NOAA Technical Memorandum NOS CS 21

VDATUM FOR GREAT SOUTH BAY, NEW YORK BIGHT AND NEW YORK HARBOR: TIDAL DATUMS, MARINE GRIDS, AND SEA SURFACE TOPOGRAPHY

Silver Spring, Maryland
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noaa National Oceanic and Atmospheric Administration

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National Ocean Service
Coast Survey Development Laboratory

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ABSTRACT

An application of VDatum, NOAA's vertical datum transformation software tool, is developed for the Great South Bay area located along the southern Long Island, NY. VDatum allows users to transform vertical elevation/depth data between various tidal, orthometric, and ellipsoid-based 3D reference systems.

The tidal datums fields for this VDatum application were derived from tidal simulations using the Advanced Circulation (ADCIRC) Model, a finite element model which uses unstructured triangular grids. A grid consisting of 218,203 nodes and 395,562 cells was created for this region. The model was forced with nine tidal constituents (M_2, S_2, N_2, K_2, K_1, P_1, O_1, Q_1, and M_4). Tidal harmonic analysis of the model results was conducted for a suite of 37 tidal constituents at each node in the grid. Time series over a National Tidal Datum Epoch (1983-2001) were reconstructed using these harmonic constants. Various tidal datum fields, including mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and mean higher high water (MHHW), were derived from the time series. Model results were validated by comparing with observations at 145 water level stations maintained by the NOAA's Center for Operational Oceanographic Products and Services (CO-OPS). Discrepancies between model results and observational datums were attributed to model errors and interpolated over the whole model domain using TCARI (Tidal Constituent And Residual Interpolation), a spatial interpolation tool based on solution of Laplace's equation. These error fields were added to the original model results to derive corrected tidal datum fields on the model grid. These final tidal datum fields were interpolated onto a regularly structured marine grid used as input by the VDatum software.

The Topography of Sea Surface (TSS), defined as the elevation of NAVD88 relative to local mean sea level (LMSL), was developed based on spatial interpolation of bench mark data maintained by CO-OPS and the National Geodetic Survey (NGS). The NAVD88-to-LMSL values were derived either by fitting tidal model results to tidal bench marks leveled in NAVD88 or by calculating orthometric-to-tidal datum relationships at NOAA tidal gauges. Results by both methodologies were coupled to create the final TSS grids by spatial interpolation.

Key Words: tides, tidal datums, Long Island Sound, New York Bight, Narragansett Bay, ADCIRC, mean sea level, bathymetry, coastline, spatial interpolation, marine grid, North American Vertical Datum of 1998.

1. INTRODUCTION

NOAA's NOS is developing a software tool called VDatum to transform elevation data among approximately 30 vertical datums (Gill and Schultz, 2001; Hess et al., 2003; Milbert, 2002; Parker, 2002; Myers et al., 2005; Spargo, et al., 2006(2); Yang et al., 2006). Once VDatum has been established for a region, data sets referenced to different vertical datums can be integrated through transformations to a common vertical datum (Parker et al., 2003). VDatum allows bathymetric and topographic data to be integrated in this manner through its inherent geoidal, ellipsoidal, and tidal relationships.

To be applicable over coastal waters, VDatum requires spatially varying fields of the tidal datums elevations and the Topography of Sea Surface (TSS). The former includes datums such as MHHW, MHW, MLW, MLLW, Mean Tide Level (MTL), and Diurnal Tide Level (DTL) defined relative to local mean sea level (LMSL). The latter refers to the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to LMSL.

This report describes the development of VDatum for the Great South Bay (GSB) area of Long Island, NY. Figure 1 displays a map encompassing Long Island Sound (LIS), New York Bight (NYB), Narragansett Bay (NB), and adjacent embayments and coastal waters (referred to as LIS-NY). In the figure, the black line represents the MHW coastline and the green line denotes 25-nm offshore demarcation. Tidal datums for VDatum are generally developed for water areas between the coastline and the 25-nm offshore limit, which encompasses the whole GSB area.

Development of VDatum begins with tidal simulations using a hydrodynamic model. Harmonic constants of 37 tidal constituents (Yang, et al., 2008(1)) were computed from a 40-day water level time series derived from the model simulation. These harmonic constants were then used to reconstruct a long water level time series over the National Tidal Datum Epoch (1983-2001) from which tidal datums were derived. The tidal datums are verified through comparisons with observational data, and error corrections were made based on these comparisons. Regularly structured VDatum marine grids were created and populated with corrected tidal datums. Finally, for the same marine grid, the NAVD88-to-LMSL field was derived by either fitting tidal model results to tidal bench marks leveled in NAVD88 or calculating orthometric-to-tidal datum relationships at NOAA tidal gauges.

This technical report is organized as follows: After an introduction in Section 1, Section 2 discusses data input needed for driving the hydrodynamic model run and the verification of the model results. Such data inputs include the digital coastline, bathymetry, and tidal datums derived from observational data. Section 3 details tidal datum simulation procedures, including an introduction of the tidal hydrodynamic model, its setup, validation of results, and error corrections. Section 4 discusses creation of the regularly structured marine grid required for the VDatum software tool and its population with error-corrected model datums. In Section 5, creation of TSS for the area is described. Finally, a summary is given in Section 6.

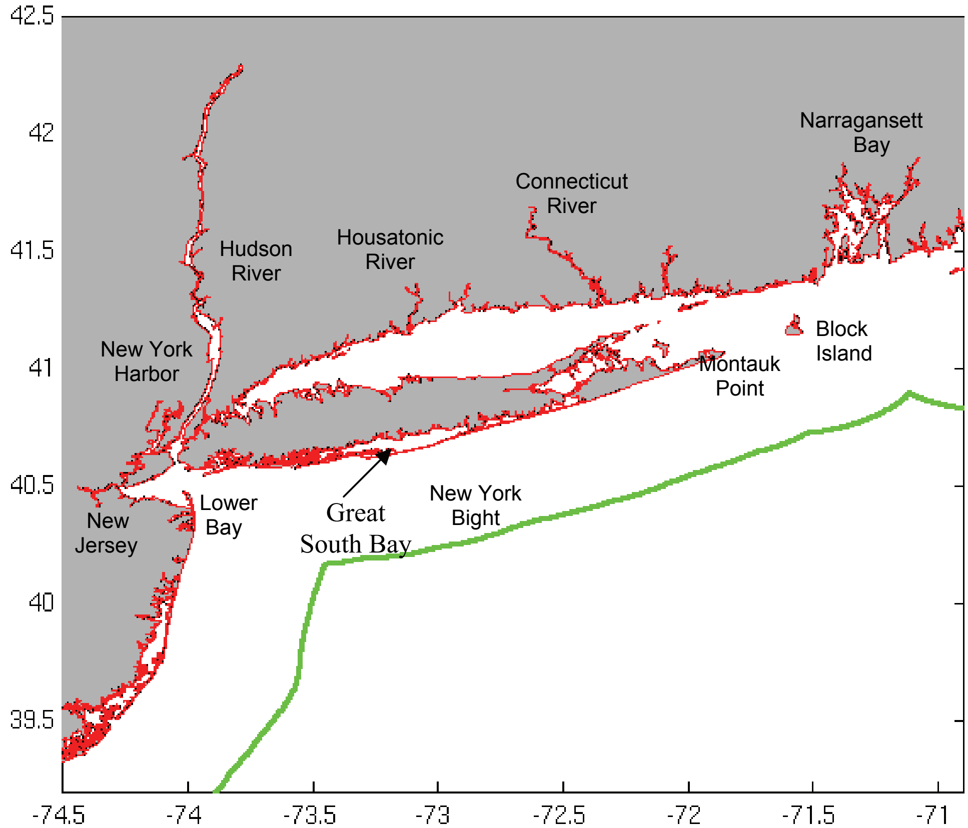

Figure 1. Map of the Long Island Sound, New York Bight, and Narragansett Bay area. Red lines illustrate the MHW shoreline. The green line denotes a distance 25-nautical miles offshore.

2. COASTLINE, BATHYMETRIC, AND WATER LEVEL DATA

VDatum requires an accurate representation of spatially varying tidal datum fields (Milbert and Hess, 2001). To achieve this, VDatum applications are developed using a combination of observational data, hydrodynamic models, and spatial interpolation techniques (Myers, 2005; Spargo and Woolard, 2005) For this VDatum application for Great South Bay, a tide model was first set up to compute spatially varying tidal datums. The modeled tidal datums were next compared with those derived from CO-OPS observational data. Finally, spatial interpolation techniques were used to create a correction field to be applied to the model results to derive a corrected field of tidal datums that are consistent with the observations.

For the tidal simulations, coastline data are required for delineating land-water boundaries so as to define hydrodynamic model domains. In addition, bathymetric data are needed to provide the model grid bathymetry. Numerical model results may not exactly match CO-OPS observations, and therefore observational data are needed to verify and correct the model results.

2.1. Digital Coastline

For VDatum, the mean high water shoreline is used as the coastline to delineate the land-water boundaries (Parker, 2002). The shoreline data used in the present study were mainly based on the Extracted Vector Shoreline (EVS) dataset available from the NOS Office of Coast Survey (OCS). However, compared to NOAA nautical chart MHW shorelines, this dataset had errors in certain nearshore marshland areas. The erroneous MHW depictions were corrected using computer-aided techniques, so they match the MHW coastlines illustrated on raster nautical charts. This was implemented via a commercial software package called Surface-Water Modeling System (SMS). Using SMS, geo-referenced raster nautical charts and the EVS data were overlaid and contrasted visually. Wherever the two did not match, the EVS was judged to be incorrect and replaced by the corresponding chart coastline. In Figure 1, the red line illustrates the final corrected coastline.

2.2. Bathymetric Data

Bathymetric data used in this study were from two sources: NOS soundings and the NOAA Electronic Navigational Charts (ENCs) bathymetry. The former were from the NOS/OCS hydrographic database maintained at the National Geophysical Data Center (NGDC) and the latter were based on the NOAA ENCs. The NOS sounding data include surveys conducted between 1930 and 2000. The datums were referenced to either MLW or MLLW, depending on the years of data collection. Figure 2 shows the survey years and locations. Figure 3 illustrates the spatial distribution of the ENC data. The ENC data were treated as referenced to MLLW. The horizontal and vertical accuracy standards for NOAA surveys are listed in Table A.1 of Appendix A .

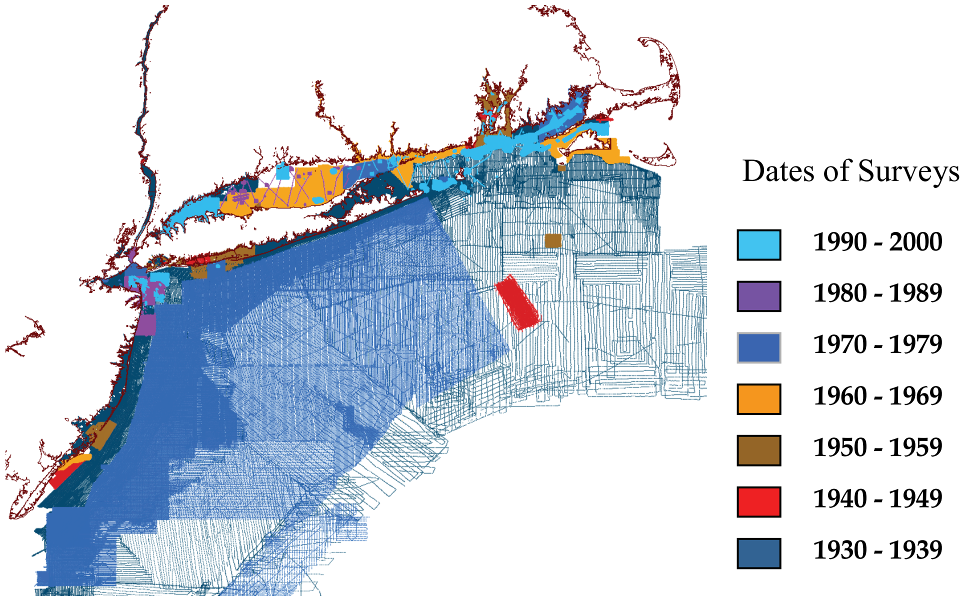

Figure 2. Dates and locations of NOS sounding surveys.

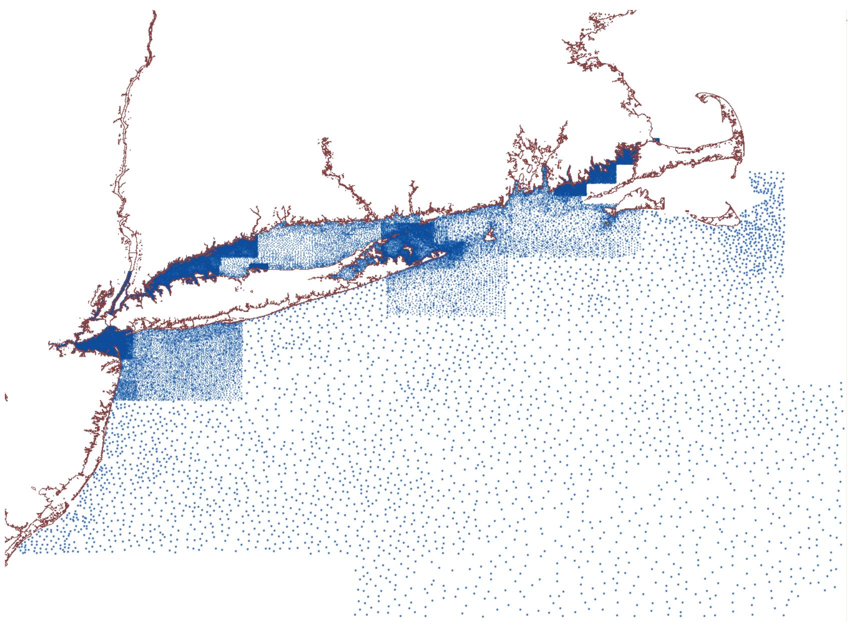

Figure 3. Spatial distribution of the ENC bathymetric data.

The NOS soundings possess a higher spatial distribution density than the ENC data. In some areas, the two are commonly available. However, neither of them provides complete coverage for the whole study area. Hence, they were blended for a better regional coverage. It is noted that even the merged data set left certain nearshore areas uncovered. NOAA nautical chart bathymetry was then manually digitized to compensate for the missing coverage. Since both the ENC and manually digitized bathymetries were grounded in nautical chart data, they were merged to form one data set and hereafter referred to as the ENC bathymetry without differentiation.

2.3. Tidal Datum Data

Tidal datum elevations from CO-OPS water level stations were used for verifying model results. These observational data are available online (Hess et al., 2005) from the official CO-OPS webpages (tidesandcurrents.noaa.gov). Many stations are located within embayments or near obstructions not mapped by the present model grid (Section 3.2), or at upper-reaches of riverine areas where datums exhibit strong seasonal variability. These observations were determined to be unsuitable for validating model results and were therefore discarded.

In addition, observational data may correspond to the National Tidal Datum Epochs (NTDE) of either (1983-2001) or (1960-1978). Datasets without explicit NTDE information were discarded. In cases where datums for both the 1983-2001 and 1960-1978 NTDE's are available, those with the recent epoch (1983-2001) are used. This resulted in 145 stations actually used for model validations. Tables B.1 and B.2 in Appendix B list the station and tidal datum information.

It is noted that the present study focuses on developing VDatum solely for Great South Bay, which represents a small portion of the whole LIS-NYB domain. There are only 7 stations located within GSB. However, model-data comparisons were conducted for the entire 145 stations so as to provide a general assessment of the model skill.

3. TIDAL DATUM SIMULATION

3.1. Hydrodynamic Model

The ADvanced CIRCulation (ADCIRC) model (Westerink and Luettich, 1993) was used to simulate water level time histories and derive tidal harmonic constant fields. The ADCIRC model is an unstructured grid hydrodynamic circulation model. It solves the shallow water equations and has been used for modeling tides in various ocean, coastal and estuarine environments (Luettich et al., 1999; Mukai et al., 2002; Myers and Hess, 2006). The ADCIRC model provides a variety of options for users to specify input parameters and execution modes. For instance, the model may be run in either 2- or 3-dimensonal modes, serial or parallel execution, linear or quadratic bottom friction formulations with constant or variable friction coefficients, etc. More details on the model setup such as model grid generation, bathymetry definitions, and parameter specifications are addressed in following sections.

3.2. Model Grid

The present model domain covers coastal waters from east of Narragansett Bay, down south to the New Jersey coast and cuts off at open ocean areas roughly along the 90-m isobath, encompassing LIS, NB, and NYB (Figure 1). A high-resolution, unstructured grid of 218,203 nodes and 395,562 triangular elements was created to map the domain up to the MHW shoreline (Figure 4). The spacing between grid nodes ranges from around 25 m to 5.5 km. In general, finer elements were created for nearshore areas compared to those in deep waters, so as to accurately resolve fine coastline features and the bathymetric-dependent variability of tidal wavelengths.

Developing VDatum for Great South Bay is the focus of the present study. Figures 5a-c show close-up views of three sections (from west to east) of the Great South Bay grid. Note that the entire model domain extends to offshore areas far beyond Great South Bay. This is for the purpose of ensuring model computational stability and pursuing accurate tidal simulations. In areas far away from shoreline, tidal currents are relatively weak and tidal fields exhibit rather gradual variability. The former helps maintain model computational stability, while the latter helps choose accurate tidal harmonic constants used as model open boundary forcings terms.

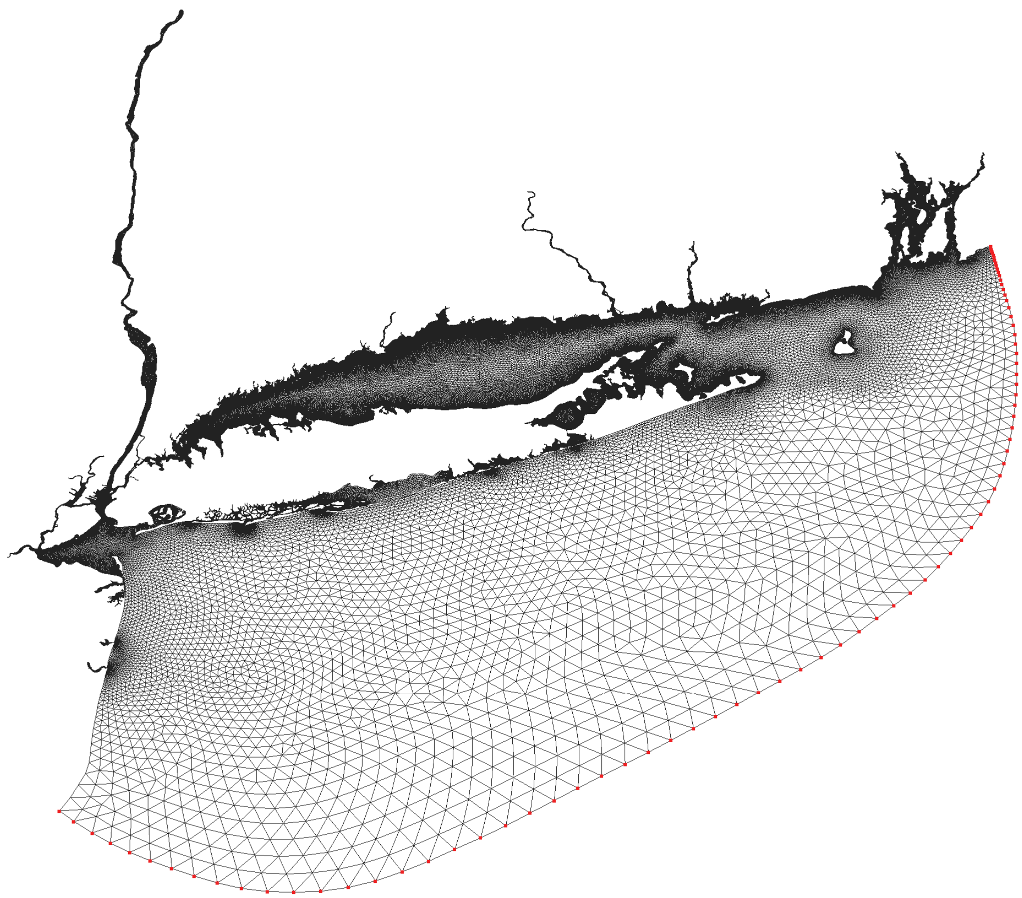

Figure 4. Finite element grid for the entire model domain. Red dots denote the model open ocean boundary nodes.

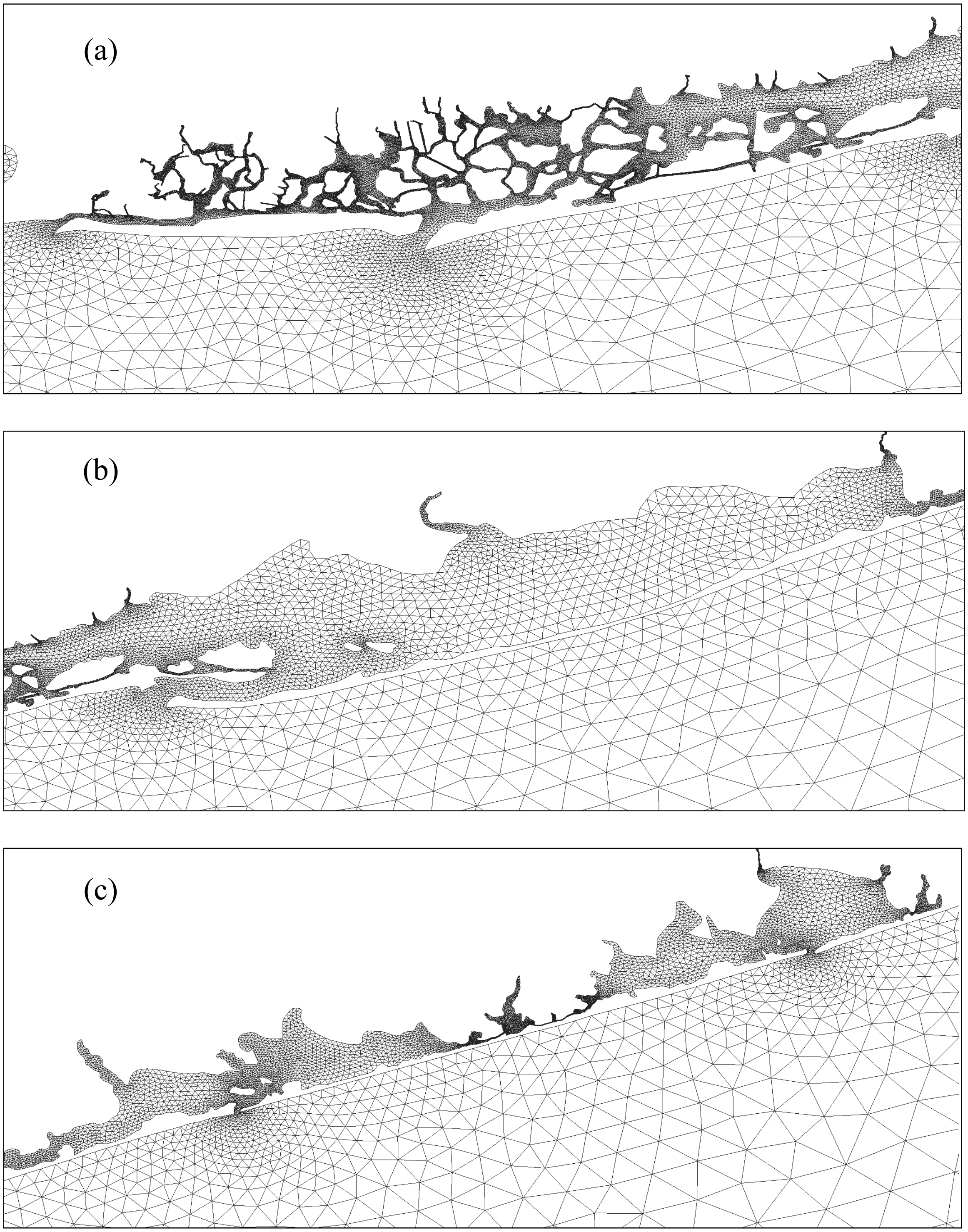

Figure 5. Close-up views of the model grid across Great South Bay (Figure 4). Plots (a), (b) and (c) displays three subareas from west to east.

3.3. Bathymetry of Model Grid

The bathymetry datasets described in Section 2.2 were used to specify the model grid bathymetry. Note that NOS soundings and ENC data were of different spatial resolution and coverage. As for the soundings alone, bathymetry may be referenced to either MLW or MLLW. Hence, they were categorized into two groups and applied to the grid separately. In short, the bathymetry data were classified into three groups: (1) MLLW NOS soundings (2) MLW NOS soundings, and (3) MLLW ENC data. The three groups were interpolated onto the model grid separately, resulting in three meshes corresponding to the three bathymetric datasets.

The algorithm used for interpolating bathymetry onto the three meshes was the same. Bathymetry at each model node represents an average of data points within the node's surrounding elements. Since element size changes throughout the model domain, the searching range for bathymetric data points varies from node to node. As the element size is smaller in coastal waters, bathymetry for nodes near the coastline were from more locally distributed data points compared to those in deep waters.

As none of the three data sets provided complete coverage of the model domain, each of the three meshes left numerous unpopulated nodes. Hence, the three meshes were combined to obtain a more complete coverage. At nodes where bathymetric data were available in more than one mesh, an arithmetic average was taken; otherwise, the value from the solely available mesh was taken. After merging the three meshes, there still remained some nodes without valid bathymetry. These nodes were populated by averaging bathymetry from adjacent nodes.

It is worthwhile to note that the bathymetry of the three meshes had two different reference datums: MLW and MLLW. Setup of the tidal model requires the grid bathymetry to be referenced to the model zero (MZ) reference, a geopotential surface. It is therefore necessary to adjust the reference datum from MLLW/MLW to MZ prior to any data blending. However, the *(MZ – MLLW/MLW)* values are unknown prior to the model runs. The adjustment was accomplished by iteratively updating the $\Delta_{MLLW} = (MZ\text{-}MLLW)$ and $\Delta_{MLW} = (MZ\text{-}MLW)$ fields based on model results from a series of simulations: initial constant values of $\Delta_{MLLW} = 0.5\ m$ and $\Delta_{MLW} = 0.4\ m$ were assumed for the whole grid. Following each model run, new sets of tidal datum fields were derived and used to update the Δ_{MLLW} and Δ_{MLW} fields. Multiple runs were conducted until invariant Δ_{MLLW} and Δ_{MLW} values were achieved. Multiple iterations were made to meet a convergence criteria of both $|\Delta_{MLLW}|$ and $|\Delta_{MLW}|$ less than 5×10^{-3} m. Figure 6 shows the bathymetry used in the final model run.

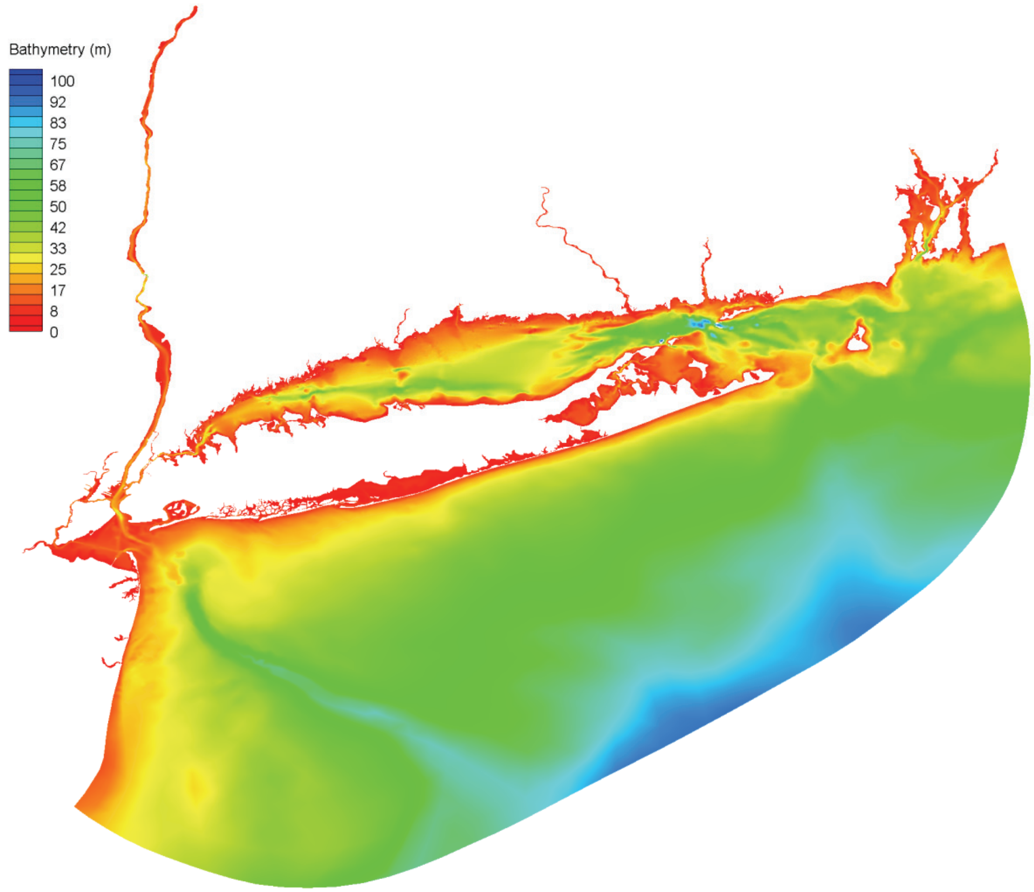

Figure 6. Model grid bathymetry relative to MZ. Color bar is meters.

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3.4. Model Parameters Setup

In the present study, model parameters were set up to solve the shallow water equations in Two-Dimensional Depth-Integrated (2DDI) mode with finite amplitude and convection terms. Lateral viscosity was set as a constant, 6.0 m s^{-2}, throughout the model domain. A quadratic friction scheme with a spatially-varying coefficient (C_f) was specified to calculate bottom friction. Multiple runs were conducted to test various C_f values in an attempt to mitigate model-data discrepancies in reproducing tidal datums. Figure 7 shows the C_f applied for the final tidal simulations.

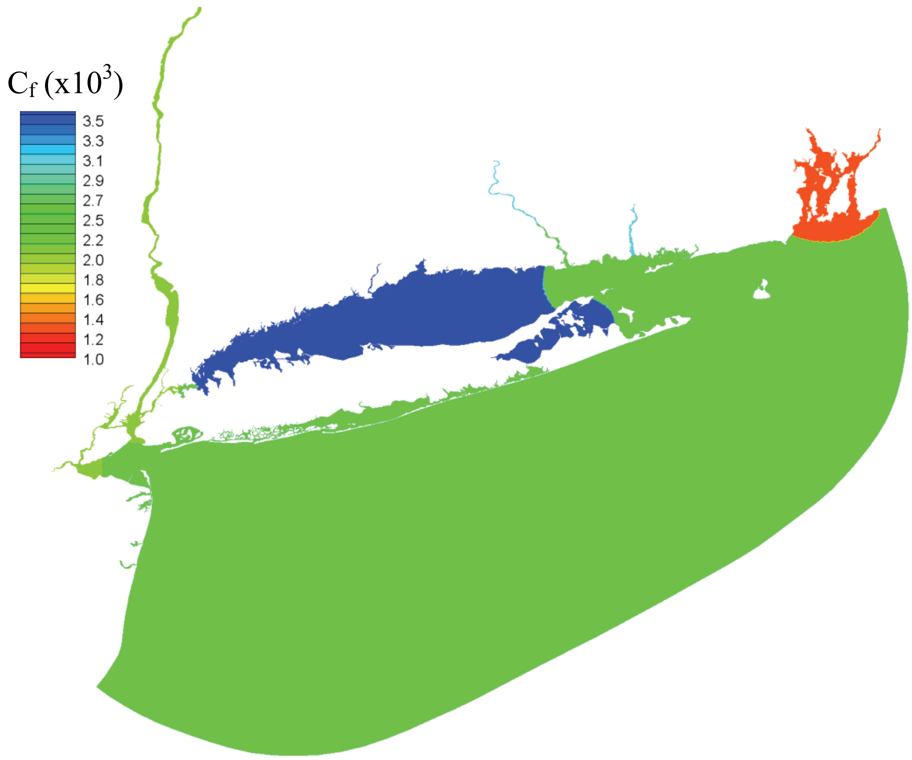

Figure 7. Spatially variable bottom friction coefficients used for model simulations.

The nine most significant astronomical tidal constituents (M_2, S_2, N_2, K_2, K_1, P_1, O_1, Q_1, and M_4) in the area were chosen to drive the model on its open boundary. Corresponding harmonic constants were interpolated based on a tidal database derived from the Western North Atlantic Ocean tidal model (WNATM) (Myers, unpublished manuscript). A time step of 1.0s was used to ensure computational stability. The simulation covered a period of over 60 days. First, the model was ramped up for 10 days with a hyperbolic tangent function. It was then run for another 10 days to allow for the tidal field to reach an equilibrium state. Afterwards, water level time series were recorded at a 30-minute interval for 40 days to allow for harmonic analysis of the 37 constituents.

The parallel version of ADCIRC model was adopted and the model run was conducted on 128-processors of the JET computer at NOAA's Earth System Research Laboratory. It took approximately thirteen hours to complete the 60-day simulation.

3.5. Tidal Datum Computation and Results

Model derived harmonic constants were used to reconstruct long period water level time series and further derive tidal datums. Water level time series were compiled at a six-minute interval for the whole 1980-2001 National Tidal Datum Epoch at each grid node, using the following equation,

$$\varsigma(t)=\sum_{i=1}^{37} f_i A_i \cos(\sigma_i t+[V_o+u]_i-\kappa_i),$$

where ζ represent the instantaneous water level relative to MSL, t is the time, i denotes one of the 37 constituents, f_i is the nodal factor, A_i is the constituent amplitude, σ_i is the constituent speed, $[V_o+u]_i$ represents the equilibrium argument at time zero, and κ_i is the Greenwich epoch. In the computation, f_i and κ_i were updated every six minutes.

The 19-year long time series were analyzed to derive tidal datum fields for MSL, MHHW, MHW, MLW, and MLLW. The latter four were then adjusted to be referenced to the MSL field. It is noted that since the reconstructed time series covers a complete 19-year epoch, the derived MSL field actually equals a constant zero.

Note that the MTL and DTL were defined as the algebraic averages between MHW and MLW and between MHHW and MLLW, respectively. The two fields were not computed until error-corrected MHHW, MHW, MLW, and MLLW fields were obtained (Section 4.2).

Figures 8a-d display the model derived tidal datum fields for MHHW, MHW, MLW, and MLLW, respectively relative to MSL. As expected, the four fields exhibit a similar spatial pattern. They demonstrate good agreement with previously published results in both spatial variability patterns and magnitudes (Swanson, 1976). In LIS, tidal range is enhanced by approximately fourfold from about 0.7 m near Block Island to 2.2 m at the western end of LIS. In NB, tidal range shows much smaller magnitude and demonstrates less severe spatial variability compared to that in LIS. Across the Bay, tidal range lies between 1.2-1.4 m, except near its upper reaches where the range could be as high as 1.6 m. In New York Harbor, tidal range remains quite homogeneous, around 1.2 m. The NYB is located in relatively open and deep waters. The average tidal range in the central Bight is about 1.1 m.

Figures 9a-d show close-up views of the GSB tidal datum fields (MHHW, MHW, MLW, and MLLW). All four fields demonstrate a three-mode spatial variability: their magnitudes are largest in the western bay; minimums appear in the central bay; and medium values show up in the eastern bay. In the western bay, tidal range reaches a maximum of about 1.5 m; it drops to around 0.5 m in the central bay; farther to the east, tidal range is enhanced to an approximate 0.9 m.

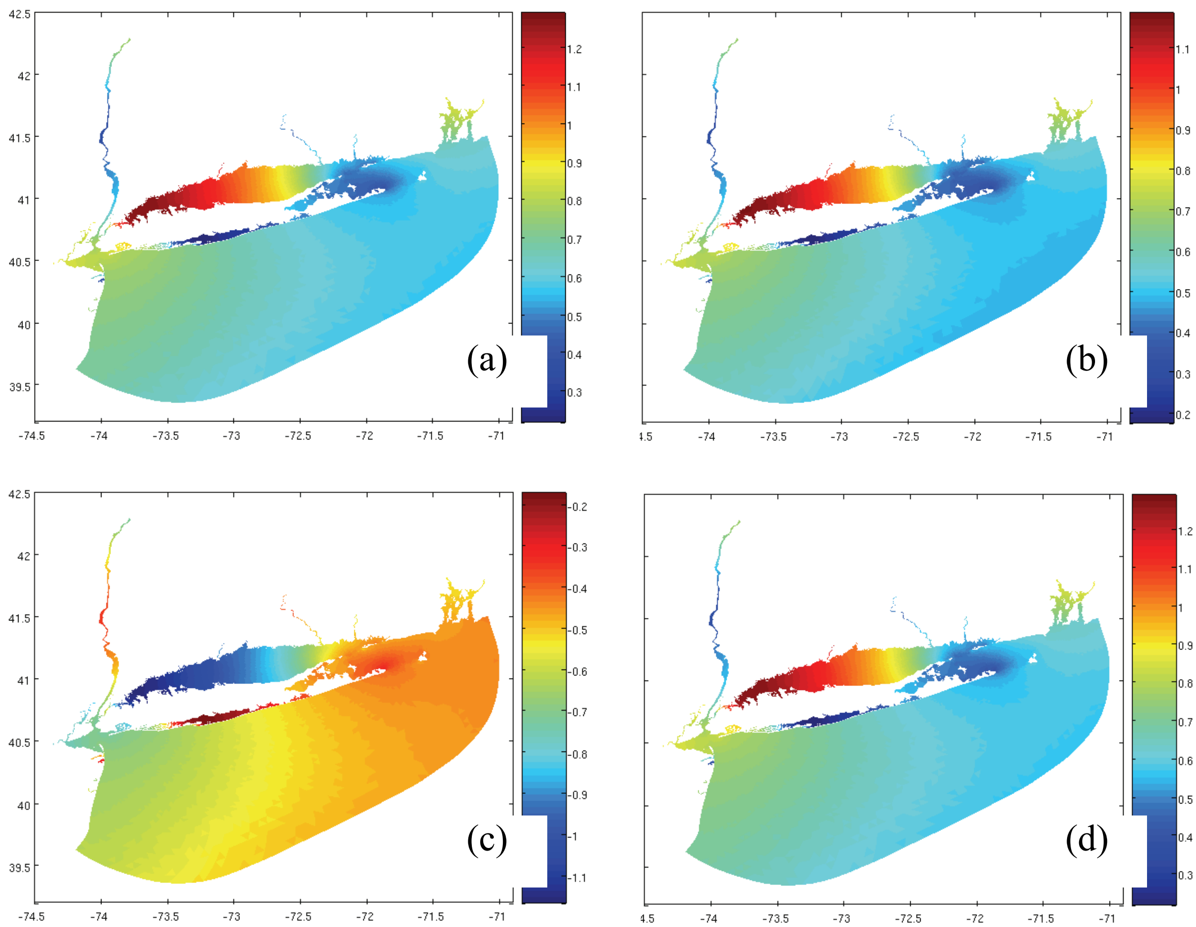

Figure 8. Model-derived tidal datum fields, (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW relative to MSL over the whole model domain. Color bars are in meters.

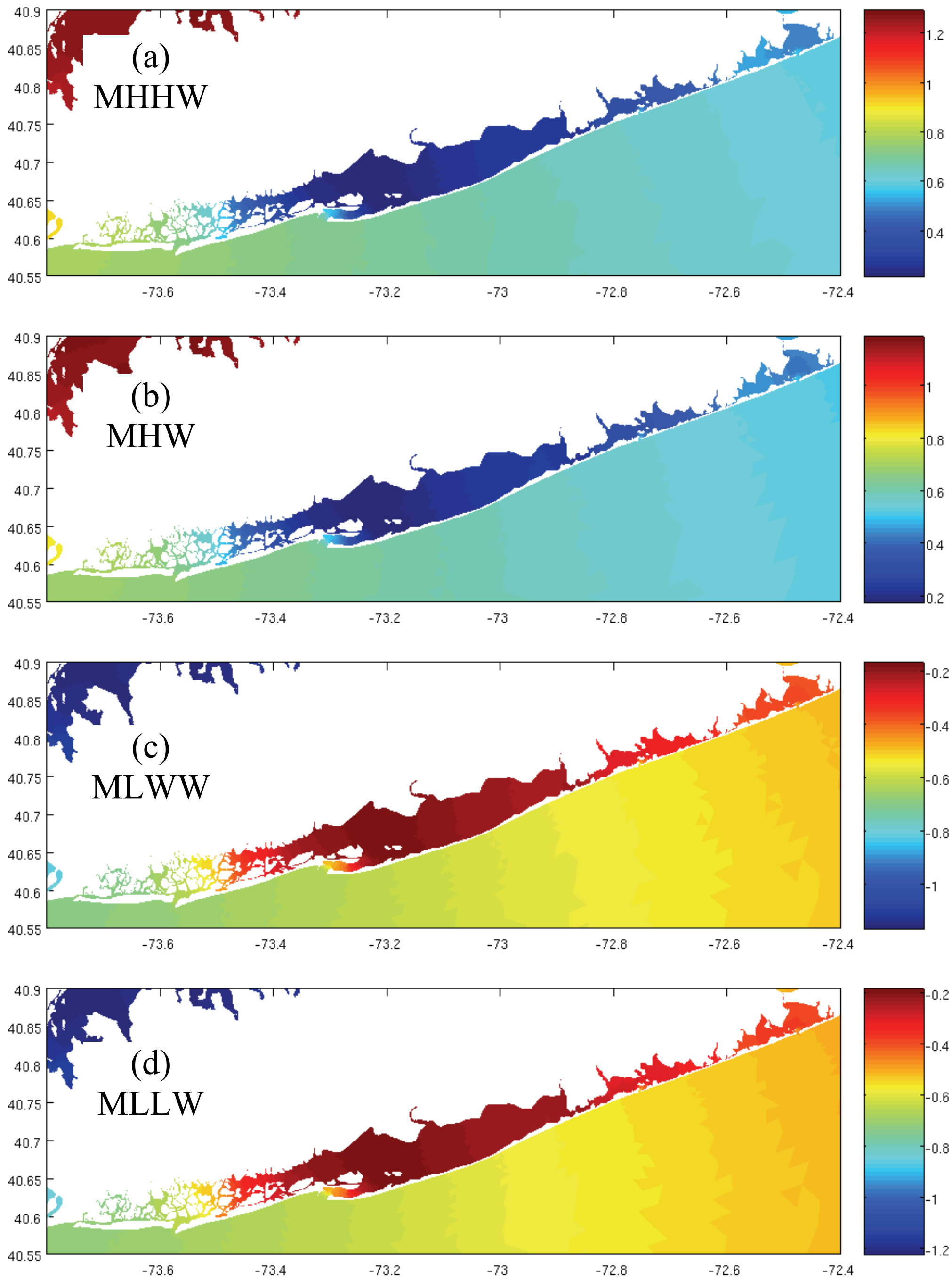

Figure 9. Model-derived tidal datum fields, (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW relative to MSL over the Great South Bay area. Color bars are in meters.

3.6. Verifications and Error Corrections

3.6.1. Comparisons with Observations

To verify model results, modeled tidal datums were compared with those from the 133 CO-OPS water level gauges in the region (Appendix B). Figures 10a-d display model-data contrasts for MHHW, MHW, MLW, and MLLW, respectively. Yellow circles in the figure represent the GSB stations and red ones correspond to the rest. In general, there exhibits good model-data agreement. Over the 145 stations, magnitudes of the model-data differences are averaged to be 4.0 cm, 3.8 cm, 4.0 cm, and 5.4 cm for MHHW, MHW, MLW, and MLLW, respectively. The model-data correlation coefficients are between 0.98-0.99 for all four tidal datums.

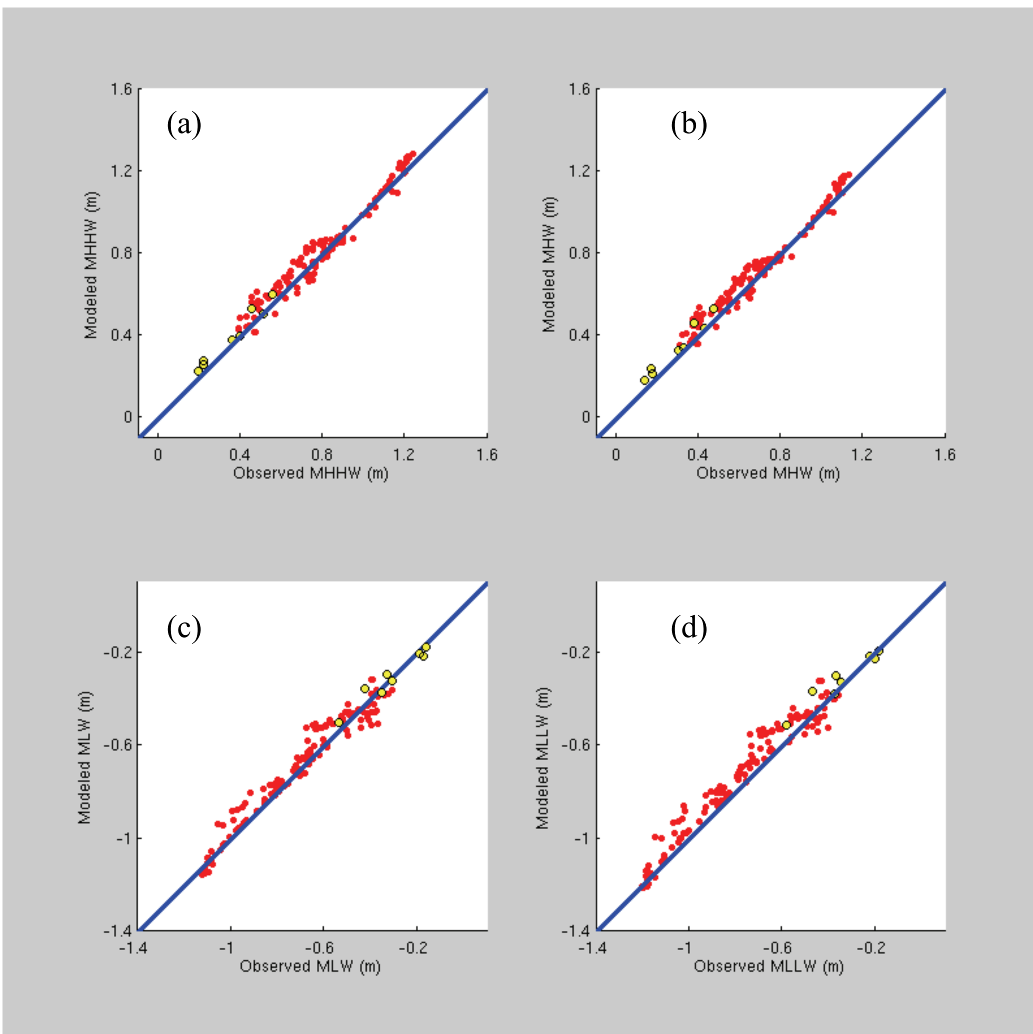

Figure 10. Comparisons of the modeled (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW datums against observations. Yellow circles represent the GSB stations and red ones correspond to the rest of the stations in the area.

For each individual station, averaged magnitudes (|Avg|) of model-data differences over the four datums are examined. Figures 11a and 11b illustrate |Avg|'s scaled in color-coded symbols. Of the seven stations within GSB, |Avg| ranges from 1.5 to 4.7 cm.

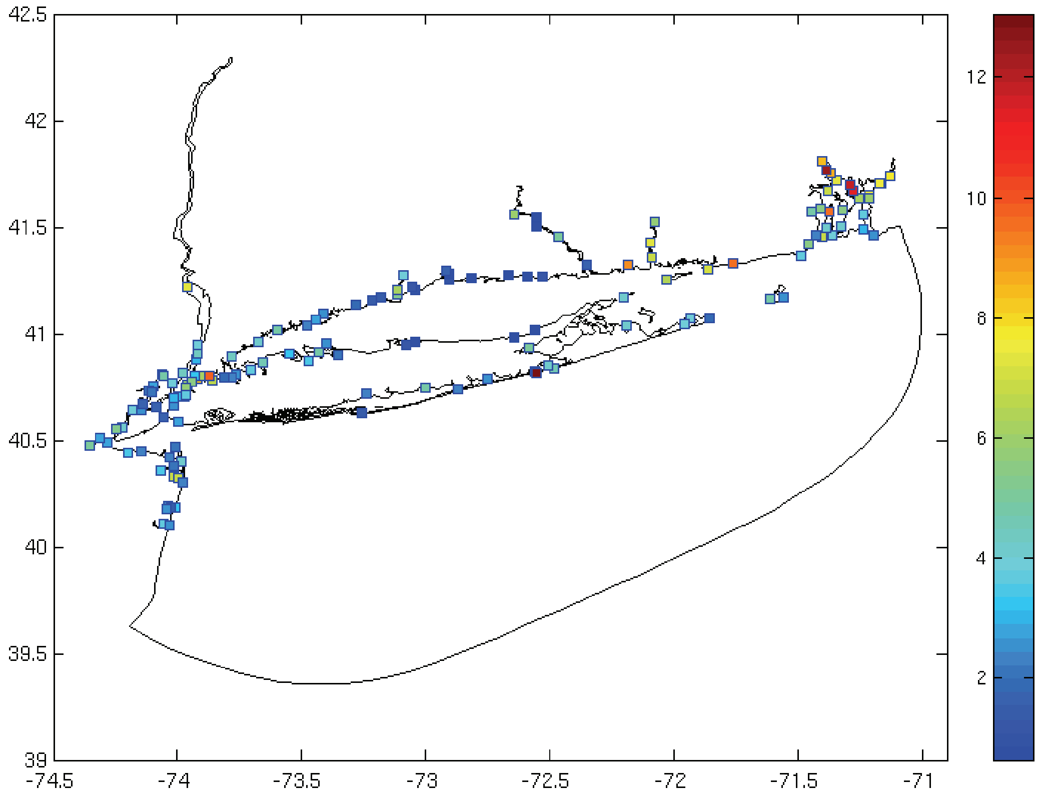

Figure 11. Color-coded averaged model-data errors (|Avg|). Color bar is in cm.

3.6.2. Match with Tidal Datums in Adjacent Areas

The present model domain (hereafter referred to as the GSB domain) overlaps with the previously developed Chesapeake and Delaware Bays (CB-DB) VDatum areas (Yang et. al, 2008(1)). The two domains intersect at areas surrounding entrances to the five inlets connecting Great South Bay and New York Bight (Figure 12).

In reality, tidal datums fields should be matched seamlessly across domain boundaries. However, this is not necessarily engendered when the two tidal datum fields datasets were developed separately with slightly differing model setups. For instance, different sets of boundary conditions for tidal harmonic constants were used by the present GSB model and those used for the CB-DB model: the former was from a direct interpolation of the WNATM tidal database (Section 3.4), while the latter corresponds to an adjusted WNATM results. Therefore, it is worthwhile to examine discrepancies and work out ways to reach seamless matches if needed.

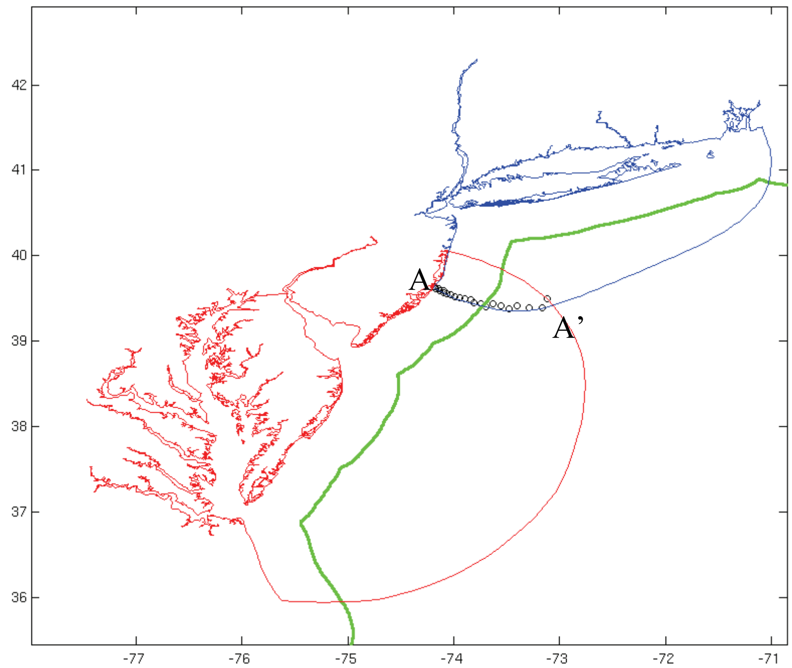

Figure 12. Model domains of the Chesapeake and Delaware Bays (red line) and the present GSB-LIS-NYB (blue lines). Black circles along transect AA’ illustrate the locations on which the agreement between tidal datums from the two models were examined.

Red dots in Figure 12 represent selected boundary control stations for comparing tidal datums from the two domains. They correspond to nodes on the GSB model grid. Four datums (MHHW, MHW, MLW, and MLLW) of CB-DB domain are separately interpolated onto the control stations. Table 1 tabulates statistics of tidal datum differences across transect AA’.

Table 1. Statistics of tidal datum differences (Δ) across the CB-DB and GSB-LIS-NY domain boundaries.

	MHHW (cm)	*MHW (cm)*	*MLW (cm)*	*MLLW (cm)*
mean(|Δ|)	0.6	1.9	1.5	1.7
Standard deviation (Δ)	0.5	0.4	0.2	0.2

Three of the four datums demonstrate maximum differences of about 2 cm. The standard deviation of the differences ranges from 0.2 to 0.5 cm. It was therefore necessary to make adjustments to the present model results so as to reach a seamless match with the previously developed CB-DB results. This was accomplished by using TCARI, the details of which are described in the next section.

3.6.3. Corrections

Tidal datum corrections were developed to eliminate model-data differences at observational stations (Section 3.6.1) as well as to minimize datum discrepancies across boundaries of different VDatum domains (Section 3.6.2). This was achieved using the TCARI (Tidal Constituent And Residual Interpolation) spatial interpolation tool (Hess, 2002, 2003). TCARI was used to spatially interpolate the error fields at a number of individual control stations onto the whole domain by solving Laplace's equation. TCARI has been developed for use by both structured and unstructured model grids, and a version of the latter was employed in this study.

To run TCARI, both the observational stations and the domain boundary stations were treated equally as control stations. For each tidal datum, both model-data differences (at 145 tidal stations) and across-boundary discrepancies were computed and merged into one dataset for input to TCARI.

After applying TCARI, error fields for MHHW, MHW, MLW, and MLLW were derived, which matched the tidal datum differences at the 145 control stations. The initial model results (Section 3.5) were then corrected by subtracting the error fields over the entire model grid. Figures 14a-d display the four corrected datum fields.

Note that the other two tidal datum fields, MTL and DTL, were produced in a different way. They were derived from the four corrected datum fields by taking the averages between MHW and MLW and between MHHW and MLLW, respectively. Figures 13a-e display the final corrected tidal datum fields relative to MSL.

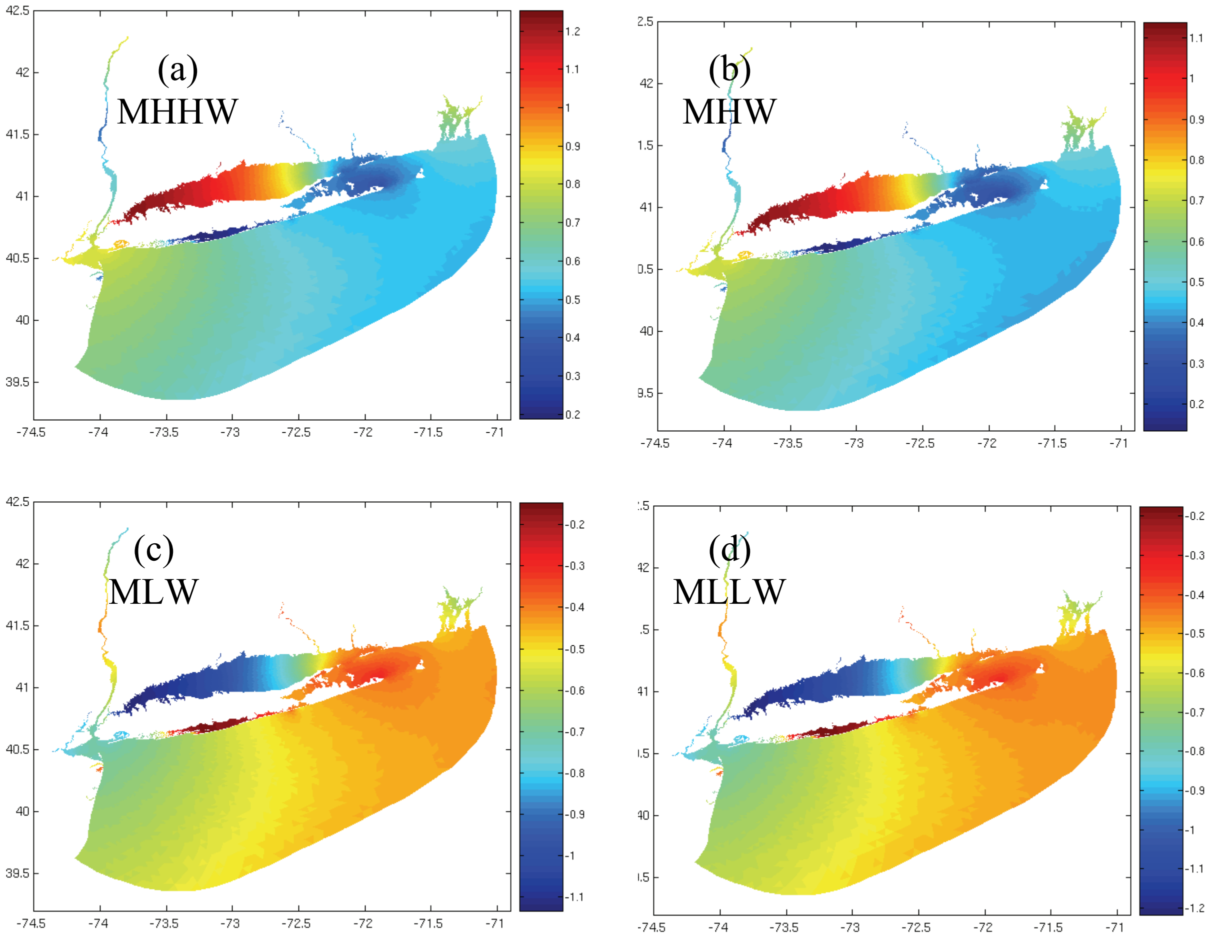

Figure 13. Error-corrected tidal datum fields relative to MSL over the whole model domain, (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW. Color bars are in meters.

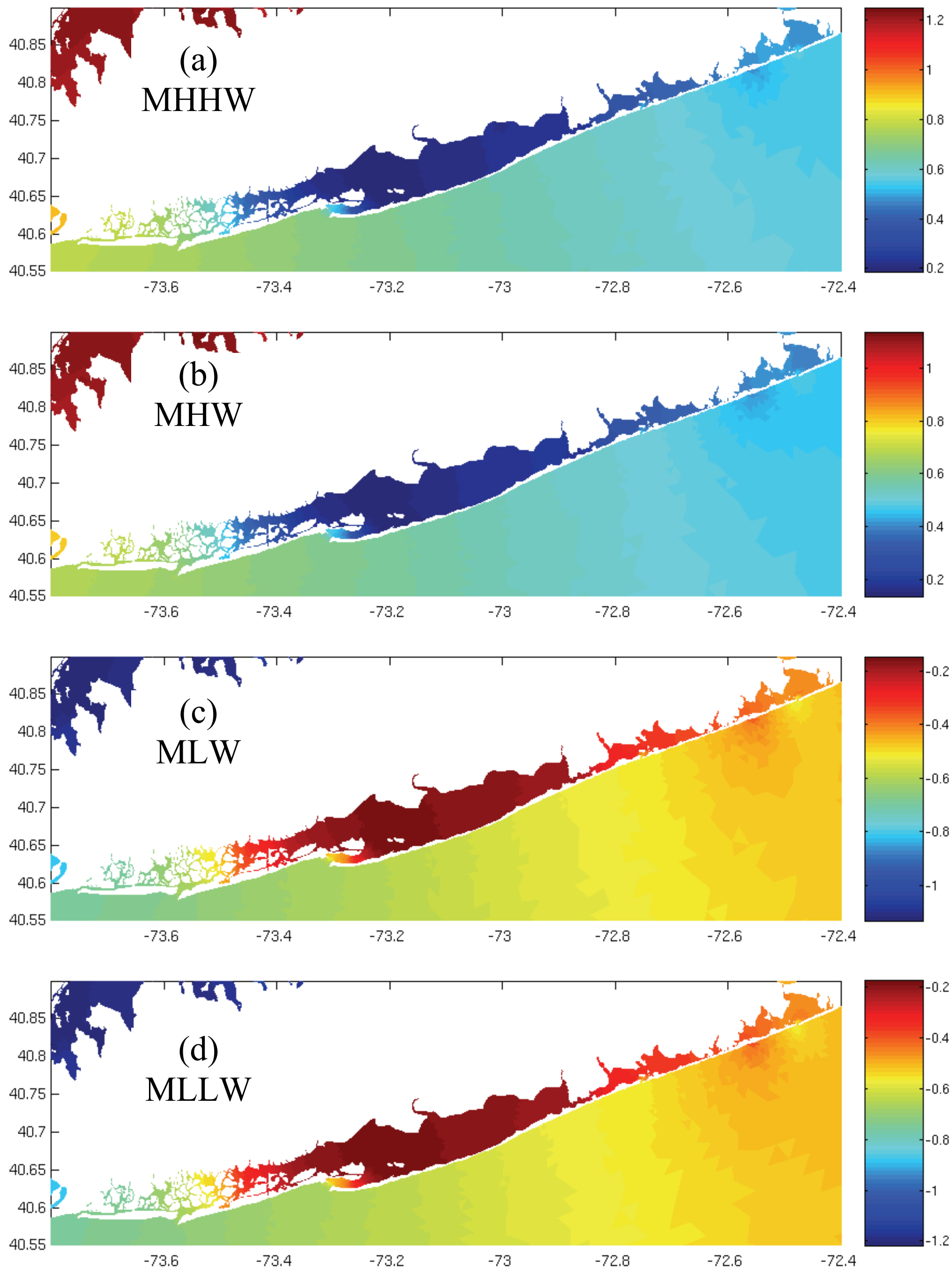

Figure 14. Close-up view of error-corrected tidal datum fields relative to MSL over the Great South Bay area, (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW. Color bars are in meters.

4. CREATION AND POPULATION OF THE MARINE GRID

4.1. Creation of VDatum Marine Grid

Tidal datums in the VDatum software are defined on a regularly structured grid, referred to as the marine grid (Hess and White, 2004). Hence, it is necessary to convert the tidal datum fields from the unstructured grid onto the equally-spaced, raster VDatum marine grid.

Nodes in the marine grid were specified as either water points or land points. The water nodes are to be populated with valid tidal datum values, and the land nodes are assigned with null values. To create and populate the marine grid, a high-resolution coastline and a bounding polygon (Figure 15) were used. The bounding polygon was setup to guide the delineation of water/land nodes. Only nodes within the bounding polygons or within one half of a cell size outside the coastline were delineated as water nodes; those outside of the bounding polygons or those more than one half of a cell size away from the coastline were marked as land nodes.

Marine grid points are equally spaced. For a point at the *i*-th row and *j*-th column relative to the point *(longitude$_0$, latitude$_0$)* at the region's southwest corner, its location *(longitude_i, latitude_j)* is defined as,

$$\text{Longitude\_i} = \text{longitude}_0 + (\text{i}-1)\times\text{del\_lon},\ \ \text{i}=1, \dots, \text{N\_lon},$$
$$\text{Latitude\_j} = \text{latitude}_0 + (\text{j}-1)\times\text{del\_lat},\ \text{j}=1, \dots, \text{N\_lat},$$

where *del_lon*, and *del_lat* denote separation between neighboring points along the meridional and zonal directions, respectively; *N_lon* and *N_lat* represent, respectively, the longitude and latitude dimensions of the raster data set. It is noted that the *del_lon* and *del_lat* are prescribed parameters representing the expected grid resolutions, while *N_lon* and *N_lat* are derived parameters according to

$$\text{N\_lon} = 1 + (\text{longitude}_1 - \text{longitude}_0)/\text{del\_lon}$$
$$\text{N\_lat} = 1 + (\text{latitude}_1 - \text{latitude}_0)/\text{del\_lat}$$

where *(longitude$_1$, latitude$_1$)* are the coordinate at the raster region's northeast corner. Table 2 lists parameters defining the five marine grids.

Table 2. Marine grid parameters

	Region	*Longitude$_0$ (degree)*	*Latitude$_0$ (degree)*	*del_lon (degree)*	*del_lat (degree)*	*N_lon*	*N_lat*
RA	NYH	-74.4	39.3	0.0017	0.0017	1589	530
RB	LIS & NYB	-74.0	39.3	0.0017	0.0017	1589	1825
RC	GSB	-73.89	40.49	0.0005	0.0002	3001	2101

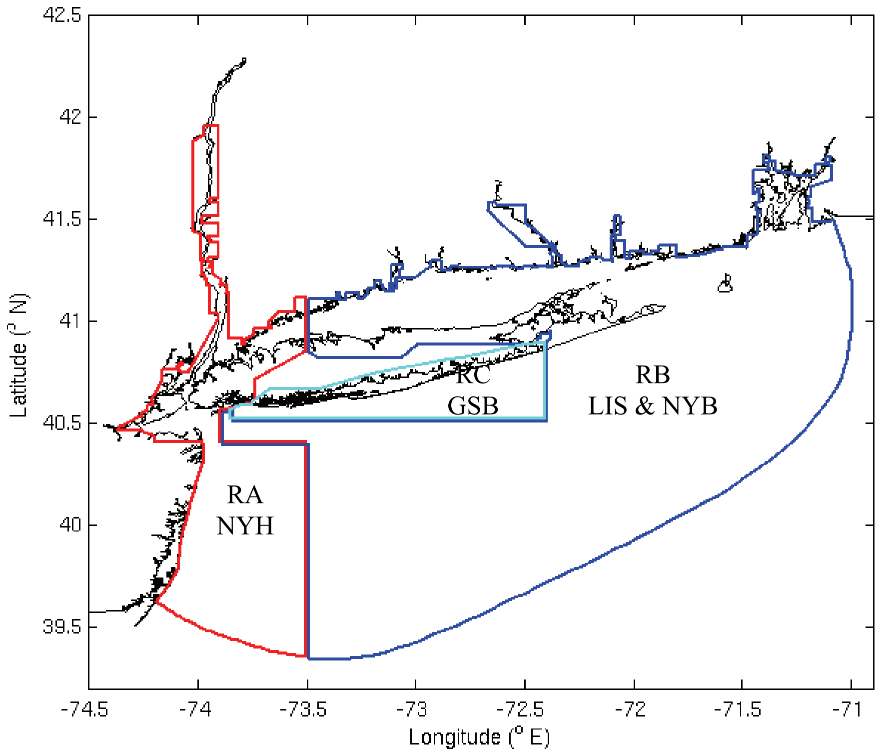

Figure 15. Definitions of three marine grid bounding polygons: New York Harbor (NYH) (red), Long Island Sound (LIS) and New York Bight (NYB) (blue), and Great South Bay (GSB) (cyan).

4.2. Population of VDatum Grid with Tidal Datums

Tidal datums on the VDatum marine grid were populated by interpolating the TCARI-corrected tidal datums (Section 3.6) following the algorithm of Hess and White (2004). Datums at each grid point were computed by averaging or linearly interpolating those within a user-specified searching radius or the closest user-specified number of points. Marine points were populated differently depending on whether a point was inside/outside of ADCIRC model grid elements. If it was inside an element, datums were calculated using an interpolation of the three nodes of the element; otherwise, datums were computed using the inverse distance weighting of the closest two node values. Figures 15a-e display the populated tidal datums (MHHW, MHW, MLW, MLLW, MTL, DTL).

Tidal datum fields were further verified by comparing with either observational data (Sector 3.6.1) or with values along the LIS-NY boundary (Sector 3.6.2). The former gives an average model-data error over four datums (MHHW, MHW, MLW, and MLLW) of around 0.1 cm and a rms error of about 0.3 cm.

Datum fields across the GSB and LIS-NYB boundary also demonstrate good consistency. For each of MHHW, MHW, MLW, and MLLW, the averaged difference and the standard deviations of the differences are both less than 0.1 cm.

5. TOPOGRAPHY OF THE SEA SURFACE

The TSS is defined as the elevation of NAVD 88 relative to local MSL. It is created by combining observed datums at NGS bench marks and CO-OPS water level stations with the tidal model results. Figure 16 illustrates the station locations used in this application (see details of the station information in Table D.1 of Appendix D). To create the TSS over the VDatum domain, the TSS values at the observation stations were first derived. These values were then interpolated over the whole domain. Afterwards, a quality control procedure was followed and appropriate changes were made to meet certain criteria.

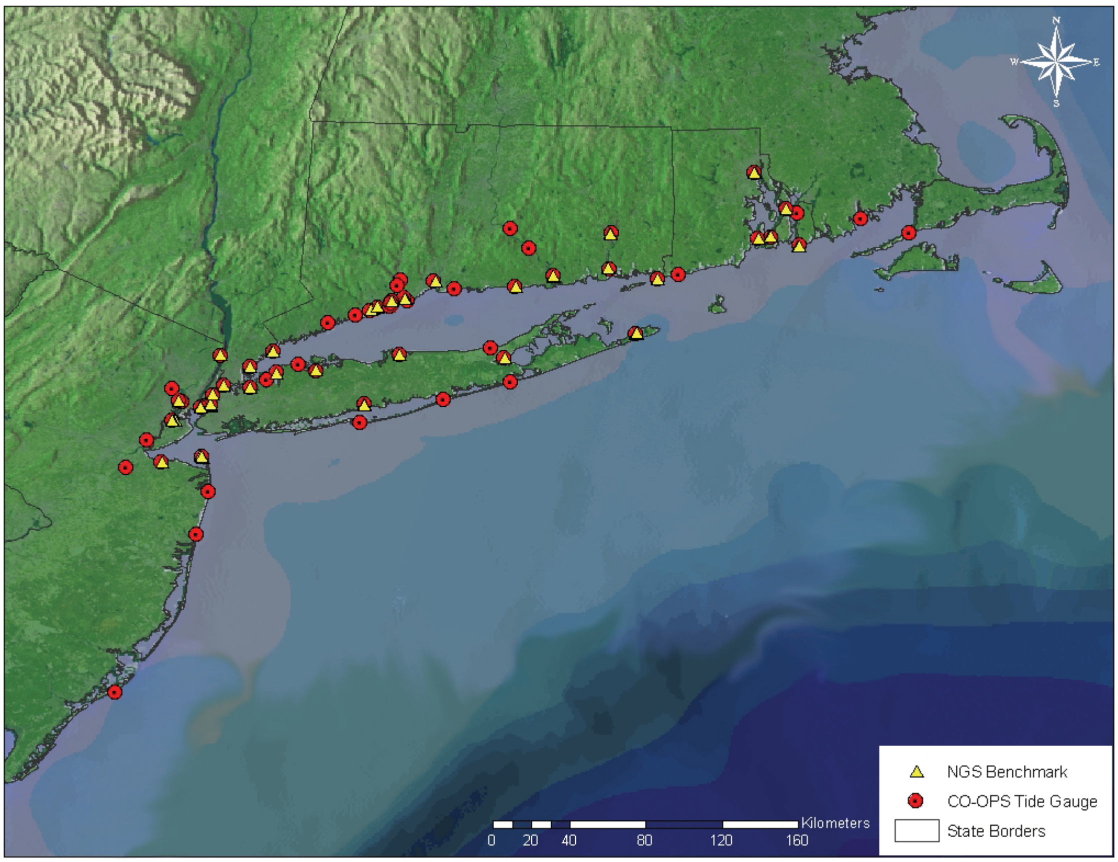

Figure 16. Location of tidal bench marks and tide stations used to compute the New Jersey to Rhode Island VDatum TSS grid.

5.1. Derivation of TSS

Two methodologies were used to compute the TSS at the observational stations: an indirect method using data from the NGS database (see Appendix D) and a direct method using data from the CO-OPS database (see Appendix E). To derive the TSS at the NGS stations, residuals (R_{datum}) at every NGS bench mark location were computed as:

$$R_{datum} = TBM_{navd88} - TBM_{datum} + VD_{datum}$$

where TBM_{navd88} and TBM_{datum} are the observed (NAVD88–MLLW) and (Datum-MLLW) differences, respectively, and VD_{datum} denotes modeled (Datum–MSL) differences. The residual, R_{datum}, represents an estimation of the (MSL-NAVD88) difference.

There are four sets of R_{datum}, corresponding to MHHW, MHW, MLW, and MLLW. Each represents an independent estimation of the quantity MSL–NAVD88 associated with a tidal datum. Tables E.1 list R_{datum}'s at stations located within the VDatum bounding polygons (Figure 15). At each station, the four R_{datum}'s were then averaged to produce a mean residual ($\overline{R}_{datum}$). $\overline{R}_{datum}$ represents an overall estimation of MSL–NAVD88 and is used for further development of the TSS grid.

The TSS values at CO-OPS stations were simply derived by calculating orthometric-to-tidal datum relationships. Table D.1 shows the station location inventories and observations of elevation information.

Next, the $\overline{R}_{datum}$ values were merged with TSS values from CO-OPS stations to form a data set for creating a TSS mesh using the gridding software, Surfer©. A grid covering the entire area of bench marks and water level stations with a spatial resolution similar to that of the VDatum marine grid was created. Breaklines were inserted to represent the influence of land. The Surfer© software's minimum curvature algorithm was employed to create a primary TSS field (TSS_{grid}) that honors the data as closely as possible. It is noted that the TSS_{grid} represents an estimation of the quantity MSL- NAVD88 and still requires further quality control and correction procedures (Section 5.2). Figure 17 shows the final TSS field covering the three VDatum regions (Table 2). In the figures, a positive value specifies that the NAVD 88 reference value is further from the center of the Earth than the local mean sea level surface.

It is noted that data derived from both the indirect and direct methodology are initially relative to NAVD88 realized through GEOID03. This data derived for both methods is transformed back through GEOID03 to an ellipsoidal reference

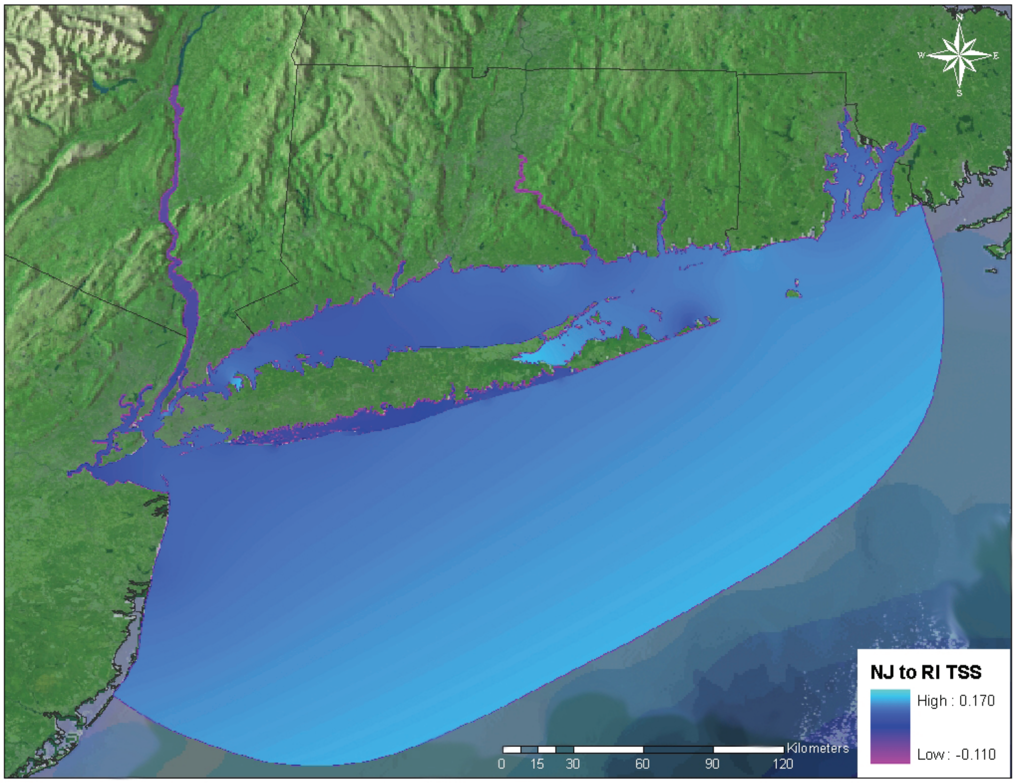

Figure 17. The New Jersey to Rhode Island TSS Grid.

5.2. Quality Control

Quality control is necessary for obtaining a final TSS field. This is facilitated through examining the differences ($\Delta_{R\text{-}TSS}$) between R_{datum} and TSS_{grid} observational stations:

$$\Delta_{R\text{-}TSS} = -(R_{datum} - TSS_{grid})$$

The $\Delta_{R\text{-}TSS}$ approximately represents the difference between the observed tidal datum and the datum as computed by the gridded fields. The mean $\Delta_{R\text{-}TSS}$ at each bench mark should be less than 0.01 m. If it is not, the input data and grids are checked, appropriate changes are made, and the values are recomputed until the criterion is met. This results in a final TSS field. Finally, a land mask is applied to denote the presence of land.

A final quality control was conducted by evaluating mean $\Delta_{R\text{-}TSS}$ over four tidal datums (MHHW, MHW, MLW, and MLLW) at each bench mark station. Note that $\Delta_{R\text{-}TSS}$ represents the difference between the observed and modeled tidal datums. Tables E.1 in Appendix E tabulates the TSS differences. Table E.2 shows the average mean $\Delta_{R\text{-}TSS}$ values and the corresponding standard deviations over the stations. Both values are less than 0.012 m, thus indicating good model-data agreement.

6. SUMMARY

VDatum tidal datum and TSS fields for Great South Bay of Long Island, NY were developed in this study. Creation of VDatum begins with creating tidal datums with numerical tidal simulations using ADCIRC model. A triangular finite-element grid consisting of 218,203 nodes and 395,562 cells was created. The model was forced with nine tidal constituents (M_2, S_2, N_2, K_2, K_1, P_1, O_1, Q_1, and M_4). Tidal harmonic constants for 37 major tidal constituents were derived from the simulations. They were then used to construct 6-minute time series for the Nation Tidal Datum Epoch of1983-2001. Various tidal datum fields, including mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and mean higher high water (MHHW), were computed based on the modeled water level time series.

A regular VDatum marine grid was created to be used as input to the VDatum software tool. Tidal datums defined on the unstructured grid were interpolated onto the regular grid to form the final datums as input to the VDatum tool. To compromise with the limitation of the TSS software in handling large-size arrays, the whole VDatum marine grid was divided into four sections. Tidal datum fields for each section were accordingly produced by extracting from those defined on the whole grid.

The TSS fields were created separately for each of the four sections of the marine grid. They were derived using two methodologies: by fitting tidal model results to tidal bench marks leveled in NAVD88 or by calculating orthometric-to-tidal datum relationships at NOAA water level gauges. Results from two methods were coupled to create the final TSS grids and incorporated into the VDatum tool.

ACKNOWLEDEGEMENTS

The present project is developed with an immense amount of help from many personnel in NOAA's CSDL and CO-OPS. Dr. Kurt Hess developed the software for the VDatum grid generation, tidal datum population, and final product quality control tests. Drs. Eugene Wei in CSDL and Stephen Gill in CO-OPS reviewed the entire manuscript. The authors would like to express genuine gratitude for their hard work.

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APPENDIX A. HORIZONTAL AND VERTICAL ACCURACY STANDARDS FOR NOAA BATHYMETRY SURVEY

Table A.1. The required horizontal and vertical accuracy standards for NOAA surveys. Accuracy requirements before 1957 were prescribed for survey projects.

Survey Year*	Horizontal Accuracy	Vertical Accuracy	Standard
1998 – present	**Order 1** 1 – 100 m depth: 5.0 m + 5% of depth **Order 2** 100 – 200 m depth: 20 m + 5% of depth **Order 3** 100 – 200 m depth: 150 m + 5% of depth	**Order 1** 1 – 100 m depth: 0.5 – 1.4 m **Order 2** 100 – 200 m depth: 2.5 – 4.7 m **Order 3** > 100 m depth: same as Order 2	IHO S-44 [1] and NOAA [2]
1988 – 1998	95% probability that the true position lies within a circle of radius 1.5 mm, at the scale of the survey	0 – 30 m depth: 0.3 m > 30 m depth: 1% of depth	IHO S-44 [1] and NOAA [2]
1982 – 1988	probable error shall seldom exceed twice the plottable error (1.0 mm) at the scale of the survey	0 – 20 m depth: 0.3 m 20 – 100 m depth: 1.0 m > 100 m depth: 1% of depth	IHO S-44 [1] and NOAA [2]
1957 – 1982	maximum error of plotted positions shall seldom exceed 1.5 mm at the scale of the survey	0 – 20 m depth: 0.3 m 20 – 100 m depth: 1.0 m > 100 m depth: 1% of depth	IHC [3] NOAA [2] and IHO S-44 [1]
before 1957	undetermined	undetermined	undocumented

* end of field collection

1 International Hydrographic Organization (IHO) Standards for Hydrographic Surveys, Special Publication 44, (First Edition, 1968; Second Edition, 1982; Third Edition, 1987; Fourth Edition, 1998).

2 U.S. Department of Commerce Coast and Geodetic Survey Hydrographic Manual (1931, 1942, 1960, 1976) NOAA NOS Office of Coast Survey Specifications and Deliverables, 1999 – 2006. NOAA was established in 1970.

3 International Hydrographic Conference, 1957.

APPENDIX B. WATER LEVEL STATION DATA

Table B.1. NOS Water Level Station Names

1	8447281	STEEPBROOK
2	8447386	FALL RIVER HOPE BAY
3	8447387	Borden Flats Light Mt Hop
4	8450768	SAKONNET
5	8450898	BAY OIL CORPORATION
6	8450948	ANTHONY POINT
7	8451301	THE GLEN SAKONNET RIVER
8	8451351	SACHUEST
9	8451552	BRISTOL FERRY
10	8451929	BRISTOL BRISTOL HARBOR RI
11	8452154	BRISTOL HIGHLANDS RI
12	8452555	NAVY PIER PRUDENCE ISLAN
13	8452660	NEWPORT NARRAGANSETT BAY
14	8452944	CONIMICUT LIGHT NARRAGAN
15	8453033	BAY SPRING BULLOCK COVE R
16	8453201	CASTLE HILL
17	8453465	CONANICUT POINT RI
18	8453572	WARWICK POINT
19	8453733	RHODE IS YACHT CLUB RI
20	8453742	WEST JAMESTOWN
21	8453999	BEAVERTAIL POINT
22	8454000	PROVIDENCE PROVIDENCE RI
23	8454049	QUONSET POINT
24	8454341	BOSTON NECK
25	8454538	WICKFORD NARRAGANSETT BAY
26	8454658	NARRAGANSETT PIER RI
27	8455083	POINT JUDITH HARBOR OF R
28	8458022	WEEKAPAUG POINT BLOCK IS
29	8458694	WATCH HILL POINT
30	8459338	BLOCK ISLAND HARBOR OLD
31	8459681	BLOCK ISLAND SW END BLO
32	8461392	NORWICH THAMES RIVER
33	8461467	YALE BOATHOUSE THAMES RI
34	8461490	NEW LONDON THAMES RIVER
35	8461925	NIANTIC NIANTIC RIVER
36	8462764	LYME HWY. BR. CT. RIVER
37	8463348	TYLERVILLE CONNECTICUT R
38	8463701	CLINTON CLINTON HARBOR
39	8463827	MAROMAS CONNECTICUT RIVE
40	8463836	HIGGANUM CREEK CONNECTIC
41	8464041	MADISON BEACH CLUB LONG I
42	8464336	MIDDLETOWN CONNECTICUT R
43	8464445	GUILFORD GUILFORD HARBOR
44	8465233	BRANFORD BRANFORD RIVER
45	8465692	LIGHTHOUSE POINT NEW HAV
46	8465705	NEW HAVEN NEW HAVEN HARB
47	8465748	NEW HAVEN
48	8466375	GULF BEACH
49	8466442	MILFORD HARBOR
50	8466664	MURPHY S BOAT YARD HOUSA
51	8466791	SNIFFENS POINT HOUSATONI
52	8466797	I-95 BRIDGE HOUSATONIC R
53	8467150	BRIDGEPORT BRIDGEPORT HA
54	8467373	BLACK ROCK HARBOR CEDAR

55	8467726	SOUTHPORT SOUTHPORT HARB
56	8468448	SOUTH NORWALK NORWALK RI
57	8468609	ROWAYTON FIVEMILE RIVER
58	8468799	LONG NECK POINT LONG ISL
59	8469549	COSCOB HARBOR CT
60	8510321	MONTAUK POINT LIGHT NY
61	8510448	U.S. COAST GUARD STATION
62	8510560	MONTAUK FORT POND BAY
63	8510719	SILVER EEL POND FISHERS
64	8511171	THREEMILE HARBOR ENTRANCE
65	8511236	PLUM ISLAND PLUM GUT HARB
66	8512354	SHINNECOCK INLET
67	8512451	PONQUOGUE POINT SHINNECOC
68	8512668	MATTITUCK INLET LONG ISL
69	8512671	SHINNECOCK BAY INSIDE OU
70	8512735	SOUTH JAMESPORT GREAT PE
71	8512769	SHINNECOCK YACHT CLUB PE
72	8512987	NORTHVILLE FUEL DOCK LON
73	8513388	MORICHES COAST GUARD STAT
74	8513825	SMITH POINT BRIDGE NARRO
75	8514322	PATCHOGUE PATCHOGUE RIVE
76	8514422	CEDAR BEACH
77	8514560	PORT JEFFERSON
78	8515102	BAYSHORE LONG ISLAND
79	8515186	FIRE ISLAND COAST GUARD S
80	8515586	NORTHPORT NORTHPORT BAY
81	8515786	EATONS NECK
82	8515921	LLOYD HARBOR LIGHTHOUSE
83	8516061	COLD SPRINGS HARBOR
84	8516299	BAYVILLE BRIDGE OYSTER B
85	8516614	GLEN COVE YACHT CLUB LON
86	8516761	PORT WASHINGTON MANHASSS
87	8516945	KINGS POINT LONG ISLAND
88	8516990	WILLETS POINT LITTLE BAY
89	8516992	WILLETS POINT WLTS NY
90	8516993	WILLETS POINT (RTWLTS) NY
91	8517125	WHITESTONE NY
92	8517276	COLLEGE PT FT OF 110TH ST
93	8517401	WARDS IS NY
94	8517732	WALLABOUT BAY BKLN NAVY Y
95	8517811	GRAVESEND BAY NORTON PT B
96	8517847	BROOKLYN BRIDGE EAST RIV
97	8517921	GOWANUS BAY NY
98	8518091	RYE BEACH AMUSEMENT PARK
99	8518490	NEW ROCHELLE
100	8518621	HUNTS PT NY
101	8518639	PORT MORRIS EAST 138TH S
102	8518643	RANDALLS IS NY
103	8518687	QUEENSBORO BRIDGE EAST R
104	8518668	HORNS HOOK E. 90TH STREE
105	8518695	EAST 41ST STREET PIER NY
106	8518699	WILLIAMSBURG BRIDGE
107	8518750	THE BATTERY NEW YORK HAR
108	8518903	SPUYTEN DUYVIL CK ENT HUD
109	8518905	RIVERDALE HUDSON RIVER NY
110	8518924	HAVERSTRAW BAY
111	8519024	FORT WADSWORTH STATEN ISL
112	8519200	PORT IVORY ARTHUR KILL NY
113	8519483	BERGEN POINT WEST REACH

114	8519789	ROSSVILLE STATEN ISLAND N
115	8530095	ALPINE HUDSON RIVER
116	8530505	EDGEWATER HUDSON RIVER NJ
117	8530528	CARLSTADT HACKENSACK RIV
118	8530531	NORTH SECAUCUS HACK RIVER
119	8530645	UNION CITY HUDSON RIVER N
120	8530696	BELLEVILLE TPKE HACKENSA
121	8530743	POINT NO POINT PASSAIC R
122	8530772	KEARNY POINT HACKENSACK
123	8530882	PORT ELIZABETH NEWARK BA
124	8530986	CONSTABLE HOOK UPPER BAY
125	8531142	PORT READING ARTHUR KILL
126	8531232	SOUTH AMBOY RARITAN RIVER
127	8531262	KEASBEY RARITAN RIVER
128	8531390	SAYREVILLE RARITAN RIVER
129	8531545	KEYPORT RARITAN BAY
130	8531592	WAACKAACK CK RARITAN BAY
131	8531662	ATLANTIC HIGHLANDS SANDY
132	8531680	SANDY HOOK
133	8531684	SANDY HOOK RTWLTS NJ
134	8531712	HIGHLANDS BRIDGE SHREWSBU
135	8531753	OCEANIC NAVESINK RIVER
136	8531833	RED BANK NAVESINK RIVER
137	8531925	GOOSENECK BRIDGE SHREWSBU
138	8531942	LONG BRANCH INSIDE
139	8531991	LONG BRANCH FISHING PIER
140	8532322	SHARK RIVER HILLS NJ
141	8532337	BELMAR OUTSIDE NJ
142	8532339	AVON SHARK RIVER NJ
143	8532371	WALL TOWNSHIP SHARK RIVER
144	8532585	POINT PLEASANT BEACH MAN
145	8532591	MANASQUAN INLET

Table B.2. Tidal datums (meters) relative to mean sea level. The 'N/A's in the table denote missing values.

No.	Station ID	Longitude (degree)	Latitude (degree)	MHHW (m)	MHW (m)	MLW (m)	MLLW (m)	NAVD88 (m)	Epoch
1	8447281	-71.1317	41.74	0.814	0.738	-0.634	-0.69	N/A	1983-2001
2	8447386	-71.1633	41.705	0.785	0.711	-0.618	-0.671	N/A	1983-2001
3	8447387	-71.1733	41.705	0.807	0.71	-0.625	-0.677	N/A	1960-1978
4	8450768	-71.1933	41.465	0.593	0.514	-0.453	-0.489	0.106	1983-2001
5	8450898	-71.21	41.6517	0.755	0.677	-0.593	-0.639	N/A	1983-2001
6	8450948	-71.2117	41.6383	0.699	0.617	-0.527	-0.581	N/A	1983-2001
7	8451301	-71.2367	41.5583	0.645	0.557	-0.479	-0.523	N/A	1983-2001
8	8451351	-71.2383	41.4867	0.589	0.518	-0.434	-0.474	N/A	1983-2001
9	8451552	-71.255	41.6367	0.752	0.676	-0.566	-0.616	N/A	1983-2001
10	8451929	-71.28	41.6683	0.719	0.634	-0.634	-0.683	N/A	1960-1978
11	8452154	-71.2933	41.6967	0.722	0.646	-0.646	-0.698	N/A	1960-1978
12	8452555	-71.3217	41.58	0.69	0.617	-0.522	-0.569	N/A	1960-1978
13	8452660	-71.3267	41.505	0.645	0.57	-0.487	-0.529	0.093	1983-2001
14	8452944	-71.3433	41.7167	0.756	0.68	-0.59	-0.639	N/A	1983-2001
15	8453033	-71.3683	41.7517	0.759	0.684	-0.61	-0.663	N/A	1983-2001
16	8453201	-71.3617	41.4633	0.611	0.537	-0.453	-0.497	N/A	1983-2001
17	8453465	-71.3717	41.5733	0.661	0.576	-0.573	-0.619	N/A	1960-1978
18	8453572	-71.3783	41.6667	0.72	0.64	-0.556	-0.602	N/A	1960-1978
19	8453733	-71.3867	41.7667	0.755	0.676	-0.677	-0.735	N/A	1960-1978
20	8453742	-71.3867	41.4967	0.639	0.567	-0.485	-0.529	N/A	1983-2001
21	8453999	-71.4017	41.4517	0.589	0.509	-0.509	-0.566	N/A	1983-2001
22	8454000	-71.4017	41.8067	0.79	0.715	-0.631	-0.686	0.069	1983-2001
23	8454049	-71.4083	41.585	0.683	0.609	-0.52	-0.567	N/A	1983-2001
24	8454341	-71.4283	41.46	0.625	0.548	-0.464	-0.502	N/A	1983-2001
25	8454538	-71.445	41.5717	0.692	0.613	-0.518	-0.563	N/A	1983-2001
26	8454658	-71.455	41.4217	0.576	0.497	-0.493	-0.533	N/A	1960-1978
27	8455083	-71.49	41.3633	0.562	0.485	-0.43	-0.468	N/A	1983-2001
28	8458022	-71.7617	41.3283	0.458	0.392	-0.378	-0.418	0.114	1983-2001
29	8458694	-71.86	41.305	0.457	0.374	-0.412	-0.457	0.096	1983-2001
30	8459338	-71.5567	41.1733	0.535	0.459	-0.411	-0.446	N/A	1983-2001
31	8459681	-71.61	41.1633	0.482	0.408	-0.383	-0.418	N/A	1983-2001
32	8461392	-72.0783	41.5233	0.524	0.426	-0.497	-0.568	0.035	1983-2001
33	8461467	-72.0933	41.43	0.488	0.395	-0.438	-0.502	N/A	1983-2001
34	8461490	-72.0867	41.355	0.462	0.372	-0.409	-0.468	0.092	1983-2001
35	8461925	-72.1867	41.325	0.472	0.386	-0.398	-0.446	N/A	1983-2001
36	8462764	-72.35	41.3217	0.59	0.506	-0.503	-0.557	N/A	1983-2001
37	8463348	-72.465	41.4517	0.488	0.413	-0.412	-0.443	N/A	1983-2001
38	8463701	-72.5317	41.2683	0.801	0.709	-0.679	-0.751	0.103	1983-2001
39	8463827	-72.5517	41.5417	0.436	0.362	-0.373	-0.404	N/A	1983-2001
40	8463836	-72.5533	41.5033	0.432	0.362	-0.37	-0.4	N/A	1983-2001
41	8464041	-72.59	41.27	0.847	0.753	-0.756	-0.826	N/A	1960-1978
42	8464336	-72.645	41.56	0.396	0.321	-0.341	-0.374	-0.188	1983-2001
43	8464445	-72.6667	41.2717	0.887	0.792	-0.79	-0.86	N/A	1983-2001
44	8465233	-72.8183	41.2617	0.992	0.896	-0.886	-0.956	0.086	1983-2001
45	8465692	-72.905	41.2517	1.035	0.934	-0.93	-1.001	N/A	1983-2001
46	8465705	-72.9083	41.2833	1.034	0.936	-0.939	-1.013	N/A	1983-2001
47	8465748	-72.9167	41.2933	1.045	0.946	-0.945	-1.021	0.076	1983-2001
48	8466375	-73.0417	41.205	1.058	0.96	-0.957	-1.034	0.074	1983-2001
49	8466442	-73.055	41.2183	1.062	0.962	-0.964	-1.039	0.071	1983-2001
50	8466664	-73.0883	41.275	1.202	1.1	-0.987	-1.062	0.02	1983-2001

No.	Station ID	Longitude (degree)	Latitude (degree)	MHHW (m)	MHW (m)	MLW (m)	MLLW (m)	NAVD88 (m)	Epoch
51	8466791	-73.1133	41.1867	1.091	0.991	-0.97	-1.043	0.185	1983-2001
52	8466797	-73.1117	41.2033	1.115	1.013	-0.993	-1.067	0.054	1983-2001
53	8467150	-73.1817	41.1733	1.127	1.025	-1.03	-1.104	0.067	1983-2001
54	8467373	-73.2133	41.1567	1.13	1.027	-1.031	-1.107	N/A	1983-2001
55	8467726	-73.2833	41.1333	1.143	1.041	-1.043	-1.117	0.051	1983-2001
56	8468448	-73.415	41.0967	1.174	1.07	-1.084	-1.163	0.05	1983-2001
57	8468609	-73.445	41.065	1.181	1.076	-1.086	-1.164	N/A	1983-2001
58	8468799	-73.48	41.0383	1.2	1.092	-1.091	-1.162	N/A	1983-2001
59	8469549	-73.5967	41.0167	1.214	1.095	-1.094	-1.173	N/A	1960-1978
60	8510321	-71.8583	41.07	0.442	0.365	-0.397	-0.427	N/A	1960-1978
61	8510448	-71.935	41.0733	0.393	0.306	-0.305	-0.357	N/A	1983-2001
62	8510560	-71.96	41.0483	0.393	0.306	-0.325	-0.377	0.02	1983-2001
63	8510719	-72.03	41.2567	0.427	0.338	-0.373	-0.434	N/A	1983-2001
64	8511171	-72.19	41.035	0.469	0.378	-0.378	-0.439	N/A	1960-1978
65	8511236	-72.205	41.1717	0.491	0.396	-0.396	-0.457	N/A	1960-1978
66	8512354	-72.48	40.8367	0.559	0.475	-0.535	-0.58	N/A	1983-2001
67	8512451	-72.5033	40.85	0.509	0.43	-0.426	-0.466	N/A	1960-1978
68	8512668	-72.5617	41.015	0.876	0.784	-0.77	-0.836	N/A	1983-2001
69	8512671	-72.5617	40.82	0.458	0.381	-0.353	-0.373	N/A	1983-2001
70	8512735	-72.5817	40.935	0.501	0.411	-0.438	-0.492	N/A	1983-2001
71	8512769	-72.5533	40.8183	0.482	0.404	-0.37	-0.403	N/A	1983-2001
72	8512987	-72.645	40.9817	0.914	0.82	-0.812	-0.878	N/A	1983-2001
73	8513388	-72.75	40.7867	0.399	0.329	-0.329	-0.366	N/A	1960-1978
74	8513825	-72.8683	40.7383	0.222	0.173	-0.188	-0.224	N/A	1983-2001
75	8514322	-73	40.75	0.218	0.17	-0.169	-0.2	N/A	1983-2001
76	8514422	-73.0433	40.965	1.086	0.988	-0.976	-1.045	N/A	1983-2001
77	8514560	-73.0767	40.95	1.108	1.01	-1.005	-1.073	0.059	1983-2001
78	8515102	-73.24	40.7167	0.193	0.14	-0.161	-0.183	N/A	1983-2001
79	8515186	-73.26	40.6267	0.361	0.305	-0.304	-0.344	0.06	1983-2001
80	8515586	-73.3533	40.9	1.212	1.105	-1.111	-1.18	N/A	1983-2001
81	8515786	-73.4	40.9533	1.189	1.083	-1.086	-1.163	N/A	1983-2001
82	8515921	-73.4317	40.91	1.175	1.066	-1.078	-1.143	N/A	1983-2001
83	8516061	-73.47	40.8733	1.22	1.109	-1.114	-1.182	N/A	1983-2001
84	8516299	-73.55	40.9033	1.242	1.132	-1.122	-1.2	N/A	1983-2001
85	8516614	-73.655	40.8633	1.217	1.106	-1.11	-1.181	0.084	1983-2001
86	8516761	-73.7033	40.8317	1.212	1.103	-1.121	-1.203	N/A	1983-2001
87	8516945	-73.765	40.81	1.191	1.081	-1.1	-1.185	N/A	1983-2001
88	8516990	-73.7817	40.7933	1.191	1.08	-1.098	-1.182	0.058	1983-2001
89	8516992	-73.7817	40.7933	1.191	1.082	-1.095	-1.18	N/A	1960-1978
90	8516993	-73.7817	40.7933	1.191	1.082	-1.095	-1.18	N/A	1960-1978
91	8517125	-73.8133	40.7983	1.195	1.086	-1.082	-1.173	N/A	1960-1978
92	8517276	-73.8567	40.7833	1.14	1.03	-1.034	-1.119	N/A	1960-1978
93	8517401	-73.9217	40.7867	1.027	0.918	-0.917	-1.024	N/A	1960-1978
94	8517732	-73.9733	40.7067	0.756	0.653	-0.652	-0.722	N/A	1960-1978
95	8517811	-73.9983	40.59	0.826	0.723	-0.722	-0.792	N/A	1960-1978
96	8517847	-73.995	40.7033	0.769	0.655	-0.719	-0.78	0.11	1983-2001
97	8517921	-74.0133	40.665	0.823	0.72	-0.722	-0.786	N/A	1960-1978
98	8518091	-73.6717	40.9617	1.216	1.106	-1.116	-1.189	N/A	1983-2001
99	8518490	-73.7817	40.8933	1.216	1.107	-1.115	-1.194	0.084	1983-2001
100	8518621	-73.8733	40.8	1.164	1.055	-1.055	-1.143	N/A	1960-1978
101	8518639	-73.9067	40.8017	1.059	0.952	-0.949	-1.03	0.043	1983-2001
102	8518643	-73.9283	40.8	0.805	0.704	-0.704	-0.777	N/A	1960-1978

No.	Station ID	Longitude (degree)	Latitude (degree)	MHHW (m)	MHW (m)	MLW (m)	MLLW (m)	NAVD88 (m)	Epoch
103	8518687	-73.9583	40.7583	0.751	0.65	-0.669	-0.733	0.061	1983-2001
104	8518668	-73.9417	40.7767	0.808	0.713	-0.714	-0.772	N/A	1960-1978
105	8518695	-73.9683	40.7467	0.758	0.655	-0.659	-0.732	N/A	1960-1978
106	8518699	-73.9683	40.7117	0.719	0.62	-0.667	-0.727	0.066	1983-2001
107	8518750	-74.015	40.7	0.758	0.66	-0.72	-0.783	0.064	1983-2001
108	8518903	-73.925	40.8783	0.68	0.588	-0.585	-0.643	N/A	1960-1978
109	8518905	-73.9167	40.9033	0.68	0.588	-0.588	-0.649	N/A	1960-1978
110	8518924	-73.9633	41.2183	0.57	0.485	-0.498	-0.55	N/A	1960-1978
111	8519024	-74.055	40.6067	0.795	0.692	-0.695	-0.759	N/A	1960-1978
112	8519200	-74.18	40.645	0.85	0.747	-0.808	-0.878	N/A	1960-1978
113	8519483	-74.1467	40.64	0.834	0.736	-0.782	-0.846	0.054	1983-2001
114	8519789	-74.2233	40.5567	0.899	0.795	-0.796	-0.881	N/A	1960-1978
115	8530095	-73.9183	40.945	0.62	0.543	-0.6	-0.658	-0.022	1983-2001
116	8530505	-73.9783	40.8133	0.732	0.646	-0.646	-0.71	N/A	1960-1978
117	8530528	-74.06	40.8067	0.901	0.803	-0.936	-1.017	N/A	1983-2001
118	8530531	-74.0533	40.805	0.951	0.856	-0.854	-0.933	N/A	1960-1978
119	8530645	-74.0183	40.7667	0.759	0.667	-0.665	-0.735	N/A	1960-1978
120	8530696	-74.0967	40.7517	0.841	0.752	-0.855	-0.926	N/A	1983-2001
121	8530743	-74.1167	40.7317	0.866	0.771	-0.816	-0.884	N/A	1983-2001
122	8530772	-74.1033	40.7283	0.862	0.762	-0.827	-0.901	0.039	1983-2001
123	8530882	-74.14	40.6733	0.848	0.744	-0.794	-0.856	N/A	1983-2001
124	8530986	-74.085	40.655	0.793	0.692	-0.719	-0.789	N/A	1960-1978
125	8531142	-74.245	40.555	0.888	0.782	-0.831	-0.906	N/A	1983-2001
126	8531232	-74.2817	40.4917	0.859	0.755	-0.796	-0.863	N/A	1960-1978
127	8531262	-74.3117	40.5083	0.879	0.777	-0.812	-0.87	N/A	1983-2001
128	8531390	-74.3567	40.4783	0.898	0.798	-0.858	-0.929	N/A	1960-1978
129	8531545	-74.1983	40.44	0.842	0.741	-0.798	-0.863	0.031	1983-2001
130	8531592	-74.1433	40.4483	0.805	0.704	-0.704	-0.753	N/A	1960-1978
131	8531662	-74.035	40.4183	0.808	0.705	-0.731	-0.792	N/A	1960-1978
132	8531680	-74.01	40.4667	0.807	0.707	-0.727	-0.785	0.073	1983-2001
133	8531684	-74.01	40.4667	0.805	0.701	-0.719	-0.78	N/A	1960-1978
134	8531712	-73.9817	40.3967	0.734	0.637	-0.64	-0.692	N/A	1960-1978
135	8531753	-74.015	40.3767	0.636	0.545	-0.494	-0.53	N/A	1983-2001
136	8531833	-74.065	40.355	0.637	0.547	-0.523	-0.558	N/A	1983-2001
137	8531925	-74.0167	40.3267	0.469	0.39	-0.393	-0.439	N/A	1960-1978
138	8531942	-73.9967	40.325	0.475	0.4	-0.392	-0.43	N/A	1983-2001
139	8531991	-73.9767	40.3033	0.76	0.655	-0.686	-0.744	0.075	1983-2001
140	8532322	-74.0383	40.1917	0.765	0.658	-0.683	-0.738	N/A	1960-1978
141	8532337	-74.0083	40.185	0.765	0.658	-0.692	-0.744	N/A	1960-1978
142	8532339	-74.0267	40.1867	0.762	0.656	-0.661	-0.71	N/A	1960-1978
143	8532371	-74.0467	40.1783	0.765	0.658	-0.686	-0.747	N/A	1960-1978
144	8532585	-74.055	40.105	0.683	0.585	-0.603	-0.652	N/A	1960-1978
145	8532591	-74.035	40.1017	0.706	0.605	-0.621	-0.676	0.063	1983-2001

APPENDIX C. TIDAL DATUM FIELDS RELATIVE TO MSL DEFINED ON VDATUM MARINE GRID

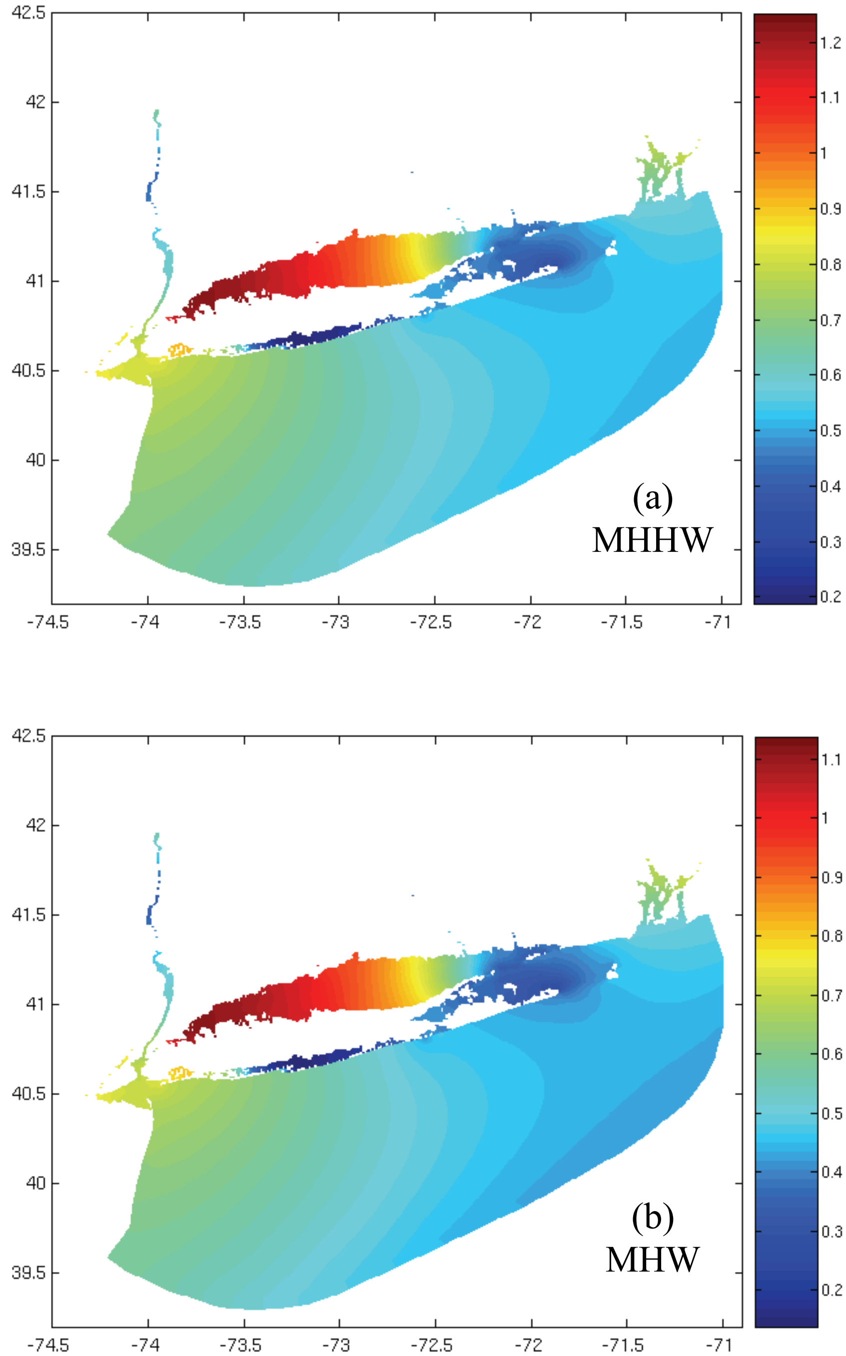


Figure C.1. Tidal Datums defined on VDatum marine grid, (a) MHHW, (b) MHW, (c) MLW, (d) MLLW, (e) MTL, and (f) DTL.

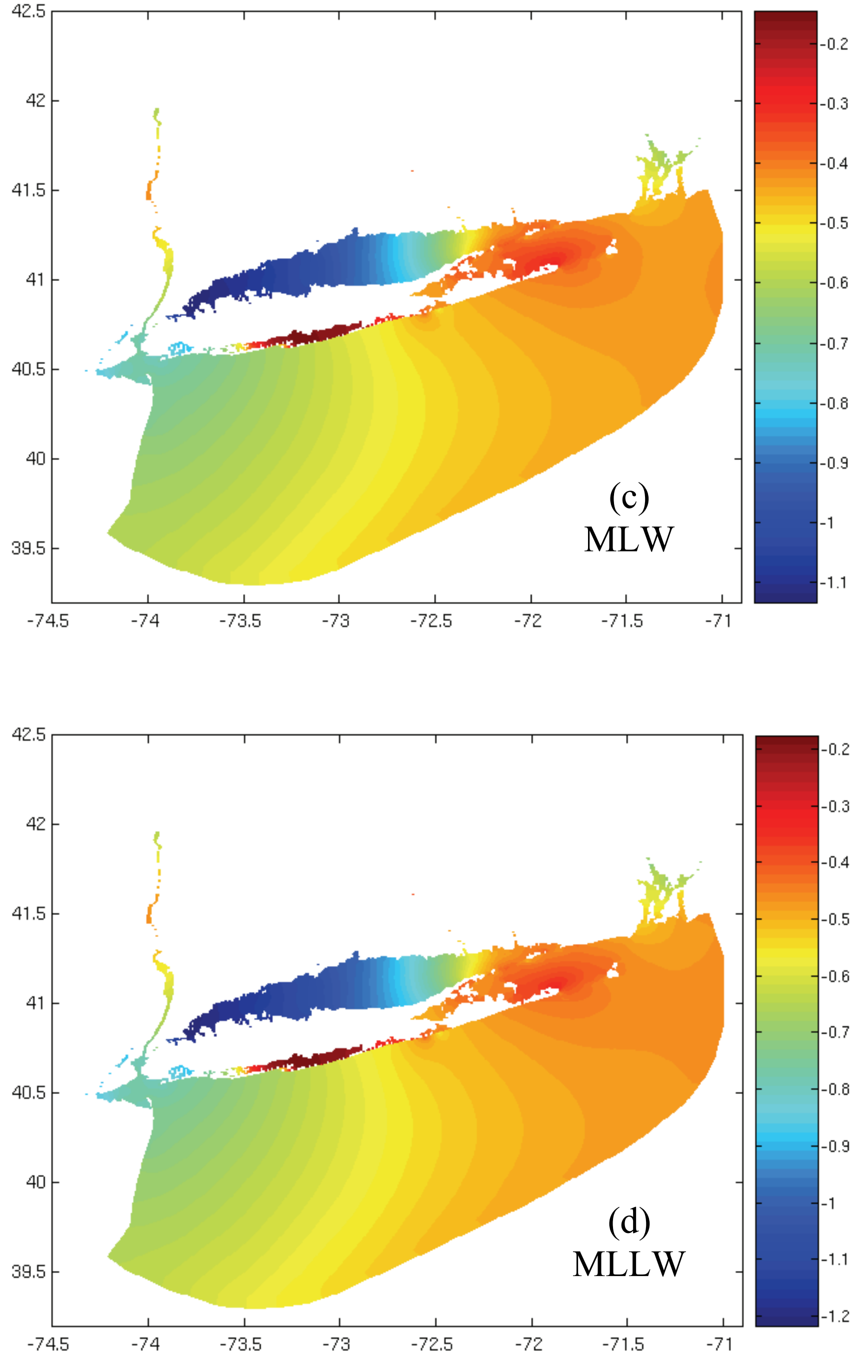
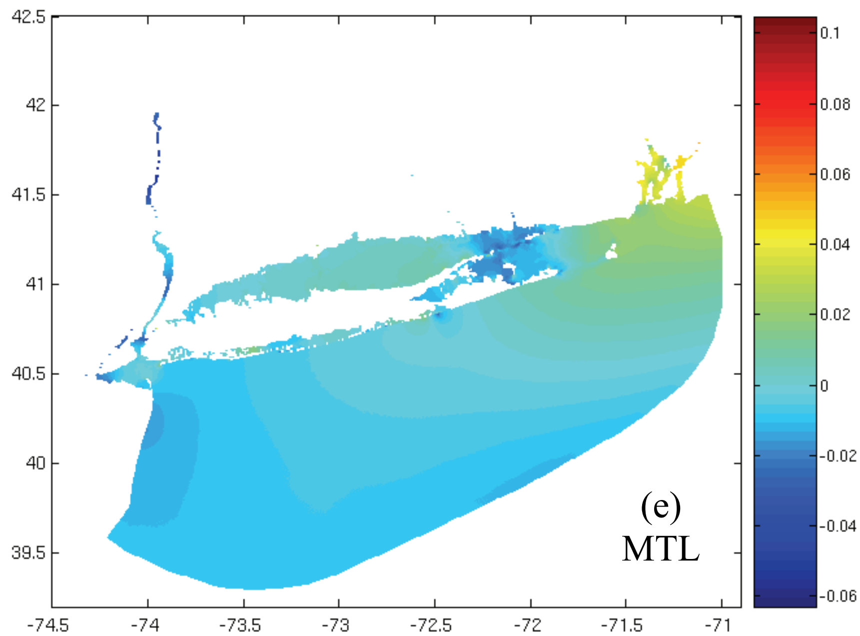


Figure C.1. (Continued)



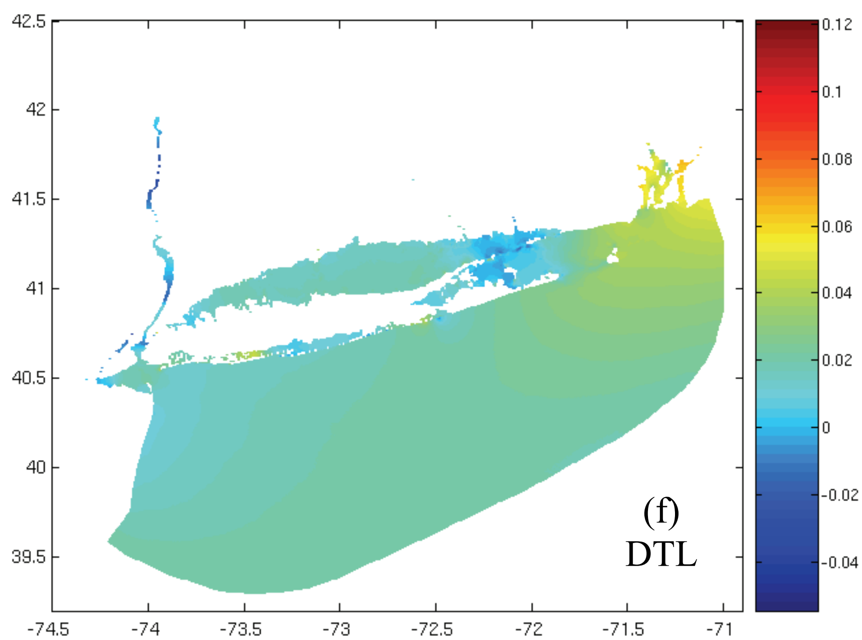


Figure C.1. (Continued)

APPENDIX D. Tidal gauge and bench marks data used to create the TSS

Table D.1. Derived NAVD 88-to-LMSL values for each tidal datum at NGS bench marks from the New Jersey to Rhode Island Vicinity Tidal Grid.

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
AB3868	40.96500	-73.67861	0.073	0.074	0.075	0.075	0.074	0.001
AB6710	40.46861	-74.01027	0.078	0.078	0.071	0.071	0.074	0.004
AB6711	40.46750	-74.00972	0.074	0.074	0.072	0.072	0.073	0.001
AB6736	40.70000	-74.01500	0.070	0.068	0.065	0.064	0.067	0.003
AB6737	40.70000	-74.01500	0.070	0.068	0.065	0.064	0.067	0.003
AH6725	41.04833	-71.96000	0.017	0.017	0.015	0.014	0.016	0.001
AH6726	41.04833	-71.96000	0.017	0.017	0.015	0.014	0.016	0.001
AH6727	41.04833	-71.96000	0.017	0.017	0.015	0.014	0.016	0.001
AH6728	41.04833	-71.96000	0.017	0.017	0.015	0.014	0.016	0.001
AH6731	40.79333	-73.78166	0.061	0.060	0.059	0.058	0.059	0.001
AH6732	40.79333	-73.78166	0.061	0.060	0.059	0.058	0.059	0.001
AH9447	41.50694	-71.32777	0.086	0.086	0.097	0.097	0.091	0.007
AH9448	41.50750	-71.32972	0.079	0.081	0.102	0.101	0.091	0.012
AH9453	41.80750	-71.40000	0.062	0.062	0.060	0.063	0.062	0.001
AI1725	41.17333	-73.18166	0.069	0.070	0.070	0.069	0.069	0.001
AI8467	40.44000	-74.19611	0.044	0.044	0.029	0.030	0.037	0.009
KU0373	40.93416	-72.57694	0.138	0.137	0.145	0.143	0.140	0.004
KU0432	40.87555	-73.46916	0.059	0.061	0.058	0.059	0.059	0.001
KU0505	40.94777	-73.07500	0.043	0.045	0.043	0.041	0.043	0.001
KU0506	40.95083	-73.07750	0.065	0.066	0.064	0.062	0.064	0.002
KU0668	40.71361	-73.24222	-0.035	-0.032	-0.034	-0.033	-0.033	0.001
KU0670	40.71305	-73.24111	-0.004	-0.002	-0.003	-0.002	-0.003	0.001
KU0976	40.79333	-73.78111	0.060	0.059	0.059	0.058	0.059	0.001
KU0977	40.79444	-73.78166	0.061	0.060	0.059	0.058	0.060	0.001
KU0978	40.79416	-73.78111	0.061	0.060	0.059	0.058	0.059	0.001
KU0979	40.79416	-73.78138	0.061	0.060	0.059	0.058	0.059	0.001
KU1012	40.80166	-73.90638	0.054	0.053	0.048	0.047	0.050	0.003
KU1013	40.80166	-73.90638	0.042	0.041	0.036	0.035	0.038	0.003
KU1042	40.70583	-73.96833	0.059	0.067	0.073	0.081	0.070	0.010
KU1043	40.71250	-73.96833	0.070	0.071	0.078	0.082	0.075	0.006
KU1044	40.71611	-73.96666	0.079	0.082	0.106	0.112	0.095	0.016
KU1418	40.75972	-73.95833	0.066	0.066	0.073	0.073	0.069	0.004
KU1593	40.86305	-73.65444	0.083	0.085	0.085	0.083	0.084	0.001
KU1594	40.86277	-73.65444	0.080	0.082	0.082	0.080	0.081	0.001
KU1595	40.86277	-73.65388	0.089	0.091	0.091	0.089	0.090	0.001
KU1630	40.94638	-73.91944	-0.019	-0.019	-0.019	-0.017	-0.018	0.001
KU1631	40.94638	-73.91944	-0.022	-0.022	-0.022	-0.020	-0.021	0.001
KU1632	40.94638	-73.91944	-0.019	-0.019	-0.019	-0.017	-0.018	0.001
KU1724	40.89166	-73.78250	0.088	0.088	0.090	0.090	0.089	0.001
KU1726	40.89055	-73.78222	0.084	0.084	0.087	0.087	0.086	0.002
KU1750	40.96472	-73.67583	0.051	0.052	0.053	0.053	0.052	0.001
KU1751	40.96444	-73.67472	0.080	0.081	0.081	0.081	0.081	0.001
KU1752	40.96388	-73.67388	0.077	0.078	0.078	0.078	0.078	0.001
KU1753	40.96388	-73.67361	0.074	0.075	0.075	0.075	0.075	0.001
KV0266	40.73222	-74.11694	0.018	0.019	0.017	0.017	0.018	0.001

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
KV0440	40.64027	-74.13277	0.072	0.073	0.025	0.031	0.050	0.026
KV0441	40.63861	-74.14305	0.055	0.055	0.050	0.052	0.053	0.003
KV0442	40.63833	-74.14444	0.059	0.060	0.055	0.057	0.058	0.002
KV0579	40.70333	-74.01416	0.073	0.073	0.088	0.085	0.080	0.008
KV0584	40.70416	-74.01583	0.074	0.074	0.085	0.081	0.078	0.005
KV0587	40.70083	-74.01555	0.066	0.065	0.071	0.069	0.067	0.003
KV0701	40.47111	-74.01194	0.085	0.084	0.075	0.074	0.079	0.006
KV0707	40.46805	-74.00833	0.073	0.073	0.072	0.072	0.072	0.001
KV0709	40.46805	-74.00861	0.073	0.073	0.072	0.072	0.072	0.001
KV0714	40.46111	-74.00416	0.074	0.075	0.072	0.072	0.073	0.001
KV0756	40.44000	-74.19250	0.048	0.049	0.028	0.029	0.039	0.011
KV2864	40.63777	-74.14638	0.058	0.058	0.056	0.057	0.057	0.001
KV3519	40.46833	-74.00694	0.073	0.073	0.072	0.072	0.073	0.001
KV3521	40.46777	-74.00888	0.077	0.077	0.077	0.076	0.076	0.000
LW0150	41.80666	-71.40138	0.066	0.066	0.064	0.066	0.066	0.001
LW0152	41.80694	-71.40194	0.063	0.063	0.061	0.063	0.062	0.001
LW0154	41.80722	-71.39916	0.062	0.062	0.060	0.062	0.062	0.001
LW0489	41.50750	-71.32861	0.078	0.080	0.102	0.102	0.091	0.013
LW0491	41.50611	-71.32777	0.085	0.086	0.102	0.102	0.094	0.010
LW0493	41.50694	-71.32722	0.091	0.091	0.099	0.098	0.095	0.005
LW0571	41.63750	-71.25361	0.090	0.091	0.092	0.092	0.091	0.001
LW0620	41.46305	-71.19583	0.110	0.110	0.104	0.102	0.106	0.004
LW0622	41.46305	-71.19583	0.104	0.104	0.098	0.096	0.100	0.004
LW0624	41.46388	-71.19083	0.106	0.105	0.104	0.103	0.104	0.001
LW0631	41.49666	-71.38500	0.084	0.086	0.085	0.087	0.086	0.001
LW0808	41.30388	-71.85916	0.101	0.101	0.108	0.109	0.105	0.004
LW0809	41.30555	-71.85805	0.093	0.092	0.105	0.106	0.099	0.007
LW0810	41.30555	-71.85805	0.093	0.092	0.105	0.106	0.099	0.007
LW0831	41.04805	-71.95722	0.061	0.061	0.057	0.056	0.059	0.003
LW0832	41.04722	-71.95833	0.018	0.018	0.014	0.013	0.016	0.003
LW0833	41.05138	-71.95777	0.105	0.105	0.099	0.098	0.102	0.004
LW5205	41.80638	-71.40111	0.069	0.069	0.067	0.069	0.069	0.001
LX0101	41.31777	-72.35027	0.079	0.078	0.063	0.066	0.071	0.009
LX0102	41.32111	-72.35111	0.055	0.054	0.042	0.047	0.049	0.006
LX0157	41.35944	-72.09111	0.092	0.093	0.093	0.095	0.093	0.001
LX0393	41.29611	-72.90250	0.076	0.073	0.070	0.068	0.072	0.004
LX0470	41.27000	-72.52833	0.103	0.101	0.102	0.103	0.102	0.001
LX0837	41.16000	-73.21277	0.054	0.054	0.054	0.054	0.054	0.000
LX0885	41.20472	-73.11166	0.060	0.061	0.061	0.060	0.061	0.001
LX0899	41.21138	-73.04722	0.071	0.070	0.075	0.077	0.073	0.003
LX0900	41.21055	-73.04722	0.071	0.070	0.075	0.077	0.073	0.003
LX0901	41.21027	-73.04694	0.074	0.073	0.078	0.080	0.076	0.003
LX0902	41.21027	-73.04888	0.065	0.064	0.069	0.071	0.067	0.003
LX2344	41.17555	-73.18000	0.066	0.067	0.067	0.065	0.066	0.001
LX3226	41.52388	-72.08000	0.033	0.034	0.032	0.033	0.033	0.001
LX3397	41.52083	-72.08111	0.037	0.038	0.036	0.037	0.037	0.001
AB3868	40.96500	-73.67861	0.073	0.074	0.075	0.075	0.074	0.001

Table D.2. Location and elevation information for NOAA tide gauges used to create the New Jersey to Rhode Island TSS grid. Tidal datums are relative to MLLW. Data are from CO-OPS. Station numbers marked with an asterisk have NAVD 88 elevations computed from NGS.

Station ID	Latitude (deg)	Longitude (deg)	MHHW (m)	MHW (m)	MSL (m)	MLW (m)	MLLW (m)	NAVD88 (m)
8461392	41.52333	-72.07833	1.092	0.994	0.568	0.071	0.000	0.603
8461490	41.35500	-72.08667	0.930	0.840	0.468	0.059	0.000	0.560
8462764*	41.32167	-72.35000	1.147	1.063	0.557	0.054	0.000	0.619
8463348*	41.45167	-72.46500	0.931	0.856	0.443	0.031	0.000	0.381
8463701	41.26833	-72.53167	1.552	1.460	0.751	0.072	0.000	0.854
8463827*	41.54167	-72.55167	0.840	0.766	0.404	0.031	0.000	0.295
8465233	41.26167	-72.81833	1.948	1.852	0.956	0.070	0.000	1.042
8465748	41.29333	-72.91667	2.066	1.967	1.021	0.076	0.000	1.097
8466375	41.20500	-73.04167	2.092	1.994	1.034	0.077	0.000	1.108
8466442	41.21833	-73.05500	2.101	2.001	1.039	0.075	0.000	1.110
8466573	41.30167	-73.07167	2.317	2.209	1.087	0.071	0.000	1.109
8466664	41.27500	-73.08833	2.264	2.162	1.062	0.075	0.000	1.082
8466791	41.18667	-73.11333	2.134	2.034	1.043	0.073	0.000	1.228
8466797	41.20333	-73.11167	2.182	2.080	1.067	0.074	0.000	1.121
8467150	41.17333	-73.18167	2.231	2.129	1.104	0.074	0.000	1.171
8467373*	41.15667	-73.21333	2.237	2.134	1.107	0.076	0.000	1.163
8467726	41.13333	-73.28333	2.260	2.158	1.117	0.074	0.000	1.168
8468448	41.09667	-73.41500	2.337	2.233	1.163	0.079	0.000	1.213
8447930	41.52333	-70.67167	0.672	0.588	0.300	0.043	0.000	0.415
8447712*	41.59333	-70.90000	1.206	1.130	0.510	0.044	0.000	0.600
8534720	39.35500	-74.41833	1.403	1.276	0.675	0.051	0.000	0.797
8532591	40.10167	-74.03500	1.382	1.281	0.676	0.055	0.000	0.739
8531991	40.30333	-73.97667	1.504	1.399	0.744	0.058	0.000	0.819
8531680	40.46667	-74.01000	1.592	1.492	0.785	0.058	0.000	0.858
8531545	40.44000	-74.19833	1.705	1.604	0.863	0.065	0.000	0.894
8531369*	40.41667	-74.36333	1.867	1.766	0.948	0.066	0.000	0.957
8531156*	40.54500	-74.26500	1.736	1.644	0.886	0.057	0.000	0.911
8530772	40.72833	-74.10333	1.763	1.663	0.901	0.074	0.000	0.940
8530743*	40.73167	-74.11667	1.750	1.655	0.884	0.068	0.000	0.910
8530591	40.78667	-74.14667	1.886	1.782	0.938	0.076	0.000	0.952
8530095	40.94500	-73.91833	1.278	1.201	0.658	0.058	0.000	0.636
8510560	41.04833	-71.96000	0.770	0.683	0.377	0.052	0.000	0.397
8512735*	40.93500	-72.58167	0.993	0.903	0.492	0.054	0.000	0.630
8512769*	40.81833	-72.55333	0.885	0.807	0.403	0.033	0.000	0.500
8514560	40.95000	-73.07667	2.181	2.083	1.073	0.068	0.000	1.132
8516061*	40.87333	-73.47000	2.402	2.291	1.182	0.068	0.000	1.240
8516299*	40.90333	-73.55000	2.442	2.332	1.200	0.078	0.000	1.276
8516614	40.86333	-73.65500	2.398	2.287	1.181	0.071	0.000	1.265
8516761*	40.83167	-73.70333	2.415	2.306	1.203	0.082	0.000	1.344
8516990	40.79333	-73.78167	2.373	2.262	1.182	0.084	0.000	1.240
8517847	40.70333	-73.99500	1.550	1.436	0.780	0.061	0.000	0.890
8518091	40.96167	-73.67167	2.405	2.295	1.189	0.073	0.000	1.245
8518490	40.89333	-73.78167	2.410	2.301	1.194	0.079	0.000	1.278
8518639	40.80167	-73.90667	2.089	1.982	1.030	0.081	0.000	1.073
8518687	40.75833	-73.95833	1.484	1.383	0.733	0.064	0.000	0.794
8518699	40.71167	-73.96833	1.446	1.347	0.727	0.060	0.000	0.793
8518750	40.70000	-74.01500	1.541	1.443	0.783	0.063	0.000	0.847

Station ID	Latitude (deg)	Longitude (deg)	MHHW (m)	MHW (m)	MSL (m)	MLW (m)	MLLW (m)	NAVD88 (m)
8519483	40.64000	-74.14667	1.680	1.582	0.846	0.064	0.000	0.900
8512987	40.98167	-72.64500	1.792	1.698	0.878	0.066	0.000	0.936
8450768	41.46500	-71.19333	1.082	1.003	0.489	0.036	0.000	0.595
8450954*	41.61833	-71.20333	1.200	1.115	0.539	0.047	0.000	0.596
8451552*	41.63667	-71.25500	1.368	1.292	0.616	0.050	0.000	0.707
8452660	41.50500	-71.32667	1.174	1.099	0.529	0.042	0.000	0.622
8453742*	41.49667	-71.38667	1.168	1.096	0.529	0.044	0.000	0.615
8454000	41.80667	-71.40167	1.476	1.401	0.686	0.055	0.000	0.754
8458022	41.32833	-71.76167	0.876	0.810	0.418	0.040	0.000	0.532
8458694	41.30500	-71.86000	0.914	0.831	0.457	0.045	0.000	0.553
8513825*	40.73833	-72.86833	0.446	0.397	0.224	0.036	0.000	0.246
8515102	40.71667	-73.24000	0.376	0.323	0.183	0.022	0.000	0.164
8515186	40.62667	-73.26000	0.705	0.649	0.344	0.040	0.000	0.404

APPENDIX E. COMPARISON OF DERIVED LIS TSS WITH OBSERVATIONS AND ERROR ANALYSIS

Table E.1. QA/QC Deltas from the New Jersey to Rhode Island TSS Grid.

PID	Latitude (deg)	Longitude (deg)	MHHW Deltas (m)	MHW Deltas (m)	MLW Deltas (m)	MLLW Deltas (m)	Avg. (m)	Std. Dev. (m)
AB3868	40.965000	-73.678610	-0.001	0.000	0.001	0.002	0.001	0.001
AB6710	40.468610	-74.010270	0.004	0.004	-0.003	-0.003	0.000	0.004
AB6711	40.467500	-74.009720	0.000	0.000	-0.001	-0.002	-0.001	0.001
AB6736	40.700000	-74.015000	0.003	0.002	-0.002	-0.003	0.000	0.003
AB6737	40.700000	-74.015000	0.003	0.002	-0.002	-0.003	0.000	0.003
AH6725	41.048330	-71.960000	-0.005	-0.005	-0.006	-0.007	-0.006	0.001
AH6726	41.048330	-71.960000	-0.005	-0.005	-0.006	-0.007	-0.006	0.001
AH6727	41.048330	-71.960000	-0.005	-0.005	-0.006	-0.007	-0.006	0.001
AH6728	41.048330	-71.960000	-0.005	-0.005	-0.006	-0.007	-0.006	0.001
AH6731	40.793330	-73.781660	0.002	0.001	0.001	-0.001	0.001	0.001
AH6732	40.793330	-73.781660	0.002	0.001	0.001	-0.001	0.001	0.001
AH9447	41.506940	-71.327770	-0.007	-0.006	0.005	0.005	-0.001	0.007
AH9448	41.507500	-71.329720	-0.012	-0.010	0.011	0.010	0.000	0.012
AH9453	41.807500	-71.400000	0.000	0.000	-0.002	0.000	0.000	0.001
AI1725	41.173330	-73.181660	0.001	0.002	0.002	0.001	0.002	0.001
AI8467	40.440000	-74.196110	0.007	0.008	-0.008	-0.007	0.000	0.009
KU0373	40.934160	-72.576940	-0.002	-0.003	0.005	0.003	0.001	0.004
KU0432	40.875550	-73.469160	0.000	0.002	-0.001	0.000	0.000	0.001
KU0505	40.947770	-73.075000	-0.002	-0.001	-0.002	-0.004	-0.002	0.001
KU0506	40.950830	-73.077500	0.001	0.002	0.000	-0.002	0.000	0.002
KU0668	40.713610	-73.242220	-0.002	0.001	-0.001	0.000	0.000	0.001
KU0670	40.713050	-73.241110	0.002	0.004	0.003	0.003	0.003	0.001
KU0976	40.793330	-73.781110	0.001	0.000	0.000	-0.001	0.000	0.001
KU0977	40.794440	-73.781660	0.001	0.001	0.000	-0.002	0.000	0.001
KU0978	40.794160	-73.781110	0.002	0.001	0.000	-0.001	0.000	0.001
KU0979	40.794160	-73.781380	0.002	0.001	0.000	-0.001	0.000	0.001
KU1012	40.801660	-73.906380	0.006	0.006	0.001	0.000	0.003	0.003
KU1013	40.801660	-73.906380	-0.006	-0.007	-0.011	-0.012	-0.009	0.003
KU1042	40.705830	-73.968330	-0.012	-0.004	0.002	0.011	-0.001	0.010
KU1043	40.712500	-73.968330	-0.003	-0.002	0.006	0.009	0.003	0.006
KU1044	40.716110	-73.966660	-0.015	-0.012	0.011	0.017	0.000	0.016
KU1418	40.759720	-73.958330	-0.002	-0.002	0.005	0.005	0.001	0.004
KU1593	40.863050	-73.654440	0.000	0.001	0.001	-0.001	0.000	0.001
KU1594	40.862770	-73.654440	-0.002	-0.001	-0.001	-0.003	-0.002	0.001
KU1595	40.862770	-73.653880	0.002	0.004	0.004	0.002	0.003	0.001
KU1630	40.946380	-73.919440	0.000	0.000	0.000	0.002	0.000	0.001
KU1631	40.946380	-73.919440	-0.003	-0.003	-0.003	-0.001	-0.003	0.001
KU1632	40.946380	-73.919440	0.000	0.000	0.000	0.002	0.000	0.001
KU1724	40.891660	-73.782500	0.000	0.000	0.002	0.003	0.001	0.001
KU1726	40.890550	-73.782220	-0.002	-0.002	0.000	0.001	-0.001	0.002
KU1750	40.964720	-73.675830	-0.005	-0.004	-0.003	-0.003	-0.004	0.001
KU1751	40.964440	-73.674720	-0.001	0.000	0.000	0.001	0.000	0.001
KU1752	40.963880	-73.673880	-0.002	-0.001	-0.001	0.000	-0.001	0.001
KU1753	40.963880	-73.673610	-0.004	-0.003	-0.003	-0.002	-0.003	0.001
KV0266	40.732220	-74.116940	-0.001	0.000	-0.002	-0.002	-0.001	0.001
KV0440	40.640270	-74.132770	0.022	0.023	-0.025	-0.020	0.000	0.026

PID	Latitude (deg)	Longitude (deg)	MHHW Deltas (m)	MHW Deltas (m)	MLW Deltas (m)	MLLW Deltas (m)	Avg. (m)	Std. Dev. (m)
KV0441	40.638610	-74.143050	0.001	0.002	-0.004	-0.002	-0.001	0.003
KV0442	40.638330	-74.144440	0.003	0.003	-0.002	0.000	0.001	0.002
KV0579	40.703330	-74.014160	-0.006	-0.007	0.008	0.006	0.000	0.008
KV0584	40.704160	-74.015830	-0.003	-0.004	0.007	0.003	0.001	0.005
KV0587	40.700830	-74.015550	-0.002	-0.003	0.003	0.001	0.000	0.003
KV0701	40.471110	-74.011940	0.006	0.006	-0.003	-0.004	0.001	0.006
KV0707	40.468050	-74.008330	0.000	0.000	0.000	-0.001	0.000	0.001
KV0709	40.468050	-74.008610	-0.001	-0.001	-0.001	-0.002	-0.001	0.001
KV0714	40.461110	-74.004160	0.001	0.002	-0.001	-0.001	0.000	0.001
KV0756	40.440000	-74.192500	0.009	0.010	-0.011	-0.010	-0.001	0.011
KV2864	40.637770	-74.146380	0.001	0.001	-0.002	0.000	0.000	0.001
KV3519	40.468330	-74.006940	0.000	0.000	-0.001	-0.002	-0.001	0.001
KV3521	40.467770	-74.008880	0.003	0.003	0.003	0.002	0.003	0.000
LW0150	41.806660	-71.401380	-0.001	-0.001	-0.003	0.000	-0.001	0.001
LW0152	41.806940	-71.401940	-0.002	-0.002	-0.004	-0.002	-0.003	0.001
LW0154	41.807220	-71.399160	-0.001	-0.001	-0.003	0.000	-0.001	0.001
LW0489	41.507500	-71.328610	-0.013	-0.011	0.011	0.011	-0.001	0.013
LW0491	41.506110	-71.327770	-0.009	-0.008	0.009	0.008	0.000	0.010
LW0493	41.506940	-71.327220	-0.004	-0.004	0.005	0.004	0.001	0.005
LW0571	41.637500	-71.253610	-0.001	0.000	0.001	0.001	0.000	0.001
LW0620	41.463050	-71.195830	0.004	0.004	-0.003	-0.004	0.000	0.004
LW0622	41.463050	-71.195830	-0.002	-0.002	-0.009	-0.010	-0.006	0.004
LW0624	41.463880	-71.190830	0.002	0.001	0.000	-0.001	0.000	0.001
LW0631	41.496660	-71.385000	-0.002	-0.001	-0.001	0.001	-0.001	0.001
LW0808	41.303880	-71.859160	-0.002	-0.002	0.005	0.006	0.002	0.004
LW0809	41.305550	-71.858050	-0.006	-0.007	0.006	0.007	0.000	0.007
LW0810	41.305550	-71.858050	-0.006	-0.007	0.006	0.007	0.000	0.007
LW0831	41.048050	-71.957220	0.002	0.001	-0.003	-0.004	-0.001	0.003
LW0832	41.047220	-71.958330	-0.011	-0.011	-0.015	-0.016	-0.013	0.003
LW0833	41.051380	-71.957770	0.003	0.002	-0.004	-0.005	-0.001	0.004
LW5205	41.806380	-71.401110	0.001	0.001	0.000	0.002	0.001	0.001
LX0101	41.317770	-72.350270	0.008	0.007	-0.009	-0.006	0.000	0.009
LX0102	41.321110	-72.351110	0.002	0.001	-0.010	-0.006	-0.003	0.006
LX0157	41.359440	-72.091110	-0.001	0.000	0.000	0.002	0.000	0.001
LX0393	41.296110	-72.902500	0.004	0.001	-0.003	-0.004	0.000	0.004
LX0470	41.270000	-72.528330	0.001	-0.001	0.000	0.001	0.000	0.001
LX0837	41.160000	-73.212770	0.000	0.000	0.000	0.000	0.000	0.000
LX0885	41.204720	-73.111660	0.000	0.001	0.001	0.000	0.001	0.001
LX0899	41.211380	-73.047220	-0.003	-0.004	0.001	0.004	-0.001	0.003
LX0900	41.210550	-73.047220	-0.003	-0.004	0.001	0.003	-0.001	0.003
LX0901	41.210270	-73.046940	-0.001	-0.002	0.003	0.005	0.001	0.003
LX0902	41.210270	-73.048880	-0.004	-0.005	0.000	0.003	-0.001	0.003
LX2344	41.175550	-73.180000	0.000	0.001	0.001	-0.001	0.000	0.001
LX3226	41.523880	-72.080000	-0.001	0.000	-0.002	-0.001	-0.001	0.001
LX3397	41.520830	-72.081110	0.000	0.001	-0.001	0.000	0.000	0.001

Table E.2. New Jersey to Rhode Island TSS Comparison to Tide Gauges and Tidal Bench marks.

PID	Latitude (deg)	Longitude (deg)	NAVD 88 to MSL (m)	TSS Derived Value (m)	Delta (m)
AB3868	40.965000	-73.678610	0.074	0.074	0.001
AB6710	40.468610	-74.010270	0.074	0.074	0.000
AB6711	40.467500	-74.009720	0.073	0.073	0.000
AB6736	40.700000	-74.015000	0.067	0.067	0.000
AB6737	40.700000	-74.015000	0.067	0.067	0.000
AH6725	41.048330	-71.960000	0.016	0.021	-0.005
AH6726	41.048330	-71.960000	0.016	0.021	-0.005
AH6727	41.048330	-71.960000	0.016	0.021	-0.005
AH6728	41.048330	-71.960000	0.016	0.021	-0.005
AH6731	40.793330	-73.781660	0.059	0.059	0.000
AH6732	40.793330	-73.781660	0.059	0.059	0.000
AH9447	41.506940	-71.327770	0.091	0.092	-0.001
AH9448	41.507500	-71.329720	0.091	0.091	0.000
AH9453	41.807500	-71.400000	0.062	0.062	0.000
AI1725	41.173330	-73.181660	0.069	0.068	0.001
AI8467	40.440000	-74.196110	0.037	0.037	0.001
KU0373	40.934160	-72.576940	0.140	0.140	0.000
KU0432	40.875550	-73.469160	0.059	0.059	0.000
KU0505	40.947770	-73.075000	0.043	0.045	-0.002
KU0506	40.950830	-73.077500	0.064	0.064	0.000
KU0668	40.713610	-73.242220	-0.033	-0.033	0.000
KU0670	40.713050	-73.241110	-0.003	-0.006	0.003
KU0976	40.793330	-73.781110	0.059	0.059	0.000
KU0977	40.794440	-73.781660	0.060	0.060	0.000
KU0978	40.794160	-73.781110	0.059	0.059	0.000
KU0979	40.794160	-73.781380	0.059	0.059	0.000
KU1012	40.801660	-73.906380	0.050	0.047	0.003
KU1013	40.801660	-73.906380	0.038	0.047	-0.009
KU1042	40.705830	-73.968330	0.070	0.070	0.000
KU1043	40.712500	-73.968330	0.075	0.073	0.003
KU1044	40.716110	-73.966660	0.095	0.094	0.001
KU1418	40.759720	-73.958330	0.069	0.068	0.001
KU1593	40.863050	-73.654440	0.084	0.084	0.001
KU1594	40.862770	-73.654440	0.081	0.083	-0.002
KU1595	40.862770	-73.653880	0.090	0.087	0.003
KU1630	40.946380	-73.919440	-0.018	-0.018	0.000
KU1631	40.946380	-73.919440	-0.021	-0.018	-0.003
KU1632	40.946380	-73.919440	-0.018	-0.018	0.000
KU1724	40.891660	-73.782500	0.089	0.088	0.002
KU1726	40.890550	-73.782220	0.086	0.087	-0.001
KU1750	40.964720	-73.675830	0.052	0.056	-0.004
KU1751	40.964440	-73.674720	0.081	0.081	0.000
KU1752	40.963880	-73.673880	0.078	0.079	-0.001
KU1753	40.963880	-73.673610	0.075	0.078	-0.003
KV0266	40.732220	-74.116940	0.018	0.019	-0.001
KV0440	40.640270	-74.132770	0.050	0.050	0.000
KV0441	40.638610	-74.143050	0.053	0.053	0.000

PID	Latitude (deg)	Longitude (deg)	NAVD 88 to MSL (m)	TSS Derived Value (m)	Delta (m)
KV0442	40.638330	-74.144440	0.058	0.057	0.001
KV0579	40.703330	-74.014160	0.080	0.079	0.001
KV0584	40.704160	-74.015830	0.078	0.078	0.001
KV0587	40.700830	-74.015550	0.067	0.067	0.000
KV0701	40.471110	-74.011940	0.079	0.078	0.001
KV0707	40.468050	-74.008330	0.072	0.073	-0.001
KV0709	40.468050	-74.008610	0.072	0.073	-0.001
KV0714	40.461110	-74.004160	0.073	0.073	0.000
KV0756	40.440000	-74.192500	0.039	0.039	0.000
KV2864	40.637770	-74.146380	0.057	0.057	0.000
KV3519	40.468330	-74.006940	0.073	0.073	0.000
KV3521	40.467770	-74.008880	0.076	0.074	0.002
LW0150	41.806660	-71.401380	0.066	0.067	-0.001
LW0152	41.806940	-71.401940	0.062	0.065	-0.003
LW0154	41.807220	-71.399160	0.062	0.063	-0.001
LW0489	41.507500	-71.328610	0.091	0.091	0.000
LW0491	41.506110	-71.327770	0.094	0.094	0.001
LW0493	41.506940	-71.327220	0.095	0.094	0.001
LW0571	41.637500	-71.253610	0.091	0.091	0.000
LW0620	41.463050	-71.195830	0.106	0.106	0.000
LW0622	41.463050	-71.195830	0.100	0.106	-0.006
LW0624	41.463880	-71.190830	0.104	0.104	0.000
LW0631	41.496660	-71.385000	0.086	0.086	0.000
LW0808	41.303880	-71.859160	0.105	0.103	0.002
LW0809	41.305550	-71.858050	0.099	0.099	0.000
LW0810	41.305550	-71.858050	0.099	0.099	0.000
LW0831	41.048050	-71.957220	0.059	0.060	-0.001
LW0832	41.047220	-71.958330	0.016	0.029	-0.013
LW0833	41.051380	-71.957770	0.102	0.103	-0.001
LW5205	41.806380	-71.401110	0.069	0.067	0.002
LX0101	41.317770	-72.350270	0.071	0.071	0.000
LX0102	41.321110	-72.351110	0.049	0.053	-0.004
LX0157	41.359440	-72.091110	0.093	0.093	0.000
LX0393	41.296110	-72.902500	0.072	0.072	0.000
LX0470	41.270000	-72.528330	0.102	0.102	0.000
LX0837	41.160000	-73.212770	0.054	0.054	0.000
LX0885	41.204720	-73.111660	0.061	0.060	0.001
LX0899	41.211380	-73.047220	0.073	0.074	-0.001
LX0900	41.210550	-73.047220	0.073	0.074	-0.001
LX0901	41.210270	-73.046940	0.076	0.075	0.001
LX0902	41.210270	-73.048880	0.067	0.069	-0.002
LX2344	41.175550	-73.180000	0.066	0.066	0.000
LX3226	41.523880	-72.080000	0.033	0.033	0.000
LX3397	41.520830	-72.081110	0.037	0.037	0.000
8461392	41.523333	-72.078333	0.035	0.035	0.000
8461490	41.355000	-72.086667	0.092	0.092	0.000
8462764	41.321667	-72.350000	0.062	0.059	0.003
8463348	41.451667	-72.465000	-0.062	-0.062	0.000
8463701	41.268333	-72.531667	0.103	0.103	0.000
8463827	41.541667	-72.551667	-0.109	-0.109	0.000
8465233	41.261667	-72.818333	0.086	0.086	0.000

PID	Latitude (deg)	Longitude (deg)	NAVD 88 to MSL (m)	TSS Derived Value (m)	Delta (m)
8465748	41.293333	-72.916667	0.076	0.076	0.000
8466375	41.205000	-73.041667	0.074	0.074	0.000
8466442	41.218333	-73.055000	0.071	0.071	0.000
8466664	41.275000	-73.088333	0.020	0.020	0.000
8466791	41.186667	-73.113333	0.185	0.173	0.012
8466797	41.203333	-73.111667	0.054	0.055	-0.001
8467150	41.173333	-73.181667	0.067	0.068	-0.001
8467373	41.156667	-73.213333	0.056	0.056	0.000
8467726	41.133333	-73.283333	0.051	0.051	0.000
8468448	41.096667	-73.415000	0.050	0.050	0.000
8532591	40.101667	-74.035000	0.063	0.063	0.000
8531991	40.303333	-73.976667	0.075	0.075	0.000
8531680	40.466667	-74.010000	0.073	0.073	0.000
8531545	40.440000	-74.198333	0.031	0.031	0.000
8530772	40.728333	-74.103333	0.039	0.039	0.000
8530743	40.731667	-74.116667	0.026	0.024	0.002
8530095	40.945000	-73.918333	-0.022	-0.021	-0.001
8510560	41.048333	-71.960000	0.020	0.021	-0.001
8512735	40.935000	-72.581667	0.138	0.138	0.000
8512769	40.818333	-72.553333	0.097	0.097	0.000
8514560	40.950000	-73.076667	0.059	0.060	-0.001
8516061	40.873333	-73.470000	0.058	0.058	0.000
8516299	40.903333	-73.550000	0.076	0.076	0.000
8516614	40.863333	-73.655000	0.084	0.084	0.000
8516761	40.831667	-73.703333	0.141	0.141	0.000
8516990	40.793333	-73.781667	0.058	0.059	-0.001
8517847	40.703333	-73.995000	0.110	0.110	0.000
8518091	40.961667	-73.671667	0.056	0.057	-0.001
8518490	40.893333	-73.781667	0.084	0.084	0.000
8518639	40.801667	-73.906667	0.043	0.045	-0.002
8518687	40.758333	-73.958333	0.061	0.062	-0.001
8518699	40.711667	-73.968333	0.066	0.067	-0.001
8518750	40.700000	-74.015000	0.064	0.067	-0.003
8519483	40.640000	-74.146667	0.054	0.054	0.000
8512987	40.981667	-72.645000	0.058	0.058	0.000
8450768	41.465000	-71.193333	0.106	0.106	0.000
8450954	41.618333	-71.203333	0.057	0.057	0.000
8451552	41.636667	-71.255000	0.091	0.091	0.000
8452660	41.505000	-71.326667	0.093	0.093	0.000
8453742	41.496667	-71.386667	0.086	0.086	0.000
8454000	41.806667	-71.401667	0.068	0.066	0.002
8458022	41.328333	-71.761667	0.114	0.114	0.000
8458694	41.305000	-71.860000	0.096	0.097	-0.001
8513825	40.738333	-72.868333	0.022	0.022	0.000
8515102	40.716667	-73.240000	-0.020	-0.021	0.001
8515186	40.626667	-73.260000	0.060	0.060	0.001