a primary channel in the south and a secondary channel in the north, which is rejoined to the primary channel. The primary channel is the drowned river valley of the Susquehanna River. Mean depth of the Bay is about 7 m, and a broad axial channel extends about 270 km from the Bay's mouth with major tributaries branching into the James, York, Rappahannock, Potomac, Patuxent, and Patapsco Rivers, on the western side from south to north and the Choptank and Chester Rivers on the eastern side (Figure 1a).

The transport in the Bay is affected by meteorological and hydrological conditions and is under the influence of astronomical tides. The variations of salinity in the Bay are shown in a wide range of scales in time and space due to complex bathymetry and shoreline configuration combined with the multiple-scales of dynamical forcing. Li *et al.* (2005) described general dynamical features of the Bay, such as a salinity gradient of 2-8 ppt vertically, and 20-30 ppt longitudinally. Stratification during high freshwater inflows and de-stratification by strong winter storms were also described in their article. The hydrological cycle shows clear seasonal variations and inter-annual variations. Meteorological forcing is dominated by frontal passages which have about a three- to seven-day cycle. For astronomical tides, semi-diurnal tides are dominant — most notably by the M2 constituent. A distinct neap-spring cycle is also known to dominate the dynamical features shown in water levels as well as in mixing throughout the water column.

A series of models for different processes for different perspectives, such as a water quality model or ecosystem model, are viable tools to understand such a complex system. Being consequential to the distribution of scalar properties such as salt, heat, and many other water quality parameters, transport is a common denominator to these models. A three-dimensional hydrodynamic model can handle the wide spectrum of scales associated with transport in such a complex system. One of the recent modeling studies was done by Li *et al.* (2005) in which the Regional Ocean Modeling System (ROMS) was used to develop a three-dimensional hydrodynamic model for the Bay. In their study, a hindcast was performed for two years — one for a high runoff year (1996), followed by a normal runoff year (1997). Their study indicated that turbulence mixing parameters were critical to replicate the transport processes, represented by varying states of stratification in space and time. Recent modeling studies of Xu *et al.* (2012) using ChesROMS and Hong and Shen (2012) using HEM-3D also analyzed response of the Bay hydrodynamics to different forcing of variable scales from tidal to climatological scales.

In this study, the US Army Corp of Engineers three-dimensional model (Johnson *et al.*, 1993), based on Curvilinear Hydrodynamics in 3-Dimensions — Waterway Experiment Station version (CH3D-WES) was modified and extended. A z-grid model representing bathymetry change with stair-steps, such as the CH3D-WES, is known to be prone to numerical diffusion unlike sigma-grid based models such as

ROMS (Beckmann and Haidvogel, 1993). However, terrain-following grids such as a sigma-grid are also subject to pressure gradient error depending on the grid resolution at the slope (Mellor *et al.*, 1994). Steep bathymetric gradients across the paleo-thalweg in the Bay would require more resolution across the channel walls if the sigma-grid model was employed to prevent dispersion across the channel. The CH3D-WES has been proved to be a successful management model for the U.S. Environmental Protection Agency (USEPA) Chesapeake Bay Program (CBP) water quality modeling system (Cerco *et al.*, 2010). One of the reasons is believed to be a faithful representation of the Bay bathymetry. It may be accepted that a z-grid model is advantageous in the case of highly varying bathymetry. Being a drowned river valley estuary, the Bay is represented by the primary channel of 30 m in depth separated from shallow shoals of about 5-m depth by abruptly dropping channel walls. In this study, a new grid was built to run the CH3D-WES, which, to a degree, tolerates nonorthogonality unlike such models as ROMS based on an orthogonal grid in the horizontal plane. A considerable effort was given to represent the direction of the long-axis following the primary paleo-thalweg.

The motivation of this model development is to provide transport to a water quality model, CE-QUAL-ICM (Cerco and Cole, 1993; Cerco *et al.*, 2010; Cerco and Nole, this issue), which has been used to manage the Bay water quality by the CBP and thus simulation time period spans over decades. One of the requirements for a hydrodynamic model is that it should be able to take a wide spectrum of scales for forcing, ranging from astronomical tides to meteorological forcing to hydrological forcing and surface heat flux. Thus, the objective of this study became to develop such a hydrodynamic model based on the CH3D-WES capable of representing the Bay dynamics. This article presents the results from a long-term simulation over a seven-year time period between 1994 and 2000, whose analyses lead to investigate the model performance as well as the dominant processes of the Bay. First, the model setup and validation strategy is presented. This includes the model grid setup and physical setting of the model for the basin hypsometry and adjacent watersheds. Description of the variation for forcing during the simulation period is also included. Transport from the model is then investigated by analyzing water level data first, focusing on dynamics in both tidal and sub-tidal frequencies. Salinity data then provides insight to mixing processes responding to astronomical tides and meteorological forcing as well as hydrological cycles. Discussion and summary follows.

MODEL SETUP AND TEST STRATEGY

The model grid was generated to represent the paleo-channels in the main Bay and the major tributaries as well as the realistic shoreline configuration. In Figure 1a, the bathymetry covers the range between 1.5 and 30 m in depth below mean tide level. A z-grid was set with 1.5-m depth interval and the

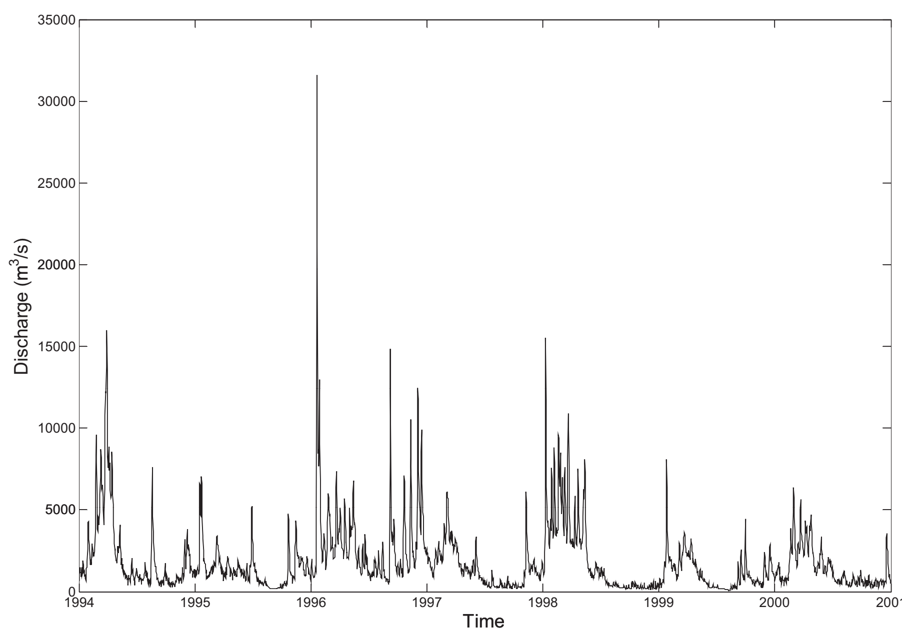

FIGURE 2. Daily Mean Discharge from Major Tributaries to the Bay Over Seven-Year Simulation Time Period Between 1994 and 2000.

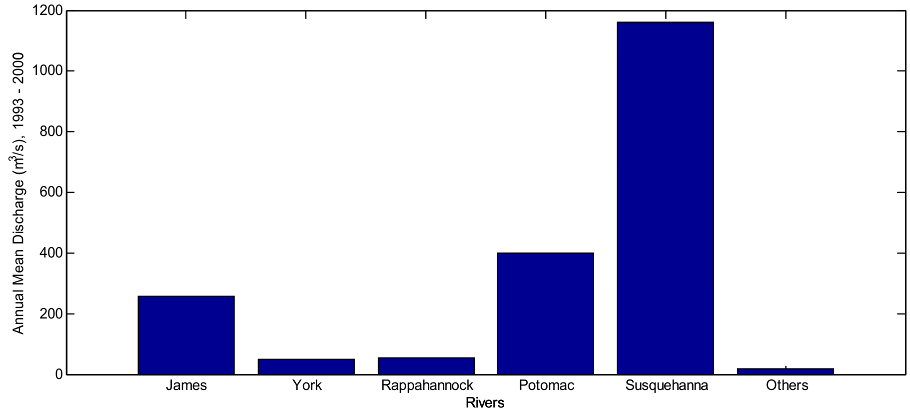

FIGURE 3. Annual Mean Discharges from Major Tributaries.

maximum number of layers is 20. The horizontal grid built into the main Bay is about 1 km with the focus on the mid- and upper Bay where the grid resolution is about 400 m (Figure 1b). In computational domain, the horizontal grid is 178 by 282. The total number of active surface cells is 11,100 and the total number of water cells is 57,138.

Hydrological cycle of Chesapeake Bay and surrounding watersheds shows typical characteristics of temperate latitudes, with charateristic inter-annual and intra-annual cycles. Figure 2 shows daily average discharge to the system over a seven-year period between 1994 and 2000. The average discharge is about 1,900 m^3/s. 1996 is considered to be a year of high flow while 1999 is low flow year. Figure 3 shows the annual average discharges from major tributaries. The most contribution of flow is from the Susquehanna River (~60%). The Potomac River flows (~21%) and the James River flows (~13%) follow. Small contributions are from the York (~3%) and the Rappahannock (~3%) Rivers. The contributions from the remaining tributaries are less than 1%. The hydrological forcing to the model is given at the upstream of each tributary as above-fall line loading and distributed flows along the tributary.

Surface winds vary over different frequencies; there exist daily variation associated with minor disturbances or sea breeze. There are fluctuations with a period of several days associated with synoptic scale winds. Figure 4 shows hourly winds (dashed line) at Thomas Point Light House (TPLM2) in the mid-Bay for 1998 (Figure 5a). Also shown is low-pass filtered

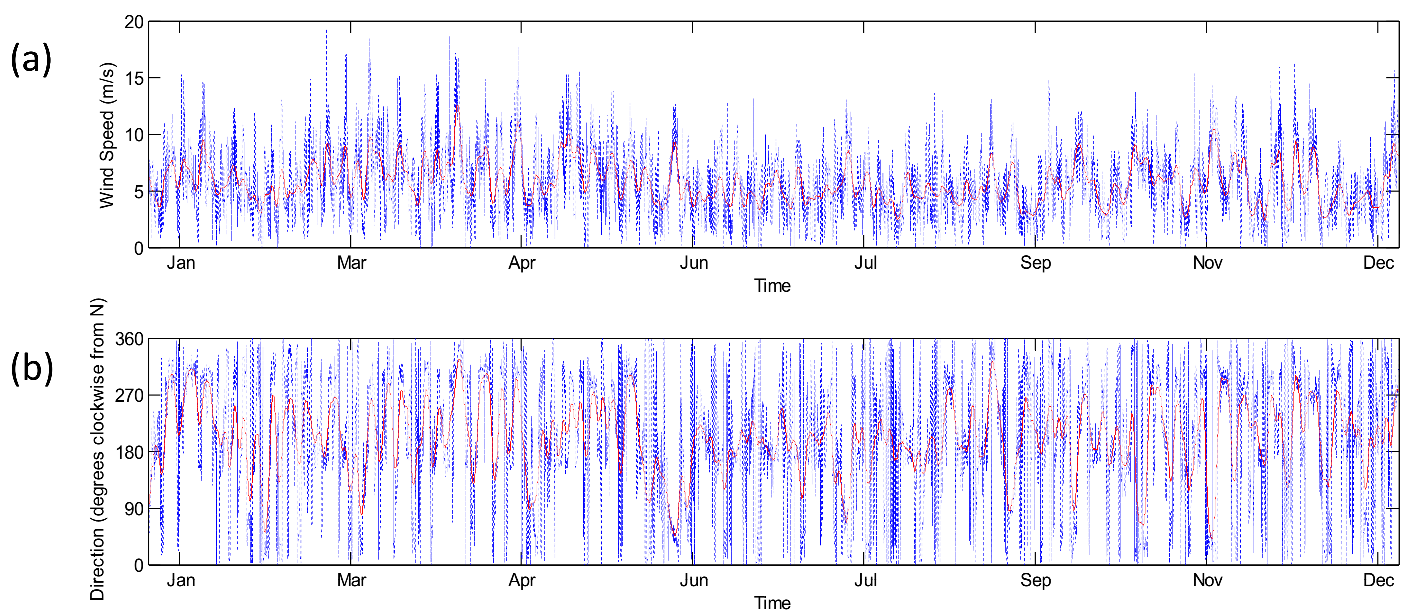

FIGURE 4. Surface Wind Data from TPLM2 in 1998. (a) Speed and (b) direction. The dashed line is from hourly data and the solid line represents 36-h low-pass filtered data.

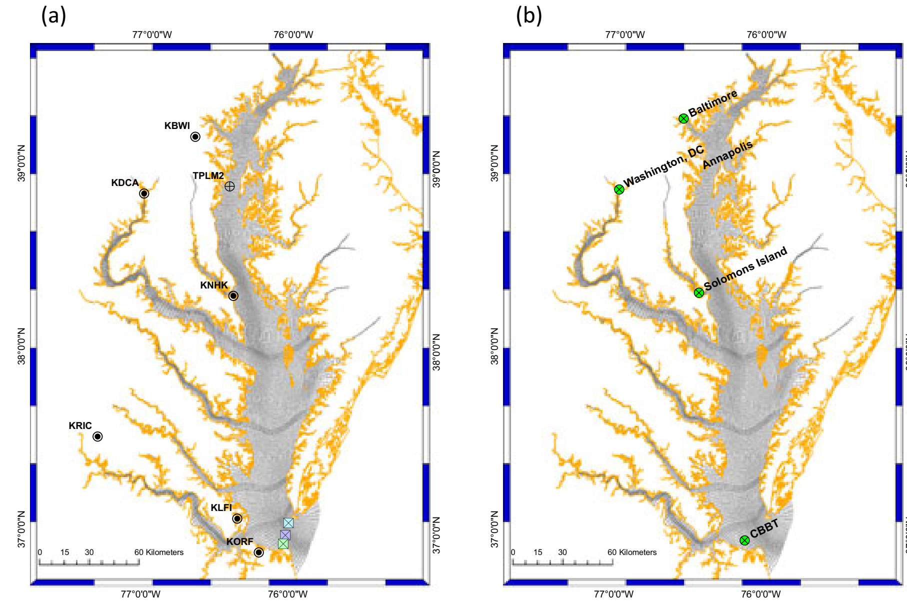

FIGURE 5. (a) Locations for Meteorological Data and Open Boundary Conditions Used in This Study. Double circles are airport locations — Baltimore International Airport (KBWI), Patuxent River (KNHK), Langley Air Force Base (KLFI), and Norfolk International Airport (KORF). Circle with cross inside is for Thomas Point Light House (TPLM2), a Chesapeake Bay Observing System (CBOS) buoy location. Squares with an X inside are the CBP long-term monitoring stations — CB7.4N, CB7.4, and CB8.1E, from north to south, respectively. (b) National Oceanic and Atmospheric Administration tide gage locations.

signal (solid line) which exhibits fluctuations with a period of several days. In general, summer seasons show weaker winds while the winter season sometimes shows stronger winds associated with frontal passages with frequencies of three to seven days. Figure 5a shows the locations of meteorological stations which provided forcing as surface winds and heat flux. Along the axis of the main Bay, the forcing was interpolated from five stations — Baltimore International Airport (KBWI), TPLM2, Patuxent River (KNHK), Langley Air Force Base (KLFI), and Norfolk International Airport (KORF). For Potomac River meteorological forcing Reagan National Airport (KDCA) was used as another additional point for interpolation while Richmond International Airport (KRIC) was used for the James and York Rivers. Also shown in Figure 5a are the locations for open boundary conditions which were set by observations from CBP long-term monitoring stations, CB7.4N, CB7.4, and CB8.1E, representing seasonal variation.

The model was set up for seven years between 1994 and 2000. A model run for one year in 1993 provided initial conditions for the simulation run. For freshwater inflows, both for above fall line flows and distributed flows, a daily discharge data from CBP watershed model were used. For meteorological forcing, surface winds were taken every 4 h from the meteorological stations and daily mean heat flux was estimated from meteorological data. At the open boundary, water levels were nudged from hourly data at Chesapeake Bay Bridge-Tunnel (CBBT) (Figure 5b). For salinity and temperature along the open boundary, the three CBP stations were used (Figure 5a). The sampling frequency of the CBP monitoring was typically twice a month between spring and fall and once during winter months. The model time step was 90 s. For model evaluation, data were archived hourly.

Wilmott (1981) gave guidance for evaluating model performance. His specific criticism was on the inadequacy of using the correlation coefficient for model evaluation. He devised the skills score using Index of Agreement (IA)

$$d = 1 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left[|P_i - \overline{O}| + |O_i - \overline{O}| \right]^2} \tag{1}$$

Here, d is IA. P represents prediction and O represents observation. Overbar denotes mean and i denotes individual samples. In essence, d depends on both the specific potential error (denominator) based on distribution of observed and predicted variate around the observed mean and the mean square error (numerator) representing the closeness of prediction to observation. He demonstrated that this descriptive statistic, IA, reflects the degree to which the observed variate is accurately estimated by the simulated variate. This IA, ranging from 0 to 1 with 1 representing perfect comparison, is used in this study to test the model performance.

WATER LEVELS AND CURRENTS

Water levels contain most distinctly astronomical tide signals as well as low frequency meteorologically induced signals. Thus, the analyses were divided into two parts — one for astronomical tides and another for low-frequency fluctuations. First harmonic analyses were applied to hourly water levels saved at 5 National Oceanic and Atmospheric Administration tide gage locations (Figure 5b). For Solomons Island and Annapolis, the harmonic analyses were done for a five-year period between 1996 and 2000 during which observed data were available. For the remaining three stations, the harmonic analyses were done for the seven-year period between 1994 and 2000. The harmonic analyses were based on seven major constituents — M2, S2, N2, K1, M4, O1, and M6. The results show reasonable agreement in amplitudes (about a 1-cm difference except for Washington, D.C. with about 6-cm difference for M2) and phases of the major constituents between observation and model results (Tables 1-5).

Figure 6 shows a portion of the seven-year sub-tidal signal in 1998. The sub-tidal signals were obtained by applying a 36-h low-pass filter to both observed and modeled data. The results show general agreement between model and observation. The IAs for water levels were 0.90, 0.94, 0.95, 0.90, and 0.82 at CBBT, Baltimore, Washington, D.C., Annapolis, and Solomons Island, respectively. The fluctuations reflected meteorological conditions, primarily the speed and direction of surface wind. Surge events from all the gage locations were aligned well over the time axis (for example, around 3/20/1998), suggesting the extent of synoptic winds affected the whole Bay.

The modeled currents were compared at a Chesapeake Bay Observing System station MB located at mid-Bay (Figure 8b). Because the dominant direction was along the channel axis, comparison was made for modeled and observed current speeds. Figure 7 shows a portion of comparisons at 18.9-m depth at MB station over a three-month period between October and

TABLE 1. Harmonic Analysis for Astronomical Tide at Chesapeake Bay Bridge-Tunnel (CBBT).

	Amplitude (m)		Phase Lag (hour)	
Constituent	**Observed**	**Predicted**	**Observed**	**Predicted**
M2	0.393513	0.368249	−5.4307	−4.8921
S2	0.066143	0.057823	−3.4633	−2.8376
N2	0.090008	0.081008	−4.7373	−4.1509
K1	0.050396	0.046838	6.9228	7.367
M4	0.004927	0.002543	−2.6371	−2.3866
O1	0.042189	0.039797	7.7579	8.4174
M6	0.00678	0.008497	1.3193	1.7596

TABLE 2. Harmonic Analysis for Astronomical Tide at Solomons Island, Maryland.

	Amplitude (m)		Phase Lag (hour)	
Constituent	**Observed**	**Predicted**	**Observed**	**Predicted**
M2	0.239477	0.23643	2.7434	2.6523
S2	0.032989	0.02825	4.4349	4.6535
N2	0.04626	0.044311	3.4388	3.437
K1	0.041784	0.042723	−6.5195	−6.8219
M4	0.010718	0.007964	1.4748	1.8163
O1	0.038591	0.032293	−8.3472	−7.6955
M6	0.002648	0.004288	−0.0012	−0.0135

TABLE 3. Harmonic Analysis for Astronomical Tide at Annapolis, Maryland.

	Amplitude (m)		Phase Lag (hour)	
Constituent	**Observed**	**Predicted**	**Observed**	**Predicted**
M2	0.136172	0.125625	3.8675	4.2186
S2	0.019321	0.016111	5.4732	−5.8265
N2	0.027909	0.026695	4.6926	5.1059
K1	0.05056	0.049974	−5.5452	−5.7275
M4	0.003535	0.003906	1.0986	2.7434
O1	0.041567	0.037226	−7.1106	−6.4379
M6	0.003676	0.002289	−0.1627	0.1287

TABLE 4. Harmonic Analysis for Astronomical Tide at Washington, D.C.

	Amplitude (m)		Phase Lag (hour)	
Constituent	**Observed**	**Predicted**	**Observed**	**Predicted**
M2	0.423701	0.360129	−5.5395	−5.5269
S2	0.053635	0.035542	−3.0392	−3.0712
N2	0.081586	0.063548	−4.9153	−5.0136
K1	0.038497	0.031032	−5.9407	−4.7637
M4	0.039035	0.039224	−0.7186	−0.5317
O1	0.027412	0.023453	−6.1981	−5.0331
M6	0.012546	0.017427	0.0061	−0.1133

TABLE 5. Harmonic Analysis for Astronomical Tide at Baltimore, Maryland.

	Amplitude (m)		Phase Lag (hour)	
Constituent	**Observed**	**Predicted**	**Observed**	**Predicted**
M2	0.154614	0.162857	5.4379	5.7536
S2	0.022836	0.021373	−4.7735	−4.4643
N2	0.034039	0.035382	6.2114	−6.198
K1	0.061139	0.05825	−4.7602	−5.1211
M4	0.007378	0.010852	−1.7933	−2.2554
O1	0.049654	0.043189	−6.3819	−5.7149
M6	0.002739	0.004632	−1.9404	1.6345

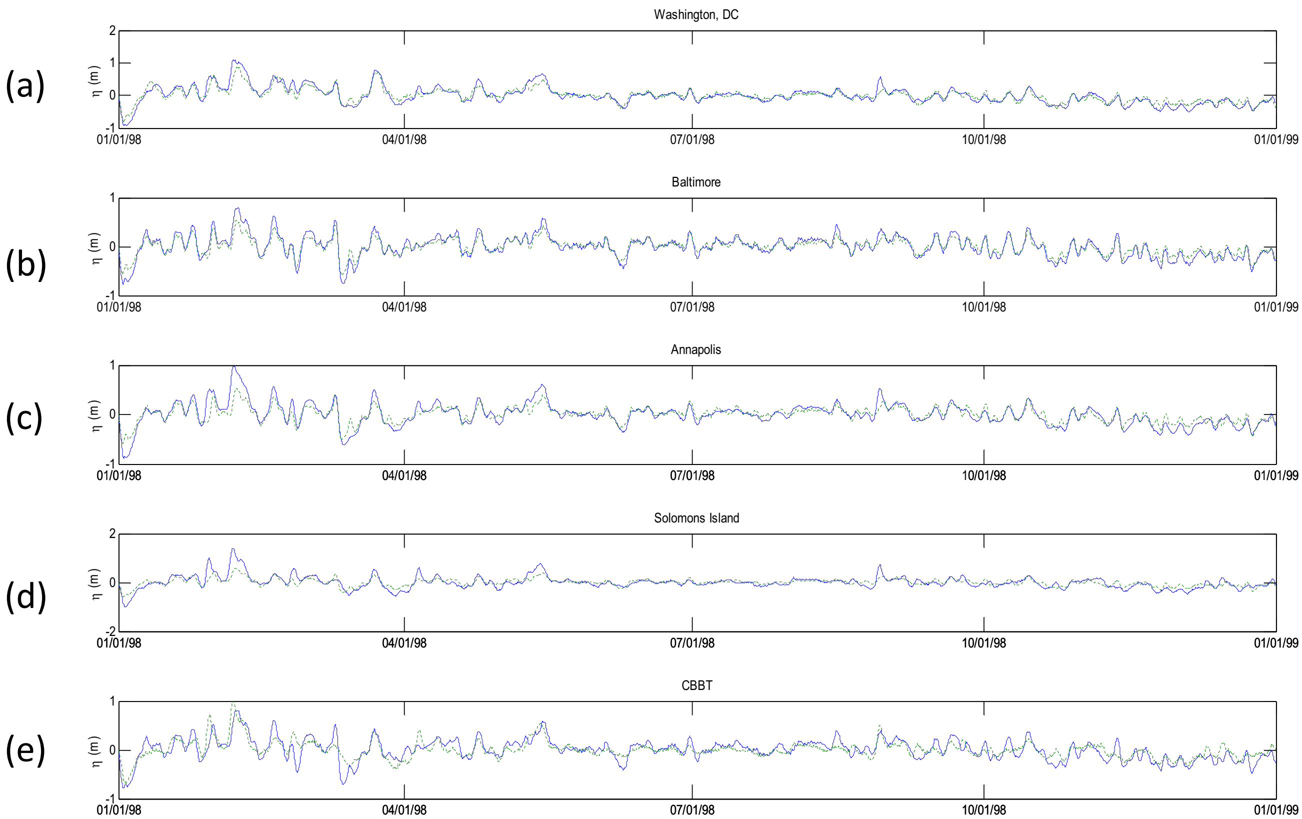

FIGURE 6. Subtidal Signals Using 48-h Low-Pass Filter for 1998 from Tide Gage Locations: (a) Washington, D.C.; (b) Baltimore; (c) Annapolis; (d) Solomons Island; and (e) Chesapeake Bay Bridge-Tunnel (CBBT). Solid lines are from model simulation and dashed lines are for observed data.

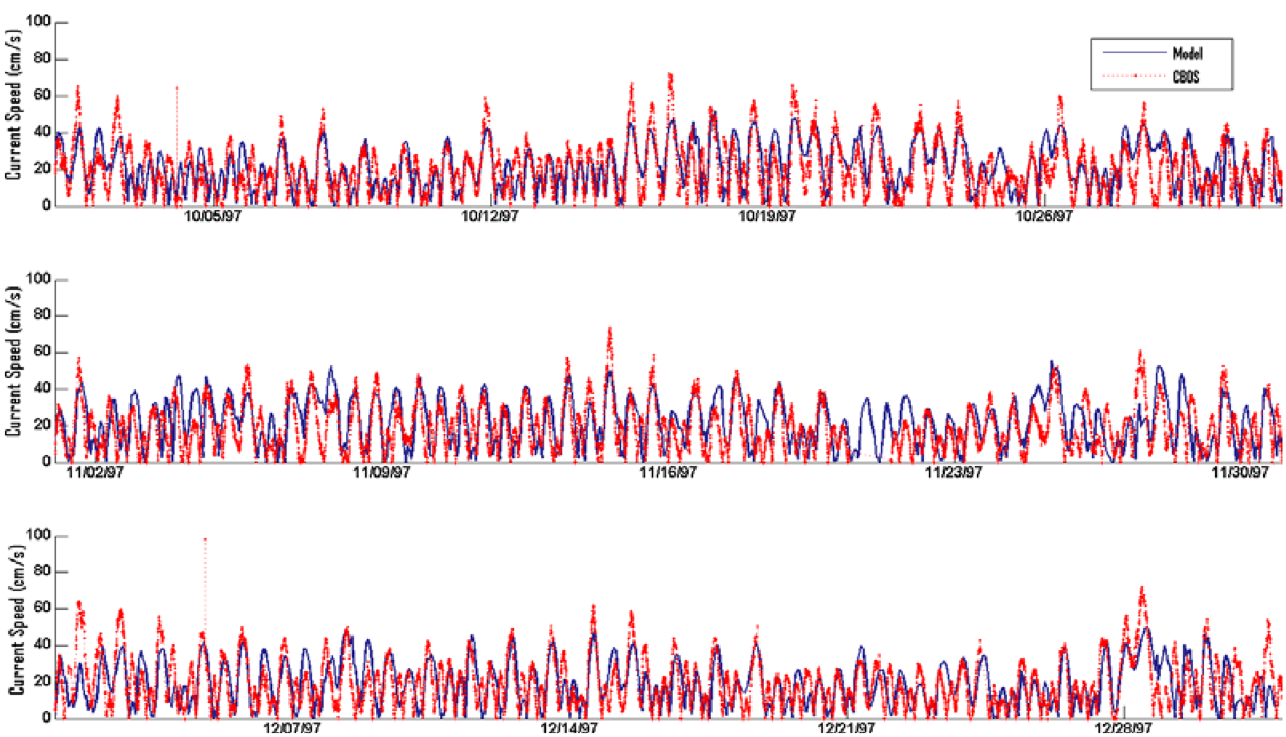

FIGURE 7. Plot for Three-Month Portion of Current Speed at 18.9 m from Surface CBOS Station in Mid-Bay, MB. The solid line represents model and dotted line with cross mark represents measured data.

TABLE 6. IA of Salinity for 1994 to 2000 at Main Bay Stations.

	Bottom	Mid-Depth	Surface
CB2.1′	0.92	0.92	0.94
CB2.2	0.79	0.88	0.90
CB3.1	0.89	0.92	0.94
CB3.2	0.91	0.88	0.92
CB3.3C	0.92	0.88	0.92
CB3.3E	0.93	0.94	0.94
CB3.3W	0.90	0.91	0.95
CB4.1C	0.94	0.93	0.95
CB4.1E	0.96	0.95	0.98
CB4.1W	0.95	0.96	0.96
CB4.2C	0.94	0.92	0.94
CB4.2E	0.95	0.95	0.96
CB4.2W	0.95	0.96	0.97
CB4.3C	0.94	0.91	0.94
CB4.3E	0.98	0.97	0.97
CB4.3W	0.97	0.97	0.97
CB4.4	0.95	0.92	0.95
CB5.1	0.94	0.94	0.94
CB5.1W	0.91	0.92	0.92
CB5.2	0.96	0.93	0.96
CB5.3	0.97	0.95	0.95
CB5.4	0.97	0.96	0.95
CB5.4W	0.96	0.96	0.95
CB5.5	0.97	0.96	0.95
CB6.1	0.97	0.95	0.95
CB6.2	0.96	0.95	0.96
CB6.3	0.96	0.96	0.96
CB6.4	0.97	0.97	0.97
CB7.1	0.96	0.97	0.97
CB7.1N	0.93	0.95	0.95
CB7.1S	0.97	0.98	0.97
CB7.2	0.98	0.98	0.97
CB7.2E	0.98	0.97	0.97
CB7.3	0.99	0.98	0.98
CB7.3E	0.97	0.96	0.98
CB7.4	0.98	0.96	0.95
CB7.4N	0.92	0.92	0.96
CB8.1	0.92	0.98	0.97
CB8.1E	0.97	0.94	0.98

Note: IA, Index of Agreement.

December of 1997. The model results show similar behavior as observation. The currents exhibit both tidal and sub-tidal signals. High speed most likely related to meteorological events, for example around December 28, were captured by model.

SALINITY

Salinity distribution from the model simulation in general reflects the observations in space and time. Table 6 contains the IAs at selected CBP long-term monitoring stations for the main Bay (Figure 8a) at bottom, mid-depth, and surface, respectively. Here, the observed values, which represent instantaneous values, were pared with the daily average. This is justified because the inter- and intra-tidal variations are not as significant as the neap-spring cycle. Average IA of about 0.95 indicates reasonable model performance in salinity transport. The lower IA value at CB2.2 appears to be caused by higher bottom salinity from the model than from observed values. Table 7 contains IA values at the tributaries. The average IA is lower than that of the main Bay, but it is about 0.85. It is speculated to be related to the lower resolution of model grid in tributaries.

Figure 9 shows time series of surface and bottom salinity at six stations over a one-year time period in 1998 along the major axis — CB7.3, CB5.4, CB4.4, CB3.3C, CB3.1, and CB2.2 from the lower Bay to upper Bay, respectively. In general, the simulation and observation show the similar long-term variations. Salinity approaches zero at CB2.2 during spring. Downstream of this station, CB3.1, shows near zero salinity at the surface but higher salinity (~5 ppt) at the bottom during the same time period, indicating the intrusion of salt water is up estuary of this location. At the lower Bay (CB7.3) bottom salinity did not exhibit any freshening at the bottom during the same time period, indicating that in the lower Bay (CB7.3 and CB5.4) and mid-Bay (CB4.4 and CB3.3C), the surface water transports were modulated by hydrological forcing but bottom water processes were modulated by bathymetric control, that is, propagation of salt water through the paleo-thalweg. Figure 10 shows the relationships between observation and prediction. The main Bay showed wider ranges of salinity than the tributaries. In general the prediction and observation are in good agreement. As IA values indicate, tributaries show more scattering than main Bay stations.

To see the seasonal variation of stratification mainly affected by the hydrological cycle, longitudinal distributions of bottom and surface salinity along the major axis of the main Bay were examined (Figure 8b). Seasonal variations of salinity distribution in space also show reasonable model reproduction (Figure 11). We estimated median and 95 and 5 percentiles for both model and observation at the monitoring stations along the major axis of the Bay. The steep gradient of salinity between CB3.3C and CB2.1 in the upper Bay shows the salt intrusion and mixing between freshwater from the Susquehanna River and Bay water. For surface water, the variations given by the range of 5 to 95 percentiles are in good agreement between model simulation and observation throughout different seasons. For bottom water, the variations are in the same range during the dry July to September period and wetter October to December period. During January to March and April to June,

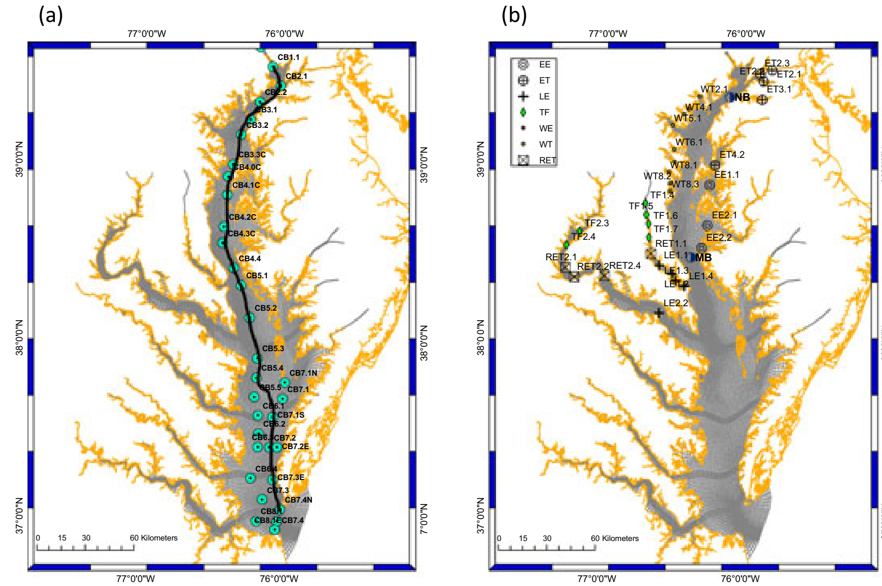

FIGURE 8. Locations of CBP Long-Term Monitoring Stations Used in Salinity Comparison. (a) Main Bay locations. Solid line represents the major channel axis for longitudinal distribution. (b) Tributary locations in mid- and upper Bay. Symbols represent different parts of tributaries. EE, lower eastern tributaries; ET, eastern tributaries; LE, lower major tributaries; RET, middle major tributaries; TF, tidal fresh major tributaries; WE, lower eastern minor tributaries; WT, western minor tributaries.

TABLE 7. IA of Salinity for 1994 to 2000 at Tributaries.

	Bottom	Mid-Depth	Surface
LE1.1	0.89	0.88	0.86
LE1.2	0.91	0.91	0.87
LE1.3	0.91	0.91	0.89
LE1.4	0.90	0.92	0.92
LE2.2	0.89	0.84	0.93
RET1.1	0.78	0.90	0.88
RET2.1	0.87	0.89	0.84
RET2.2	0.80	0.87	0.85
RET2.4	0.86	0.87	0.93
TF1.4	0.71	0.71	0.71
TF1.5	0.83	0.85	0.83
TF1.6	0.89	0.89	0.89
TF1.7	0.91	0.89	0.89
TF2.3	0.77	0.69	0.61
TF2.4	0.88	0.88	0.84
WT2.1	0.73	0.72	0.72
WT3.1	0.72	0.76	0.76
WT4.1	0.89	0.90	0.90
WT5.1	0.84	0.90	0.89
WT6.1	0.97	0.97	0.96
WT7.1	0.98	0.98	0.97
WT8.1	0.96	0.96	0.96
WT8.2	0.96	0.96	0.96
WT8.3	0.88	0.88	0.88
EE1.1	0.88	0.95	0.97
EE2.1	0.93	0.94	0.96
EE2.2	0.89	0.94	0.96
ET2.1	0.83	0.86	0.82
ET2.2	0.81	0.82	0.84
ET2.3	0.79	0.87	0.88
ET3.1	0.77	0.76	0.74
ET4.2	0.76	0.83	0.92

Note: IA, Index of Agreement.

the model gives higher ranges of variations compared to observations for bottom salinity. Modeled vertical profiles of salinity were also compared. This provides assurance of resolving the behavior of pycnocline, which plays a critical role in distribution of water quality parameters such as dissolved oxygen. Figure 12 shows an example which shows vertical profiles at CB3.3C in the upper Bay for 1997-2000 from the seven-year simulation. The circles represent observation and the solid line represents model. Because the monitoring data are obtained as an instantaneous value at a certain depth, it can be argued that the comparison cannot be made at the instant considering the variability forcing scales. For example, the model responds to tidal forcing but at the same time to subtidal and even seasonal scales including hydrological and meteorological forcing. Thus the comparison was made between the instantaneous observed profiles and profiles from daily average values from the model for the sampling date. The comparison suggests that the model reproduced by pycnoclines are reasonable.

DISCUSSION AND CONCLUSION

The forcing used in this model — astronomical tides, meteorology, hydrology, and salinity and temperature profile at the open boundary — sufficiently covers the wide range of frequencies and spatial

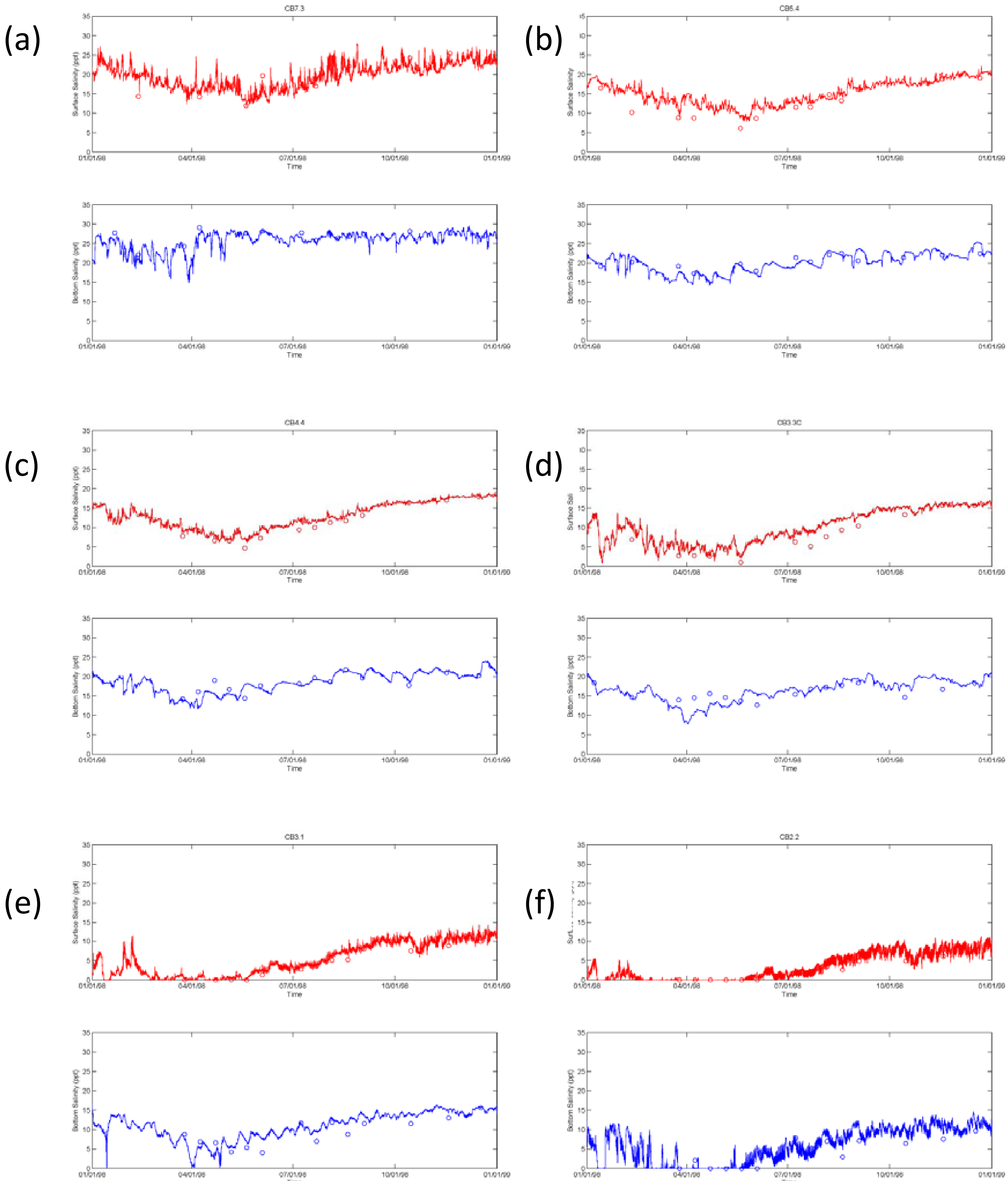

FIGURE 9. Time Series of Surface (upper panels) and Bottom (lower panels) Salinity Distribution for 1998. Solid lines represent model and circles represent observed values. Six stations in the main Bay were selected: (a) CB7.3, (b) CB5.4, (c) CB4.4, (d) CB3.3C, (e) CB3.1, and (f) CB2.2, from lower Bay to upper Bay, respectively.

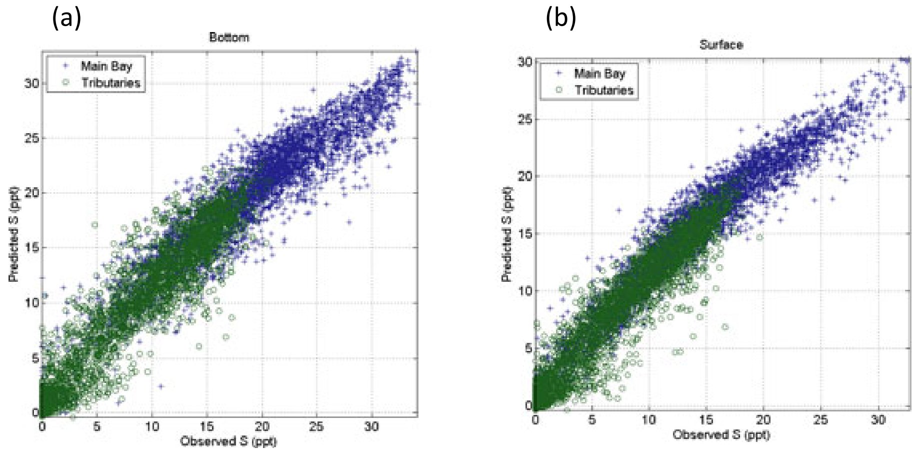

FIGURE 10. Scattered Plots for Predicted *vs.* Observed Values. Open circles are for tributaries and crosses are for the main Bay stations. Predicted values were obtained as daily average corresponding to the times of observation.

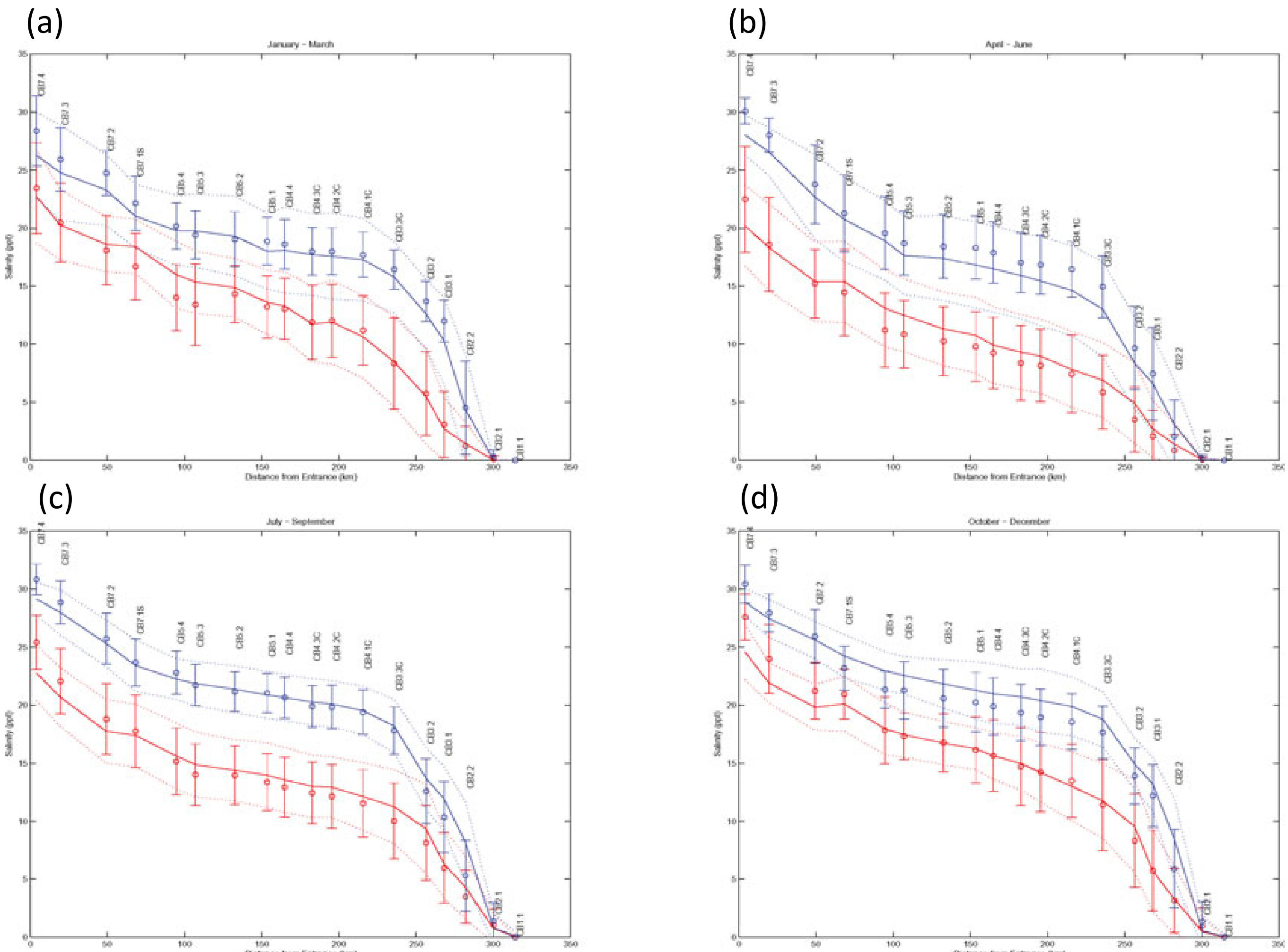

FIGURE 11. Longitudinal Distribution of Bottom (Top Lines) and Surface (Bottom Lines) Along the Major Axis of the Main Bay. Solid lines represent median from seven-year model simulation, which are bounded by dashed lines of five percentile and 95 percentile. Open circles represent median of observed values over seven years, which are bounded by closed bars of five and 95 percentiles. Analyses were divided for seasonal variations — (a) January to March, (b) April to June, (c) July to September, and (d) October to December.

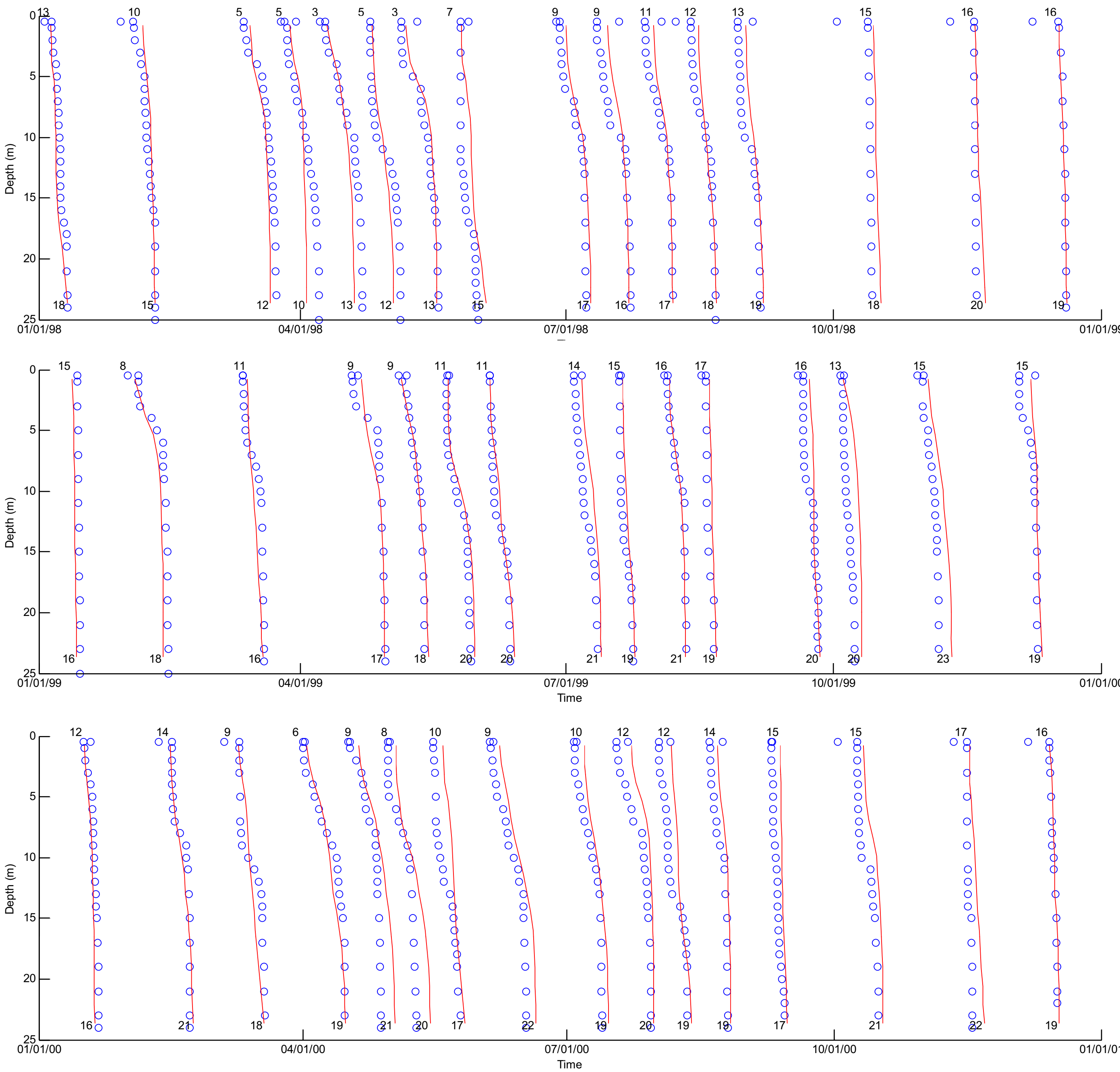

FIGURE 12. Vertical Profiles of Salinity at CPB Monitoring Station CB3.3C in Upper Bay for 1997 to 2000. Circles represent monitoring data and solid lines represent profiles from daily average on the date of monitoring. Numbers at end of lines denote the surface and bottom salinity from model profiles.

variations. Hydrological forcing by the CBP Watershed Model (Shenk and Linker, this issue) was applied to all the major tributaries by above fall line discharges from upstream watersheds and distributed flows from connected watersheds along the paths of the tributaries. The daily input frequency of hydrological forcing appears acceptable. Meteorological forcing from the five stations scattered over the model domain should be adequate considering the scales of typical extratropical system prevailing over the region. The open boundary conditions for salinity and temperature structures may need further study. But comparisons of salinity time series at lower Bay suggest that the open boundary conditions are acceptable.

The existing model applications to the Bay revealed that mixing is the key process to be represented. Blumberg and Goodrich (1990) provided one of the first major modeling studies of the Bay adopting a turbulence model for vertical mixing. One of the significant findings of their model was that the fall destratification is primarily the result of vertical mixing rather than advective processes. Recently, Li and Zhong (2009) investigated intra-tidal and spring-neap variation of turbulent mixing, stratification, and residual circulation in the Bay. They attributed ebb-flood asymmetry to turbulent mixing. They showed significant variation in the stratification and the residual circulation over neap-spring cycle, causing fortnightly and monthly fluctuation. CH3D-WES employs the k-ε turbulence model (Chapman *et al.*, 1996). The stratification from this model represents realistic vertical structures of salinity distribution (see Figures 8 and 10). The mixing processes through water column and over varying frequencies were considered to be apparently realized.

The results from the seven-year simulation reasonably reproduced the dynamic processes of the Bay when compared with observations. The other models applied to the Bay, for example, Li *et al.* (2005), have been successfully reproducing fundamental dynamical processes. However, most of the presentations were limited to broader sense of the main Bay or the entrance of tributaries if any. The primary goal of this model application was to supply adequate transport mechanism to the water quality model (Cerco and Noel, this issue) to run Total Maximum Daily Load (TMDL) loading control scenarios. The application has to cover the areas for which many different entities of regulatory agencies, from local to federal levels, oversee and manage and should reasonably represent the coastline, especially associated with smaller watershed segments. The grid and associated bathymetry for this model application provides the foundation needed to resolve varying scales of processes, not only in the main Bay, but in the tributaries as well ensuring a well-founded transport mechanism to the CBP water quality model, CE-QUAL-ICM.

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