NOAA Technical Memorandum NOS CS 16

VDATUM FOR THE LONG ISLAND SOUND, NARRAGANSETT BAY, AND NEW YORK BIGHT: TIDAL DATUMS, MARINE GRIDS, AND SEA SURFACE TOPOGRAPHY

Silver Spring, Maryland
November 2008

noaa National Oceanic and Atmospheric Administration

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

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

An application of the vertical datum transformation software tool, VDatum, is developed for the Long Island Sound (LIS), Narragansett Bay, New York Harbor and New York Bight areas. It performs conversions between various tidal datum fields and mean sea level as well as between mean sea level and the North American Vertical Datum of 1988 (NAVD88).

The tidal datums fields were created using an unstructured, two-dimensional, barotropic hydrodynamic model, the ADvanced CIRCulation (ADCIRC) model. A triangular finite-element grid consisting of 181,798 nodes and 333,910 cells was created for this tide model application. The model run was forced with seven tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, Q_1) and tidal-induced water level undulations were simulated for 37 days. 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 water level time series from the final 30 days of the simulation. Model results were validated by comparing modeled and accepted datums from 123 water level stations maintained by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS). Discrepancies between model results and accepted datums were attributed to model errors and were interpolated over the whole model domain using the tidal constituent and residual interpolation (TCARI) software to obtain a domain-wide error field for each tidal datum. The error fields were applied to the model results to achieve error-corrected tidal datums on the unstructured model grid. Finally, tidal datum fields were interpolated onto a regular VDatum grid of 0.0017 degree by 0.0017 degree (approximately 185 m by 185 m) resolution.

A topography of the sea surface (TSS), defined as the elevation of NAVD88 relative to local mean sea level (LMSL), was derived based on data from the most recent National Tidal Datum Epoch (1983-2001). The NAVD88-to-LMSL spatially-varying transformations were computed using orthometric-to-tidal datum relationships at NOAA tidal gauges and at tide station benchmarks. Results from both methodologies were coupled to create a final TSS grid using spatial interpolation techniques.

Key Words: tides, tidal datums, VDatum, 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 National Ocean Service (NOS) is developing a software tool called VDatum to transform elevation data among approximately 30 vertical datums (Milbert, 2002; Parker, 2002; Myers et al., 2005). Once VDatum has been established for a region, data can be incorporated into integrated bathymetric-topographic digital elevation models (DEMs) for use in coastal GIS applications (Parker et al., 2003). VDatum allows bathymetric and topographic data to be integrated through its inherent orthometric, ellipsoidal, and tidal relationships.

To be applicable over coastal waters, VDatum requires spatially-varying fields of the tidal datums. These include mean higher high water (MHHW), mean high water (MHW), mean low water (MLW), mean lower low water (MLLW), mean tide level (MTL) and diurnal tide level (DTL). The tidal datums are combined with orthometric and ellipsoidal models, and relationships between these groups of vertical datums are established as input to the VDatum software. Tidal datum fields have previously been produced by NOS for many U.S. coastal areas: Tampa Bay (Hess, 2001), coastal southern Louisiana (Hess et al., 2004), the New York Bight (Hess, 2001), central coastal California (Myers and Hess, 2005), Delaware Bay (Hess, 2003), Puget Sound (Hess and Gill, 2003), and the Calcasieu River from Lake Charles to the Gulf of Mexico (Spargo and Woolard, 2005). As a continuing effort in support of the VDatum development, the present study focuses on resolving tidal datum fields and the Topography of Sea Surface (TSS) for an area over the southern New England shelf, encompassing the Long Island Sound (LIS), Narragansett Bay (NB), and New York Bight (NYB) regions. Figure 1 displays a map for the region of interest. In the figure, the red lines represent the MHW coastline, and the green line denotes locations 25 nautical miles offshore. Tidal datums for VDatum are usually computed between the MHW shoreline and the 25 nautical mile offshore limit.

This report describes the creation of the tidal datum and TSS fields in support of VDatum for the LIS, NYB, and NB areas. Computed tidal datums include MHHW, MHW, MLW, MLLW, MTL, DTL and local mean sea level (LMSL). The topography of the sea surface is the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to LMSL. Creation of VDatum begins with numerically simulating water level time series with an unstructured two-dimensional hydrodynamic model. The tidal datums were derived from the modeled time series and error corrections were made using computed model-data differences. A regular VDatum marine grid was created and populated with corrected tidal datums. Finally, for the same marine grid, the NAVD88-to-LMSL differences were derived by fitting a surface to the observed orthometric-to-tidal datum relationships at NOAA tidal gauges and benchmarks.

This technical report is organized as follows: After an introduction in Section 1, Section 2 discusses bathymetric, coastline and tidal datum data gathered to drive the hydrodynamic model and verify its results. Section 3 details the tidal simulation procedures, including an introduction of the hydrodynamic model, its setup, result validation, and error corrections. Section 4 discusses the creation of a regular VDatum marine grid required for the VDatum software tool and its population with error-corrected model datums. In

Section 5, creation of the TSS for the area is described. Finally, a summary is given in Section 6.

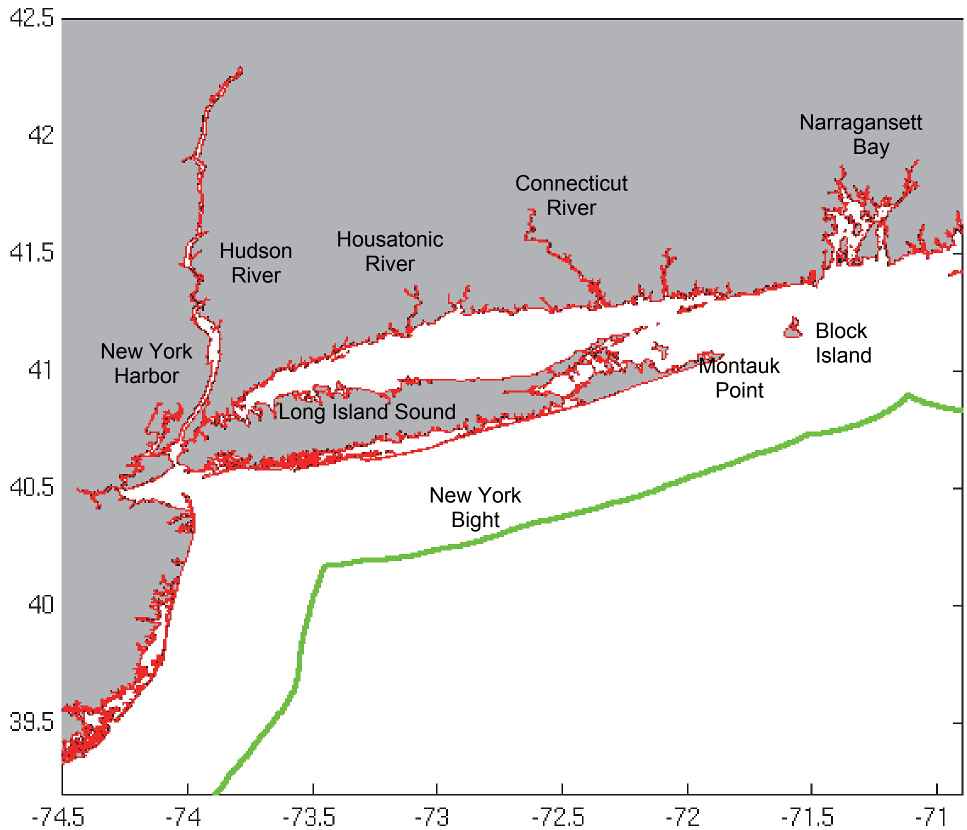


Figure 1. Map of the Long Island Sound, New York Bight, and Narragansett Bay area. Red lines show the MHW coastline, and the green line denotes a distance 25 nautical miles offshore.

2. COASTLINE, BATHYMETRIC, AND WATER LEVEL DATA

Knowledge of the spatial distribution of tidal datums is necessary for developing VDatum (Milbert and Hess, 2001). NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) computes tidal datums using water level time histories available from their National Water Level Observation Network (NWLON). To compute the spatially-varying fields of tidal datums between these stations, tidal models can be used to simulate water level time histories from which modeled tidal datums may be computed. Hydrodynamic models are capable of resolving the spatial variability of tidal datum fields with flexible resolutions (Myers, 2001; Spargo and Woolard, 2005). To setup the tide simulations, coastline data are required for delineating land-water boundaries. In addition, bathymetric data are needed to provide the model grid bathymetry. Tidal datums computed by CO-OPS from observations are also required to verify the model results and provide corrections in producing final tidal datum fields.

2.1. Digital Coastline

The mean high water shoreline is used as the coastline to delineate the land-water boundaries (Parker, 2002). In the present study, the MHW shoreline was initially based on the digitized data of the Extracted Vector Shoreline (EVS) from the NOS Office of Coast Survey (OCS). However, when compared to NOAA nautical chart MHW shorelines, this data set demonstrated evident errors at certain nearshore marshland areas. By employing computer-aided techniques, erroneous segments of the EVS coastlines were corrected, so that the refined coastline matches the MHW coastline illustrated on geo-referenced, digital nautical charts. A commercial software package called Surface-water Modeling System (SMS) was used to implement the correction. First, both the nautical charts and the EVS data were loaded into the SMS environment and contrasted with each other through the computer display. Wherever the two do not match, the EVS was judged to be incorrect. The corresponding segment of coastline was digitized according to the chart MHW coastline and the erroneous EVS coastline was replaced by the chart coastline. In Figure 1, red lines illustrate the final corrected coastline. The coastline specification was expressed as (longitude, latitude) pairs and possessed a precision up to the 6-th decimal point in degree (about 0.1 m).

2.2. Bathymetric Data

Bathymetric data used in this study were from two sources: a NOS soundings database 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 2004 editions of the NOAA ENCs. The NOS sounding data included surveys conducted between 1930 and 2000. The datums were referenced to either MLW or MLLW, depending on the years of data collections. Figure 2 shows the survey years and locations. Figure 3 illustrates the spatial distribution of the ENC data points. It was known that the ENC data were referenced to both MLW and MLLW. However, available documents do not ensure any feasible way to distinguish the two for individual data points. Therefore, the whole ENC data set was treated as being solely referenced to MLLW. Tables A.1 and A.2 list sources of bathymetry data and the corresponding NOAA survey standards.

Comparing Figures 2 and 3, it is evident that in most locations, NOS soundings possess a higher spatial distribution density than the ENC data. In some areas the two are both available. However, neither of them provides complete coverage for the whole study area. Blending the two data sets turned out to be necessary for a better regional coverage. For areas where both soundings and ENC data were available, soundings were used first, considering their superior spatial resolution. It is noted that even the blended data set left certain nearshore areas along the north LIS coast uncovered. NOAA nautical chart bathymetry was then manually digitized using computer-aided techniques to compensate for the missing coverage. Since both the ENC and manually digitized bathymetries were grounded in nautical chart data, they were then blended to form one data set and hereafter referred to as the ENC bathymetry without differentiation.

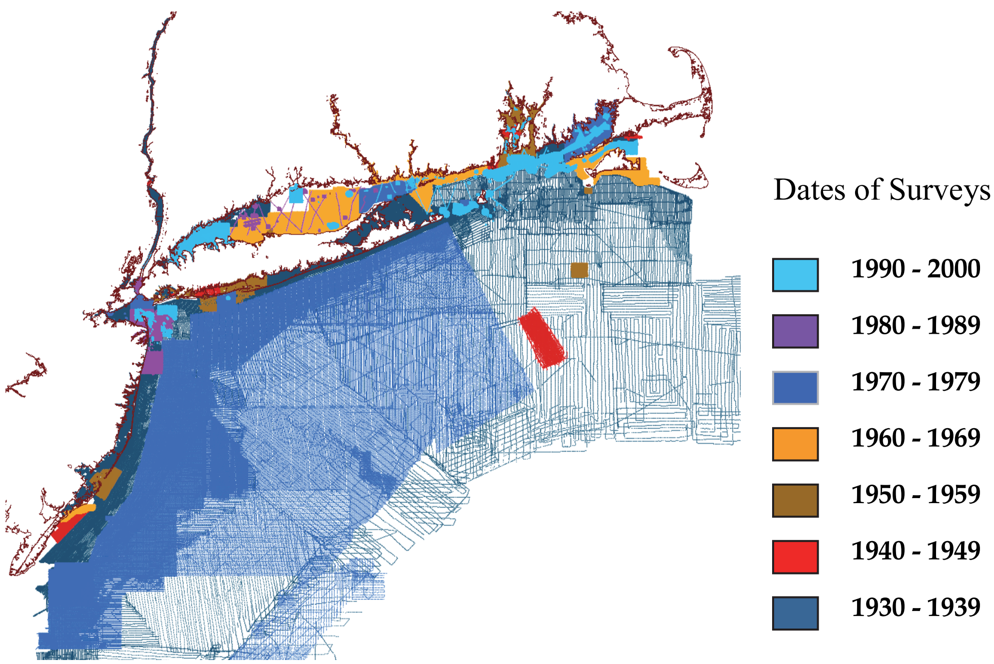


Figure 2. Dates and locations of NOS sounding surveys.

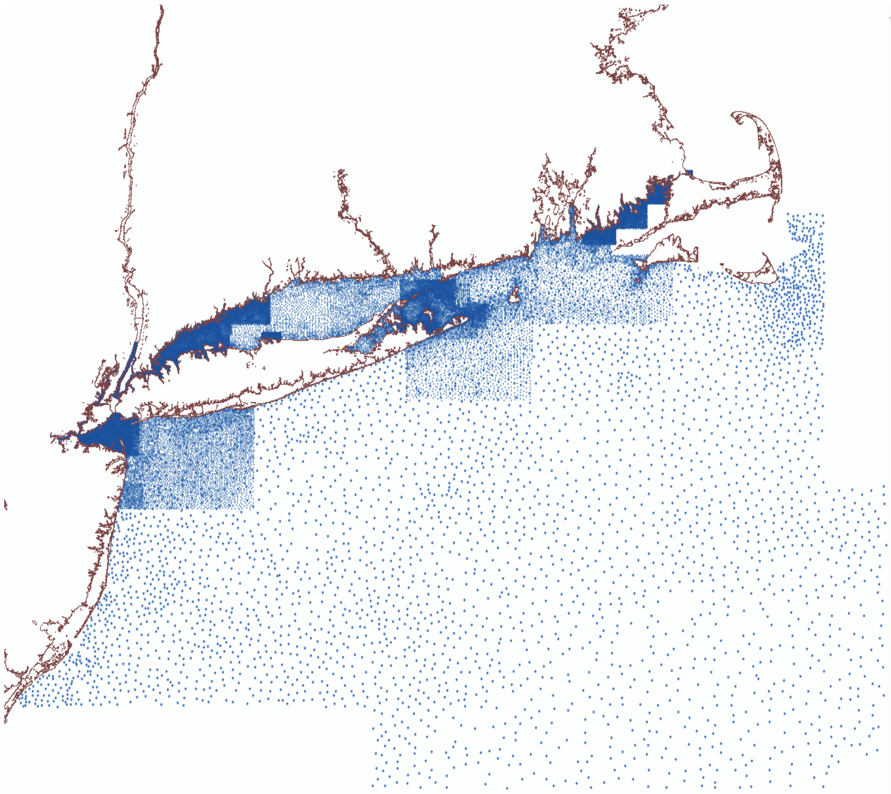


Figure 3. Spatial distribution of the ENC bathymetric data.

2.3. Tidal Datum Data

Tidal datums from CO-OPS water level stations are available online (Hess and Spargo, 2005) and were used to verify and correct model results. Many stations in the region of interest are located within either embayments or near obstructions not represented in the present model grid (Section 3.2), or at upper reaches of riverine regions where datums exhibit strong seasonal variability. Observations at these stations were determined to be unsuitable for validating model results and were thus discarded. This resulted in 123 stations actually used for validating and correcting the model results. Tables B.1 and B.2 in Appendix B list the station and tidal datum information.

It is indicated in Table B.1 that tidal datums at the 123 stations correspond to different national tidal epochs (NTDE). In the present project, tidal datums of all stations are treated as of the same quality without distinction. This is justified by comparing tidal datums at 72 stations with both 1960-1978 and 1983-2001 epochs data available. Table B.3 in Appendix B list mean tidal ranges of different epochs, their ratios, differences, and percentages of the differences. Of all the stations, the averaged ratio is 0.99; the averaged absolute difference is 0.013 m, with differences at each individual station ranging from 0.0 cm to 3.8 cm; the average percentage of differences is 1.0%. Tidal datums from epochs before 1983-2001 are therefore deemed to be reliable and used in model-data error corrections.

3. TIDAL DATUM SIMULATION

3.1. Hydrodynamic Model

The ADCIRC model (Westerink and Luettich, 1993; Luettich et al., 1999) was employed to model water level time histories and derive tidal datum fields. The ADCIRC model is a prognostic, unstructured grid, hydrodynamic circulation model. It simulates tides by solving the shallow water equations and has been proved to be valid for modeling tides in various oceanic environments from open oceans to coastal and estuarine waters (Luettich et al., 1999; Mukai et al., 2002; Myers 2005). The ADCIRC model provides a variety of options for users to specify various aspects of tidal dynamics and execution modes. For instance, the model run could be in either 2- or 3-dimensonal modes, serial or parallel execution dependent on machine infrastructures, linear or quadratic bottom friction formulations with constant or variable friction coefficients, etc.

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, 5.0 m s^{-2}, throughout the model domain. A quadratic friction scheme with spatially-varied coefficient (C_d) was specified to calculate bottom friction. Multiple test runs were conducted to test various C_d values (Figure 4) in an attempt to mitigate model-data discrepancy of tidal datums. In general, final adopted C_d increased eastward throughout LIS from 2.0×10^{-3} to 3.2×10^{-3}; $C_d=3.2\times10^{-3}$ was used across the Block Island Sound and Rhode Island Sound (RIS); in the NB area C_d varied from 3.2×10^{-3} at RIS to 2.1×10^{-3} near the upper bay; C_d was 3.0×10^{-3} throughout NYB and dropped to 2.1×10^{-3} near the New York Harbor (NYH) area. The values corresponded to an optimal model-data agreement.

A model time step of 1.0 second was used to ensure numerical stability in the simulations. A 37-day model run was conducted. The model was ramped up for the first 5 days with a hyperbolic tangent function. At each grid node, water level time histories were recorded at 6-minute intervals for the last 30 days. The parallel version was adopted and the model run utilized 72 processors of the JET computer at NOAA's Earth System Research Laboratory's High Performance Computing System. It took approximately 18 hours to complete the 37-day simulation.

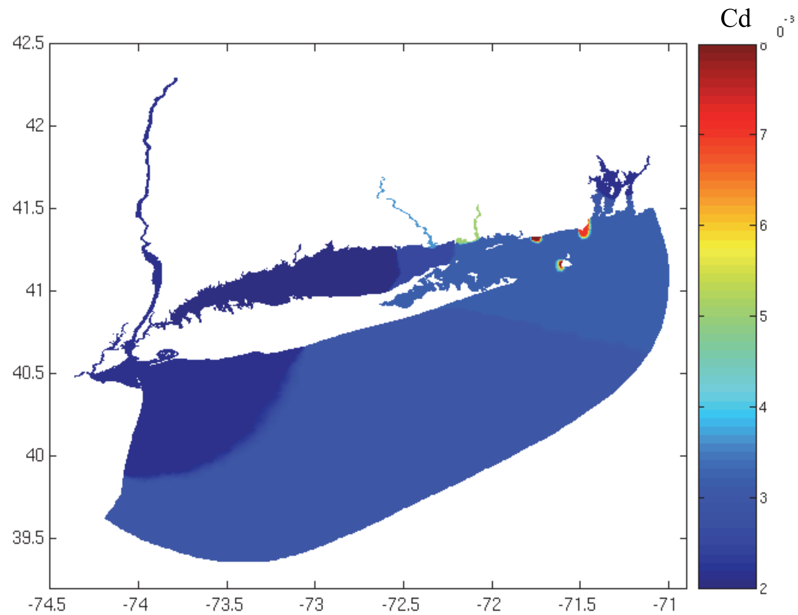


Figure 4. Spatially variable bottom friction coefficient (C_d) employed in model computation.

3.2. Model Grid

The model domain covers coastal waters from east of Narragansett Bay south to the coast of New Jersey, encompassing LIS, NB, NYH, and NYB (Figure 5). The ocean boundary is set approximately along the 90 meter isobath. A high-resolution, unstructured grid with 333,910 triangular elements and 181,798 nodes was created to represent the domain up to the MHW shoreline. Element spacing for the grid ranges from around 25 m in nearshore waters to 5.5 km in the open ocean. In general, finer elements were created for nearshore areas compared to those in deep waters, so as to accurately resolve fine coastline features and reflect bathymetry variability. Figures 5a-c show close-up views of the grid at three domain sections near NYH, NB, and LIS, respectively. It is noted that lagoons along south coast of Long Island were not represented in the present grid. This is because tidal datums in these lagoon areas were not the interest of this project and a previous study (Swanson, 1976) indicates that their existence does not exert evident influence on tidal fields in adjacent coastal waters, probably due to the very limited inlet cross-sectional area for tidal waves to pass through. Therefore, the lagoon areas were excluded from the present modeling consideration.

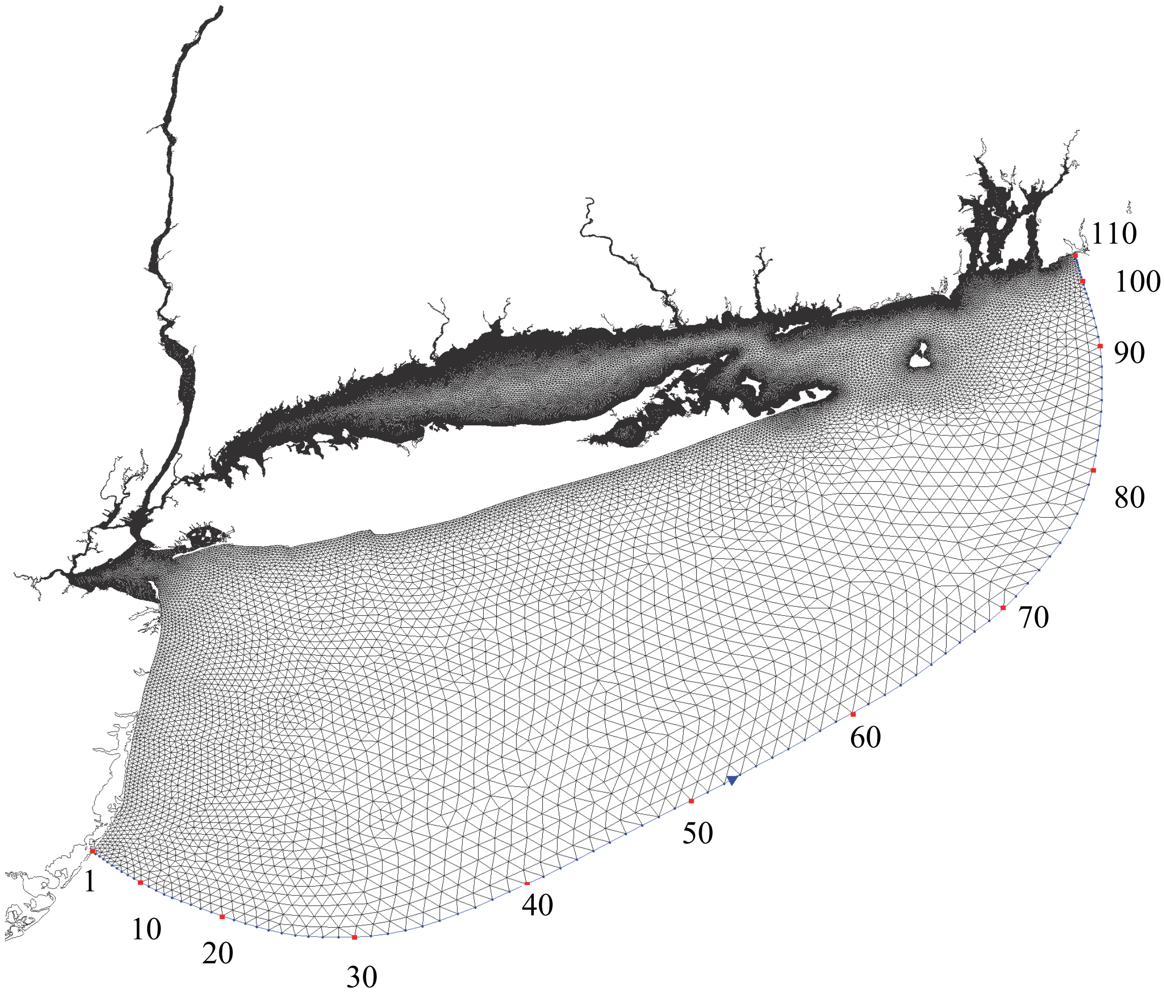


Figure 5. Finite element grid for the entire model domain. Blue line represents the model open boundary. Numbers labelled along the boundary denote the node identification numbers of adjacent red dots.

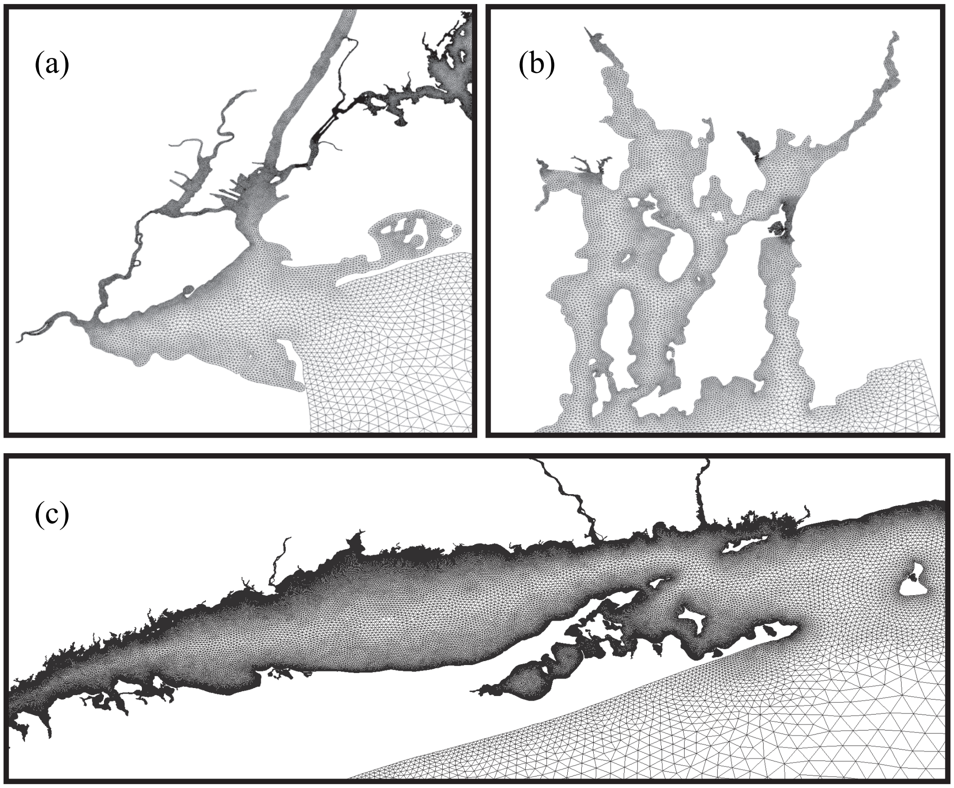


Figure 6. Zoom of the model grid near (a) New York Harbor, (b) Narragansett Bay, and (c) Long Island Sound.

3.3. Bathymetry for the Model Grid

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

The algorithm used for populating the three meshes was the same. For a given node, bathymetric data located within the area delineated by that node's surrounding elements were searched and interpolated onto the node through inverse-squared distance interpolation. Since element size changes throughout the model domain, the searching ranges for bathymetric data points vary from node to node. As the element size is smaller in shallower water, bathymetry for nodes near the coastline were from more locally distributed data points than 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. The three meshes were then

combined to obtain a more complete coverage. The two NOS sounding meshes were merged first. For each node with bathymetry available in both meshes, an arithmetic average of the two values was taken; for those with bathymetry available only in either of the two, the available one was used. It is noted that the two sets of NOS sounding mesh bathymetries were referenced to different datums, either MLLW or MLW depth. Therefore, soundings referenced to MLW datum were first adjusted by adding a difference, $\Delta H_{MLLW-MLW}$= MLLW-MLW, to ensure that both meshes were using the same MLLW depths. The $\Delta H_{MLLW-MLW}$ varies throughout the domain. However, before the initial model run, the spatial variability was unknown. It was thus initiated with an estimated constant value of 0.06 m, which approximated an average $\Delta H_{MLLW-MLW}$ over all CO-OPS observations in the LIS area. This constant $\Delta H_{MLLW-MLW}$ was later updated by a spatially-varied one from model outputs. After merging the two sounding meshes, the ENC mesh was then incorporated to fill in unpopulated nodes. However, even after merging the three meshes, there still remained many nodes without valid bathymetry. Bathymetry of these nodes were interpolated from adjacent nodes through nearest-neighbor extrapolation.

The hydrodynamic model implementation requires bathymetry referenced to MSL. It was necessary to adjust the reference datum of the grid bathymetry from MLLW to MSL. It was accomplished by iteratively updating MLLW-MSL field using both observational data and model results from a series of simulations. Since the MSL-MLLW difference was unknown prior to model runs, an offset of MSL-MLLW=0.8 m was applied on the whole grid as an initial estimate based on observed datums at CO-OPS water level stations in the area. Following each model run, new sets of tidal datum fields were derived and used to update aforementioned MLW-MLLW and MSL-MLLW fields. In pursuit of model result convergence, multiple runs were made until invariant values of four datums (MHHW, MHW, MLW, and MLLW) were achieved. In the present study, three iterations were made to satisfy a convergence criteria of 0.1 cm in the difference of datums from subsequent simulations. Figure 7 displays the final bathymetry used by the hydrodynamic model.

3.4. Boundary Forcing and Model Run

Barotropic tidal elevations were simulated with the ADCIRC model. The model was forced with harmonic constants of seven astronomical tidal constituents (K_1, O_1, Q_1, M_2, S_2, N_2, and K_2) on the model's open boundary. At each boundary node, water level was determined according to

$$\varsigma(t) = \sum_{i=1}^{7} f_i A_i \cos(\sigma_i t + [V_o + u]_i - \kappa_i), \qquad i \in \{K_1, O_1, Q_1, M_2, S_2, N_2, and \quad K_2\},$$

where ζ represents the instantaneous water level relative to model zero, t is the time, i denotes one of the seven 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. Table 1 lists values of σ_i, f_i, and $[V_o+u]_i$ used in the simulation; for the latter two, the values correspond to those of mid-1992, at which f_{M_2} approximates unity. The A_i and κ_i values were interpolated from results of a Western North Atlantic Ocean tidal model (WNATM) (Meyers, unpublished manuscript).

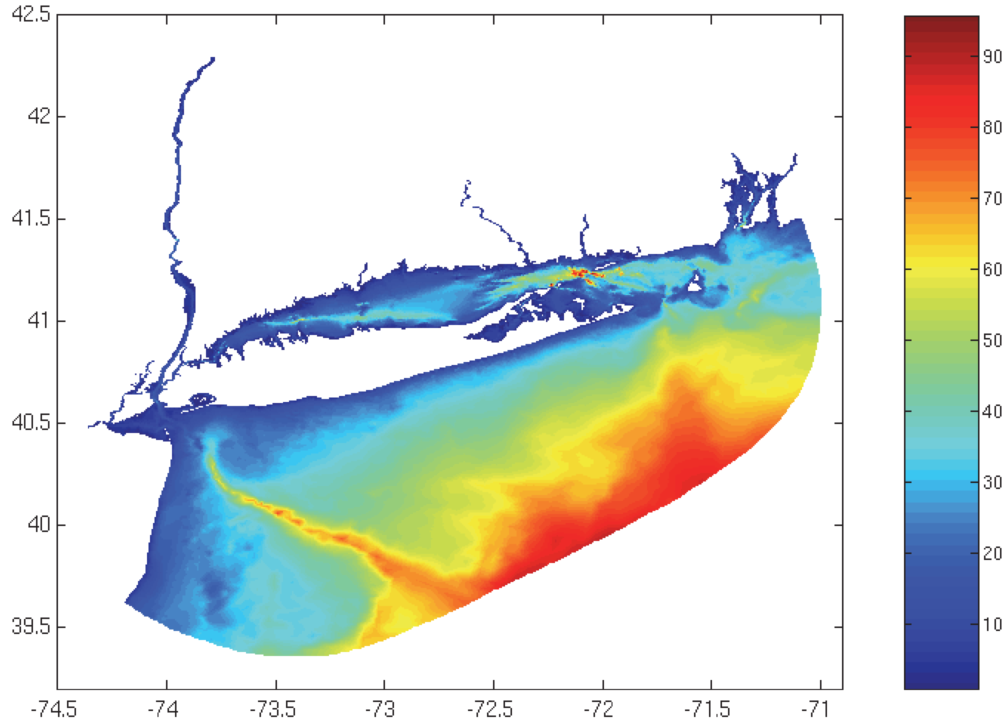


Figure 7. Model grid bathymetry relative to MSL. Color bar is in meters.

Table 1. Speeds, nodal factors, and equilibrium argument of seven tidal constituents used for forcing model runs

Constituent	Speed (10^{-5} s^{-1}) σ_i	Nodal Factor f_i	Equilibrium Argument (degrees) $[V_o+u]_i$
K_1	7.2921158358	1.030	18.70
O_1	6.7597744151	1.024	78.70
Q_1	6.4958541129	1.024	326.2
M_2	14.0518902509	1.000	101.3
S_2	14.5444104333	1.000	0.000
N_2	13.7879699487	1.000	348.8
K_2	14.5842317201	1.016	217.6

Some adjustments were made on the M_2 amplitudes at nodes toward NB to improve model-data agreement at stations near upper NB. Figure 8 shows the two data sets, one (blue circles) representing the direct interpolation of the WNATM tidal database and the other (red triangles) displaying those after the adjustment. The adjustment starts from nodes near the middle of the open boundary. The change of amplitude gradually increases toward NB and reaches a maximum of around 5 cm on nodes close to the mouth of NB.

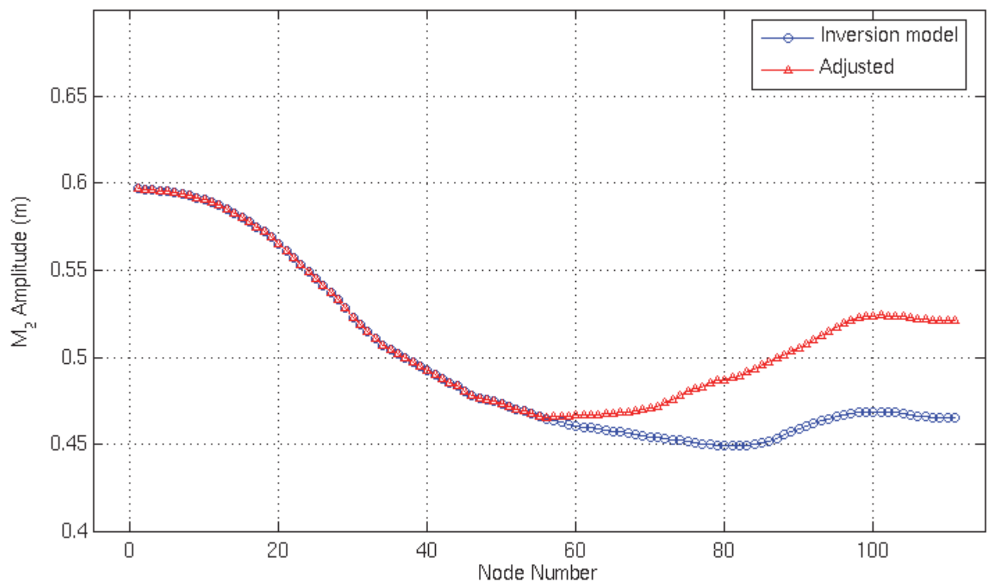


Figure 8. M_2 amplitudes on the model open boundary nodes. Blue circles represent those interpolated from WNATM and red triangles denote those after adjustment. Locations of the open boundary nodes are illustrated in Figure 5.

3.5. Results

Water level time series from the ADCIRC simulation were recorded at 6-minute intervals at each grid node. They were passed into the FORTRAN program lv3.f (Hess, 2001) to calculate the following tidal datum fields: MSL, MHHW, MHW, MLW, and MLLW. The computed datums were referenced to the model zero (MZ). The latter four were then adjusted to be referenced to the MSL field. Henceforth, references to each of the tidal datums shall imply this adjusted value relative to MSL. Note that MTL is defined as the algebraic average of MHW and MLW, and DTL is the algebraic average of MHHW and MLLW. The two fields were not computed until error-corrected MHHW, MHW, MLW, and MLLW fields were obtained (Section 4.2). For reference, the modeled MSL field is displayed in Figure 9. Note that it simply represents the difference between the averaged model water level time histories and MZ.

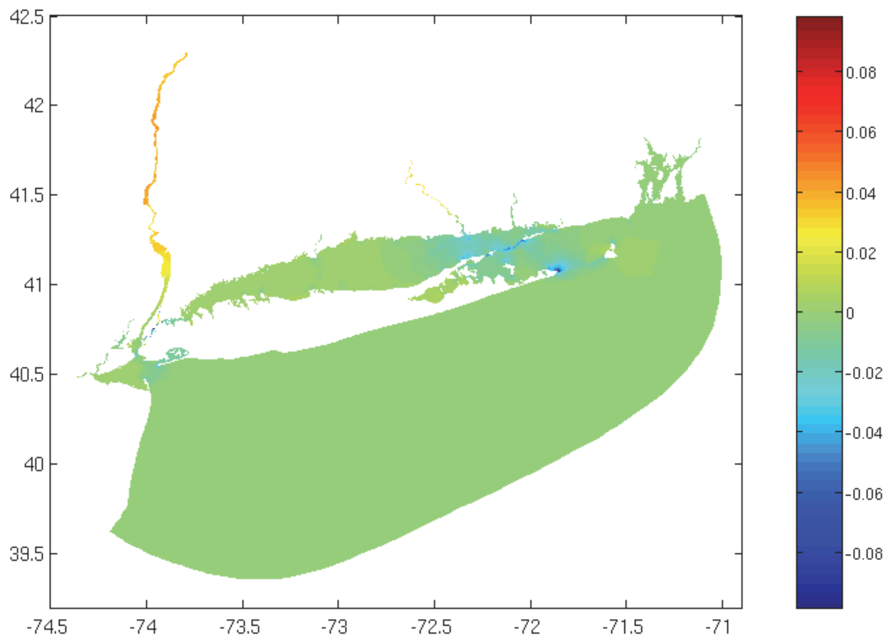


Figure 9. Model derived MSL field relative to MZ (units are cm).

Figures 10a-d display the MHHW, MHW, MLW, MLLW fields, respectively. Modeled datum fields demonstrate good agreement with previously published results in both spatial variability patterns and magnitudes (Swanson, 1976). As expected, the four tidal datum fields exhibit a similar spatial pattern. 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, the 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 for 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. Along the south coast of Long Island, the range drops from 1.2 m near NYH in the east to 0.7 m near Montauk Point in the west.

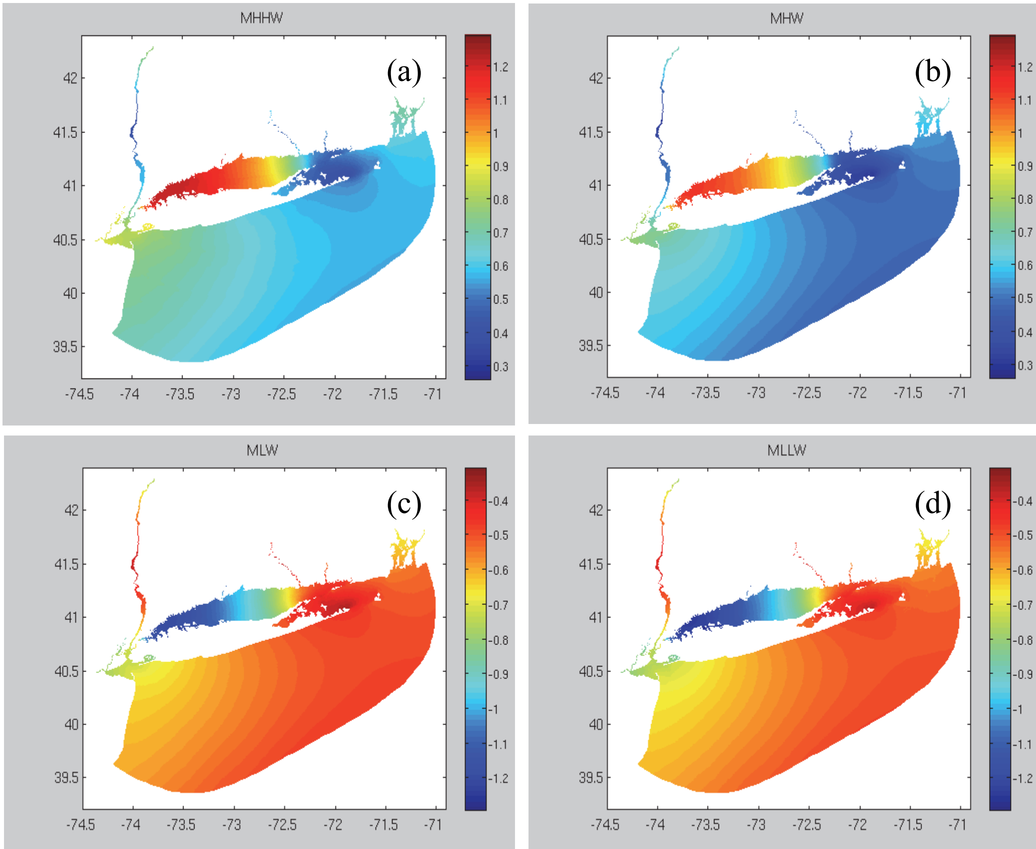


Figure 10. Tidal datum fields, (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW relative to MSL, as computed by the hydrodynamic model. Color bars are in meters.

3.6. Verifications and Error Corrections

To verify model results, simulated tidal datums were compared with those from 123 CO-OPS tidal gauge observations. For each datum, model results were interpolated onto the CO-OPS station locations using an inverse-squared distance algorithm.

Figures 11a-d display model-data contrasts for MHHW, MHW, MLW, and MLLW, respectively. In general, there is good model and data agreement. Over the 123 stations, average differences between the modeled and observed values are 2.3 cm, 2.2 cm, 3.4 cm, and 2.6 cm for MHHW, MHW, MLW, and MLLW, respectively. For each individual station, the averaged absolute difference (|Avg|) between the model and observations over the four datums is examined and is displayed as color-coded symbols in Figures 12a-d. Figure 12a displays overall station distributions and Figures 12b-c show zoomed views near LIS, NYH, and NB, respectively. Magnitudes of discrepancy are smaller than 6.0 cm at over 90% of stations. For the remaining 10%, they are smaller than 7.2 cm except for one station (station ID number: 8458022) at (71.75^{o}W, 41.32^{o}N), which gives |Avg|=10.4 cm; see the red color-coded symbol in Figure 12b.

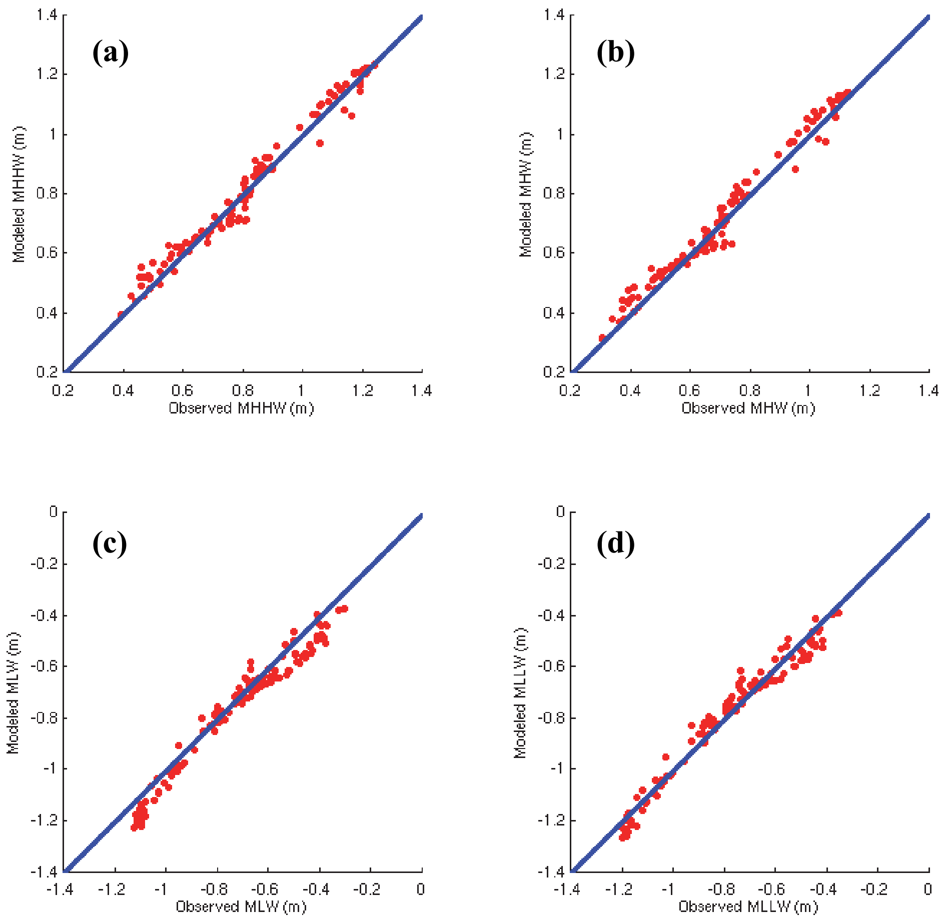


Figure 11. Comparisons of the modeled (1) MHHW, (2) MHW, (3) MLW, and (4) MLLW datums against observations.

The relatively large model-data discrepancy at this station may result from either model errors or relatively low accuracy of observation data. According to NOS (2003), error magnitudes of CO-OPS tidal datum data varies with duration of tidal gauge measurements. For those less than 4 months, data accuracy may only be ensured to be around 4 cm. Inventory for station 8458022 indicated that water level observations spanned only about a 2-month period. Therefore, the apparent model errors could be attributed to possible inaccuracy inherited in the observational data.

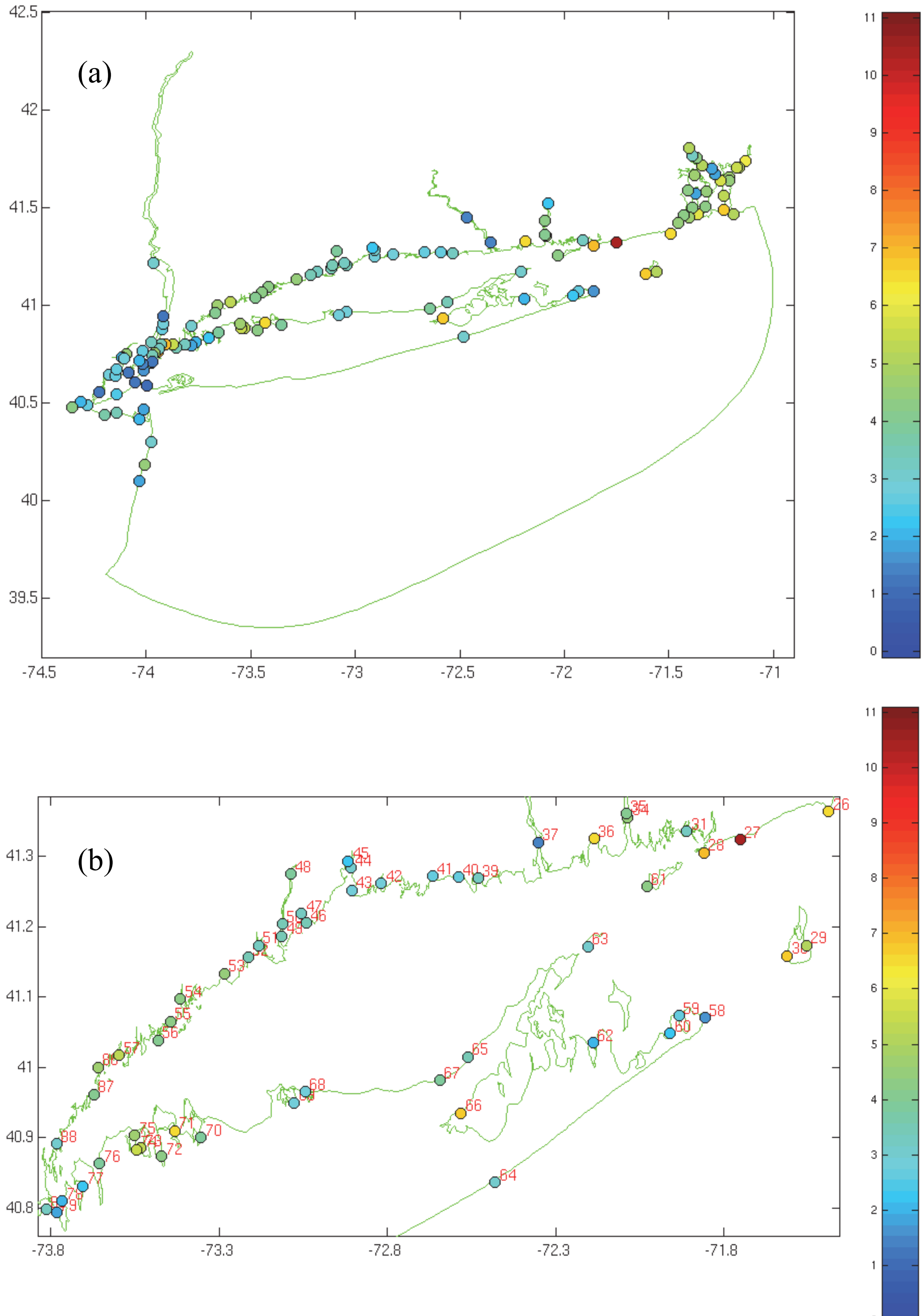


Figure 12.1. Color-coded model-data errors at control stations over (a) the whole domain and (b) LIS. The errors represent averaged magnitudes of the model-data difference over four tidal datums: MHHW, MHW, MLW, and MLLW. The red numbers correspond to station numbers listed on the first column of Tables B.1 and B.2. Color bars are in cm.

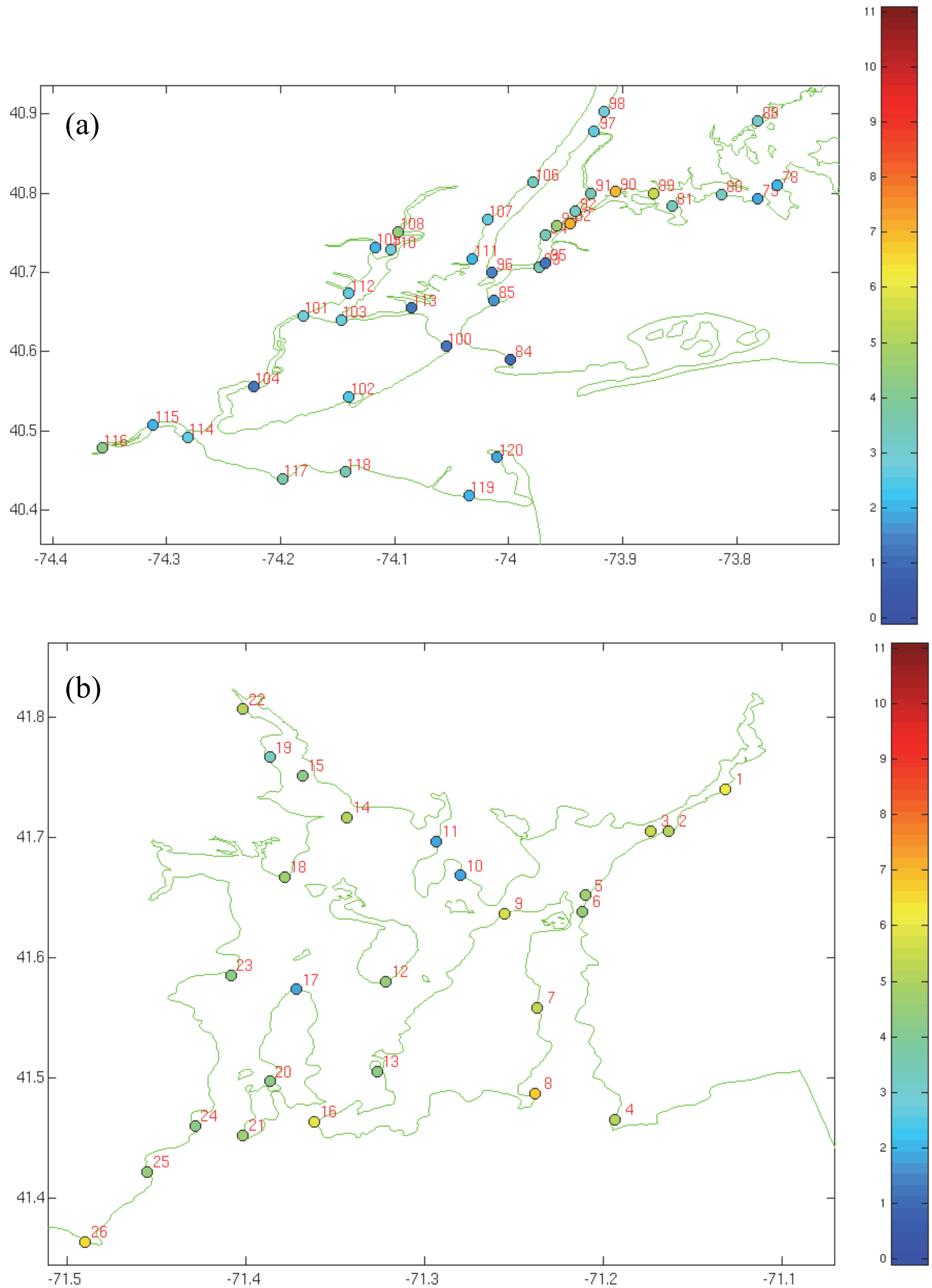


Figure 12.2. Color-coded model-data errors at control stations over (a) NYH, and (b) NB. The errors represent averaged magnitudes of the model-data difference over four tidal datums: MHHW, MHW, MLW, and MLLW. The red numbers correspond to station numbers listed on the first column of Tables B.1 and B.2. Color bars are in cm.

The model-data differences at the control stations show the pattern of model errors over the whole model domain. To correct errors on the entire model grid, spatial distributions of the error fields need to be calculated. This was achieved via the tidal constituent and residual interpolation (TCARI) technique (Hess, 2001; Hess, 2002). TCARI spatially interpolates the error fields on each grid node from values at a number of individual control stations by solving Laplace's equation. TCARI has been developed for both structured and unstructured model grids at CSDL, and the unstructured version was used in this study. After applying TCARI, the error fields for MHHW, MHW, MLW, and MLLW were derived, which matched the model-data difference at the control stations. The modeled tidal datum fields were then corrected by subtracting the interpolated errors. Figures C.1a-d display the four corrected datum fields on the entire model grid.

Note that the other two tidal datum fields, MTL and DTL, were produced in a different way. They were derived from the four corrected datums by taking the arithmetic averages between MHW and MLW and between MHHW and MLLW, respectively.

4. CREATION AND POPULATION OF THE MARINE GRID

4.1. Creation of VDatum Marine Grid

The VDatum software uses tidal datum transformations defined on a regular grid (Hess and White, 2004). Hence, it is necessary to interpolate the tidal datum fields from the unstructured finite-element grid onto an equally-spaced VDatum marine grid.

Marine grid points were categorized as either water points (darker gray area in Figure 13) or land points (lighter gray area in Figure 13). The water points are to be populated with valid tidal datum values and the land points are to be specified with null values. To create and populate the marine grid, a high-resolution coastline and a bounding polygon were used. The coastline (see Section 2 and Figure 1) delineated the land-water boundaries. A marine grid bounding polygon (yellow line in Figure 13) was created to guide the selection of the water points as well as the population of tidal datum fields. The marine grid (Figure 13) was created using the FORTRAN program vgridder5.f.

Considering the limitation of the VDatum software on the maximum manageable file size, the VDatum marine grid was further divided into four sections, namely New York Harbor, Long Island Sound, Block Island Sound, and Outer New York Bight, respectively (Figure 13). Each section corresponds to a rectangular region in geographic coordinates. Marine grid points are equally spaced within each region. For a point in the *i*-th row and *j*-th column relative to the point of origin *(*$longitude_0$*,* $latitude_0$*)* at the region's southwest corner, its location *(longitude_i, latitude_j)* is defined as,

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

where *del_lon*, and *del_lat* denote separation between adjacent points along the eastward and northward 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. The coordinates at the rectangular region's northeast corner ($longitude_1$, $latitude_1$) are derived as

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

Table 2 lists the parameters used to define the marine grids of the above four sections.

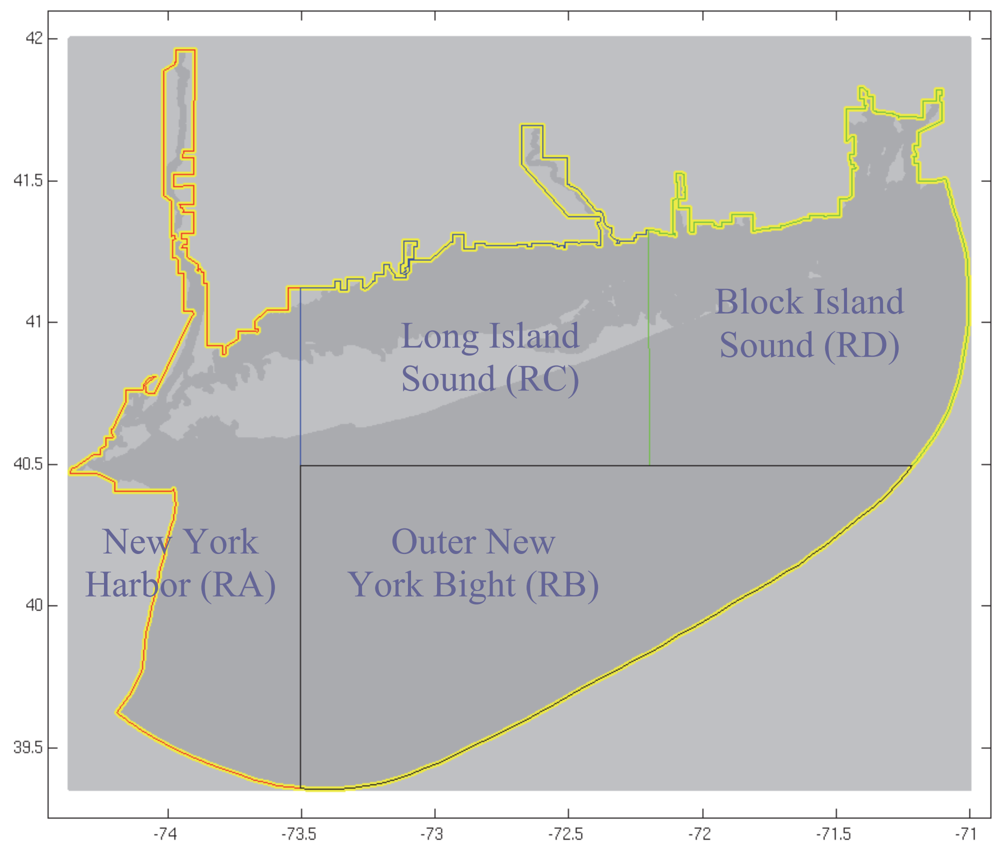


Figure 13. Distribution of VDatum marine grid points. Dark grey area represents water points populated with tidal datums and light grey area denotes those assigned with null values (i.e., land). Yellow line illustrates the marine grid bounding polygon. Color lines (red, blue, green, and black) delineate the four VDatum bounding polygons for the New York Harbor, Long Island Sound, Block Island Sound, and Outer New York Bight regions.

Table 2. Marine Grid Parameters for New York Harbor, Long Island Sound, Block Island Sound, and Outer New York Bight.

	Region	*Longitude$_0$ (degree)*	*Latitude$_0$ (degree)*	*del_lon (degree)*	*del_lat (degree)*	*N_lon*	*N_lat*
RA	New York Harbor	285.6341 (-74.3659)	39.3553	0.0017	0.0017	628	1557
RB	Outer New York Bight	286.3005 (-73.6995)	39.3553	0.0017	0.0017	1589	674
RC	Long Island Sound	286.3005 (-73.6995)	40.5011	0.0017	0.0017	706	785
RD	Block Island Sound	287.5007 (-72.4993)	40.5011	0.0017	0.0017	883	785

4.2. Population of VDatum Grid with Tidal Datums

Tidal datums on the Vdatum marine grid were populated by interpolating TCARI-corrected model values (Section 3.6) using the algorithm of Hess and White (2004). Datums on each VDatum marine grid point were calculated by averaging or linearly interpolating those within a user-specified searching radius or the closest user-specified number of points. In the present case, the interpolation was accomplished using the FORTRAN program vpop10.f. It populates marine points differently depending on whether the point is inside/outside of ADCIRC grid elements. If the point is inside an element, datums were calculated by interpolating values from the element's three vertices; if the point lies outside of any elements, datums were computed using the inverse distance weighting of the closest two node values. Compared with tidal datums from 123 observation stations, maximum errors are 1.8 cm for MHHW, 1.8 cm for MHW, 1.4 cm for MLW, and 1.4 cm for MLLW.

Figures 14a-f display the populated MHHW, MHW, MLW, MLLW, MTL, and DTL on the VDatum marine grid. Tidal datum fields demonstrate significant spatial variability. For the LIS area, tidal range (MHW-MLW) was around 0.8 m at the Sound's eastern end and increased to nearly 2.4 m at the western end near the East River. In the NB region, tidal range increased by twofold from about 1.2 m at the Bay mouth to 2.4 m in the upper Bay. Compared to the former two, the NYH region seems to belong to a different tidal regime. The tides demonstrated quite homogeneous tidal datum fields with a tidal range of about 1.6 m.

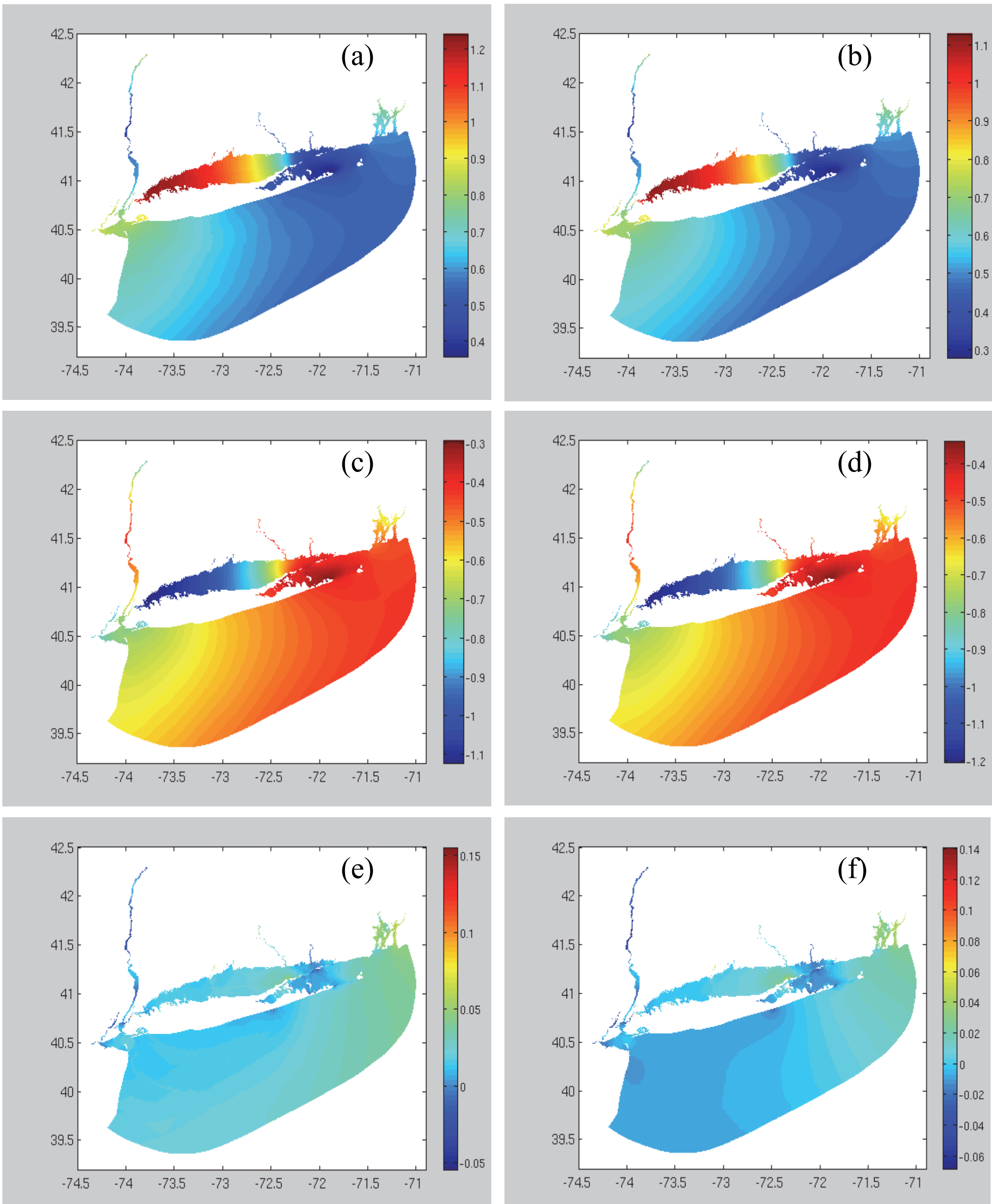


Figure 14. Tidal datum fields on the VDatum marine grid, (a) MHHW, (b) MHW, (c) MLW, (d) MLLW, (e) MTL, and (f) DTL. Color bars are in meters.

4.3. Comparison with Previous Results

Tidal datum fields for the Long Island Sound, Narragansett Bay, New York Harbor, New York Bight areas (referred to as LIS-NY in the following) were developed in this project. It is noted that a portion of the present domain overlaps with that of a previously developed New York Bight (NYB) VDatum project (Hess, 2001). Figure 15 illustrates the two domains. In the figure the shaded area represents LIS-NY marine grid points and the red line denotes the NYB domain. The two domains overlap over outer New York Bight and Lower Bay; in the figure, this overlap area is shown as the shaded area west of transect BB' and north of transect CC'.

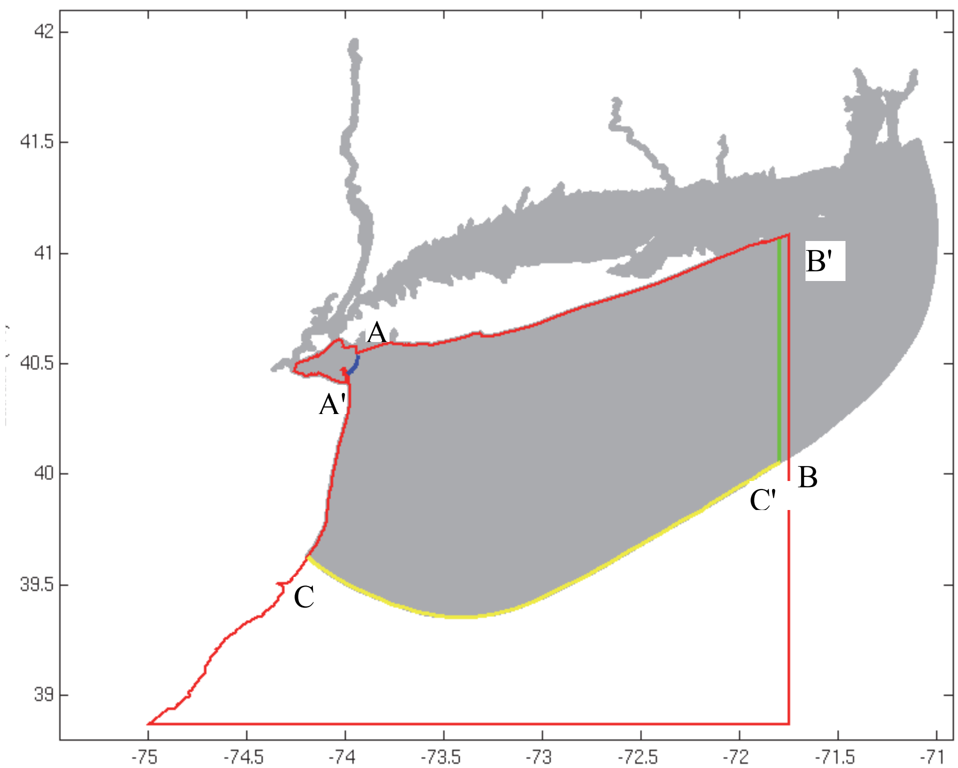


Figure 15. Coverage of the LIS-NY (shaded area) and NYB (polygon area outlined by red line) marine grid areas and locations of three transects, AA', BB', CC' along which tidal datums from LIS-NY and NYB are compared.

Since datum fields for the two regions were developed separately through different approaches, they are not necessarily matched seamlessly along CC'. Existence of any significant discrepancy would be physically unrealistic, and would lead to VDatum not being seamless across these regions. Hence it is necessary to compare the two sets of results and determine how to match the two products.

Three characteristic transects (AA', BB', and CC' in Figure 15) are selected for the comparison. Transect AA' corresponds to locations near the entrance to the Lower Bay west of New York Bight, and BB' and CC' represent, respectively, the southern and eastern borders of the NYB marine grid. Comparisons along the three transects should provide insight into the level of agreement between the LIS-NY and NYB results along their west, east, and south boundaries, respectively.

Along each transect, locations where marine grid points from both LIS-NY and NYB coincide were selected as locations for comparison (Figure 15). The points are roughly equally-distanced. Four tidal datums (MHHW, MHW, MLW, and MLLW) of LIS_NY and NYB are separately interpolated onto these locations. Figures 16.1-4 displays, respectively, MHHW, MHW, MLW, and MLLW along the three transects. Table 3 lists the root mean square (rms) of the datum differences between the LIS-NY and NYB regions. Along the three transects, MLLW demonstrates the best match of the four datums, with rms differences between 0.786 cm (transect CC') and 2.635 cm (transect AA'); the other three datums exhibit similar degree of agreement but slightly greater rms differences of between 1.83 cm and 3.55 cm.

Table 3. The root mean square of differences between the LIS-NY and NYB tidal datums along three transects.

Transects	*MHHW (cm)*	*MHW (cm)*	*MLW (cm)*	*MLLW (cm)*
AA'	2.34	3.04	2.98	1.25
BB'	3.20	3.01	3.55	2.64
CC'	1.83	2.58	1.97	0.79

On each plot of Figure 16, the abscissa represents node numbers counted from the beginning points of the three transects (Figure 15), i.e., A, B, or C respectively for transects AA', BB', and CC'. As indicated in Figure 16.1-4, datum differences are evenly distributed with gradual variation along transects AA' and CC', as well as most of transect BB'. For the latter, datum differences exhibit dramatic changes and display significant magnitudes close to its north end (Montauk Point). The maximum difference for MHHW, MHW, MLW, MLLW are 10.0 cm, 9.2 cm, 6.6 cm, and 8.6 cm, respectively. The reason for the evidently large differences could be associated with different degrees of proximity of the two model coastlines to the true coastline near the Point. Large coastline curvature near the Point heavily affects tidal fields and introduces dramatic spatial variability in tidal datum fields (Figure C.1). Therefore, even a small discrepancy in the two model coastlines can result in significant differences in the resulting tidal datum fields.

Comparison along transect CC′ is of major interest, since of the three transects only CC' represents an intersection between a LIS-NY boundary and the NYB domain. Datum matches along CC' is crucial for a seamless transition between the two domains. In fact, the LIS-NY and NYB datums demonstrate good agreement along CC′. Maximum magnitudes of MHHW, MHW, MLW, MLLW differences are 2.93 cm, 3.58 cm, 3.84 cm, and 2.20 cm, respectively. The rms differences for the same four datums are 1.83 cm, 2.58 cm, 1.97 cm, and 0.79 cm, respectively.

It is noted that the NYB results are planed to be phased out. For the overlapping area north of transect CC' (Figure 15), the present LIS-NY results will apply. VDatum for the rest of the NYB area (south of transect CC') will be updated by those from a combined Chesapeake Bay and Delaware Bay (CHK-DEL) project currently under development (Yang, et al., unpublished manuscript). Note that in developing the CHK-DEL VDatum, information of the LIS-NY tidal datums along their common border (transect CC') will be incorporated into the TCARI (Section 3.6) adjustment procedures (Yang, et al., 2003) and therefore a seamless datum match across CC’ will be obtained. The potential tidal datum mismatches demonstrated in Figure 16 will be avoided.

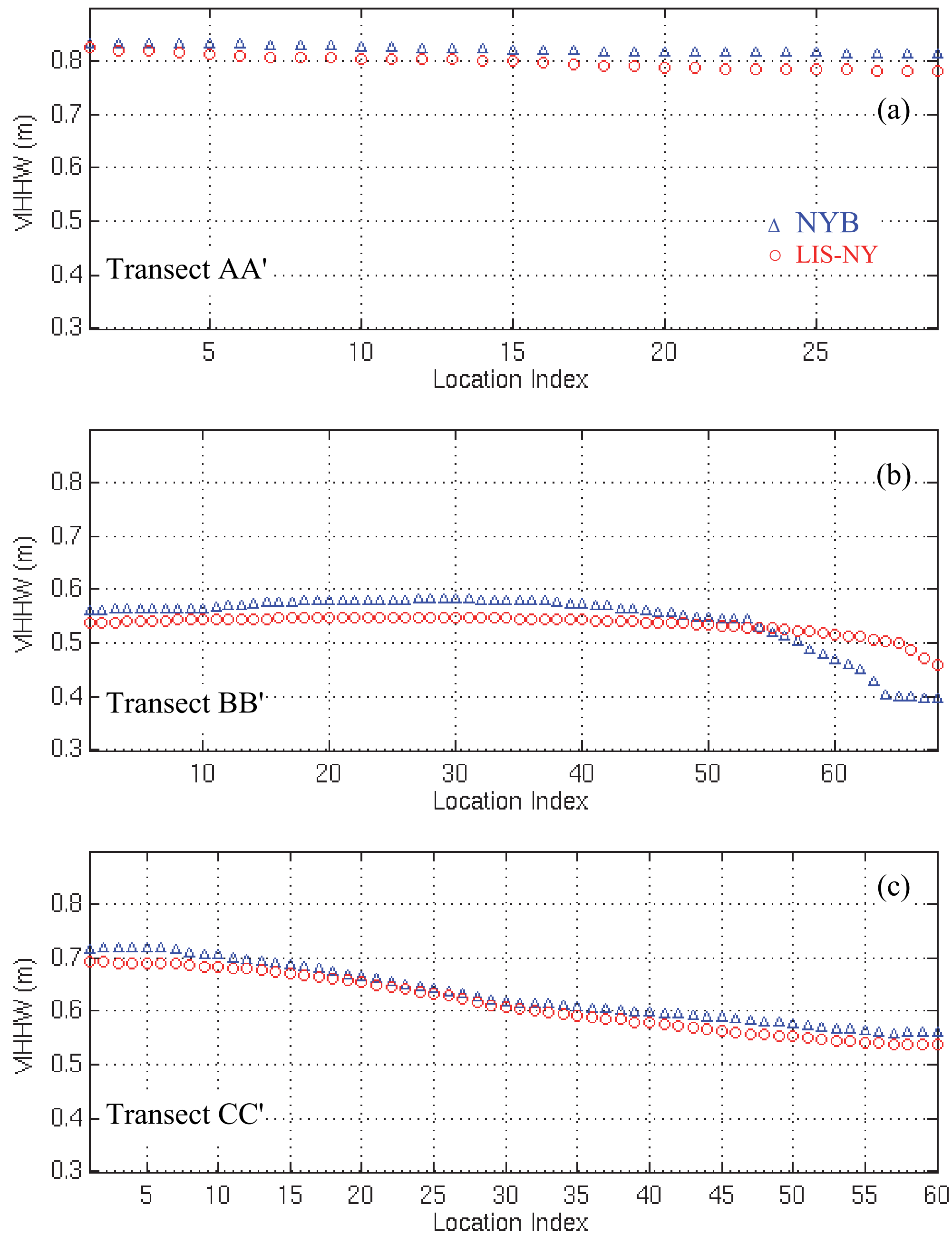


Figure 16.1. Comparisons of the LIS-NY and NYB MHHW along transects (a) AA', (b) BB', and (c) CC'. Location index represents indices of data points relative to the starting point (A, B, or C) of each transect.

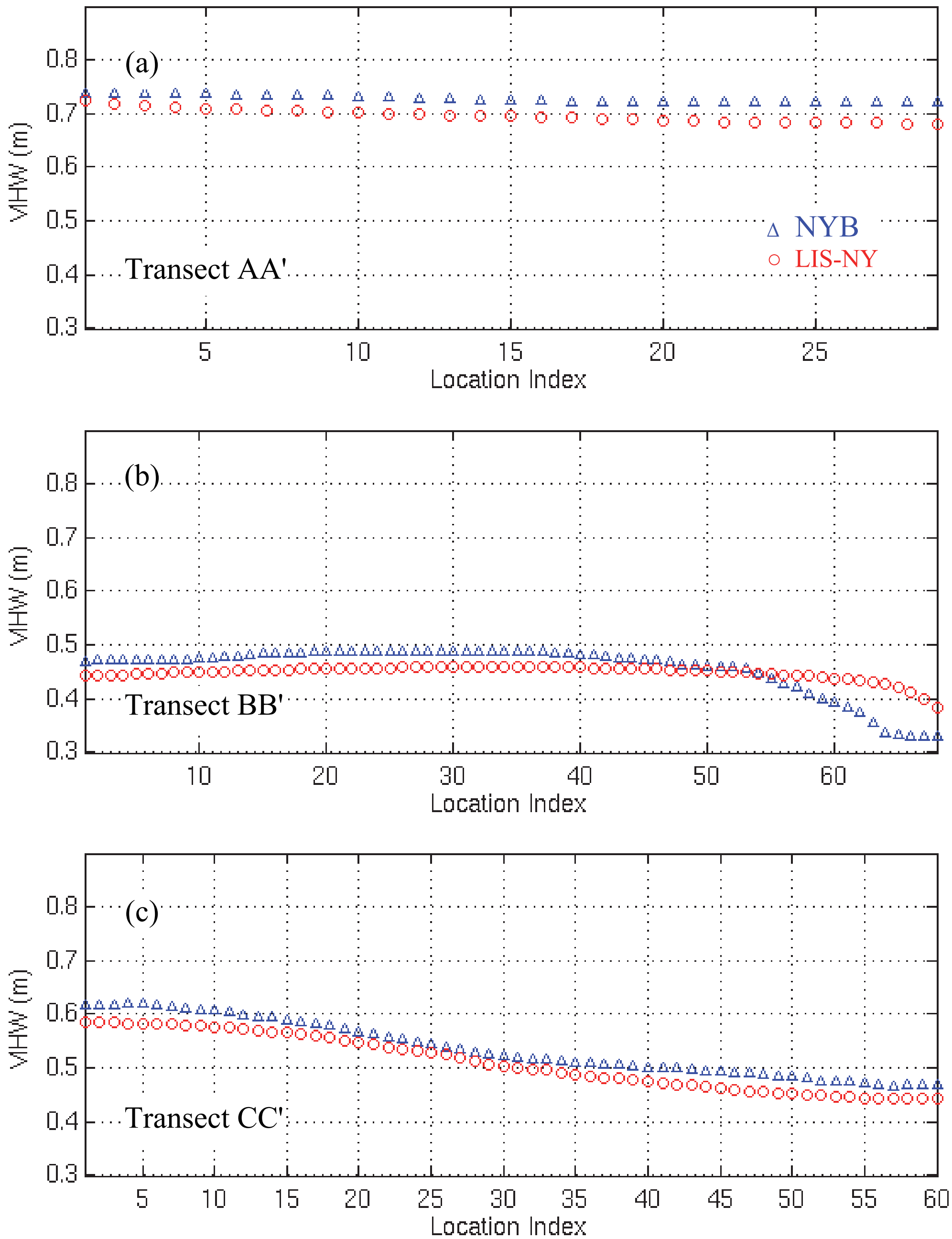


Figure 16.2. Comparisons of the LIS-NY and NYB MHW along transects (a) AA', (b) BB', and (c) CC'. Location index represents indices of data points relative to the starting point (A, B, or C) of each transect.

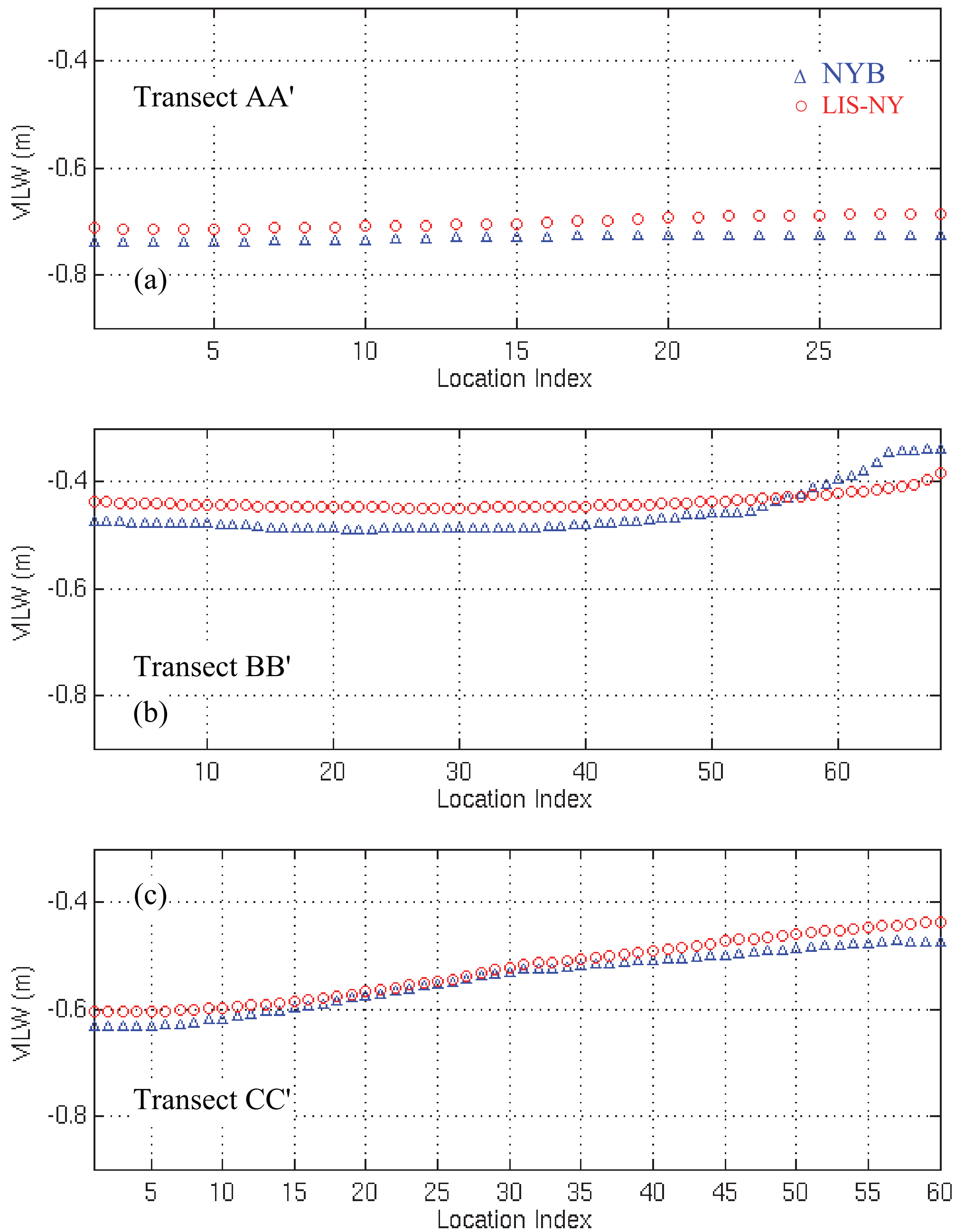
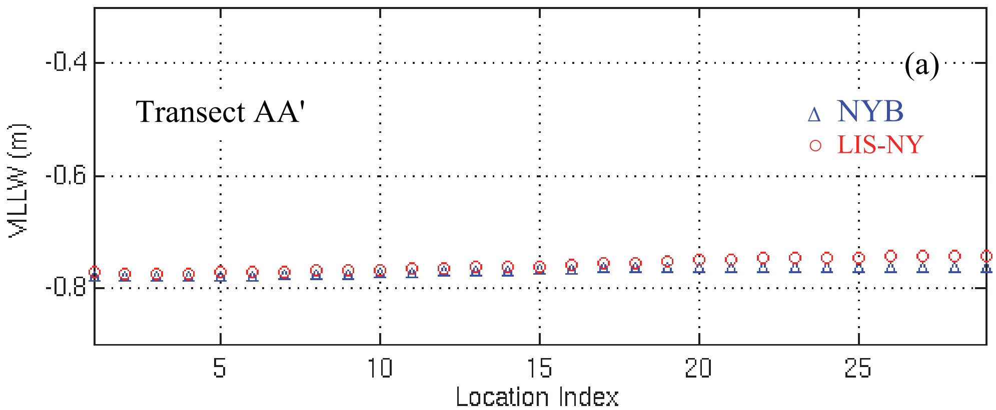
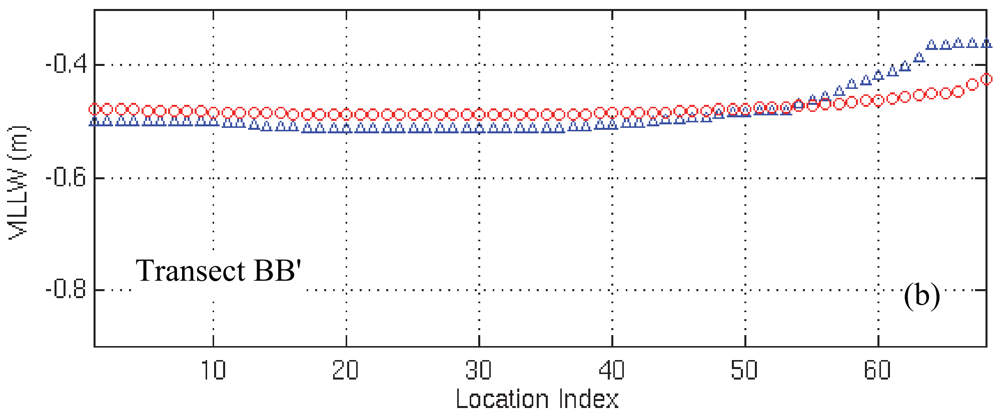


Figure 16.3. Comparisons of the LIS-NY and NYB MLW along transects (a) AA', (b) BB', and (c) CC'. Location index represents indices of data points relative to the starting point (A, B, or C) of each transect.





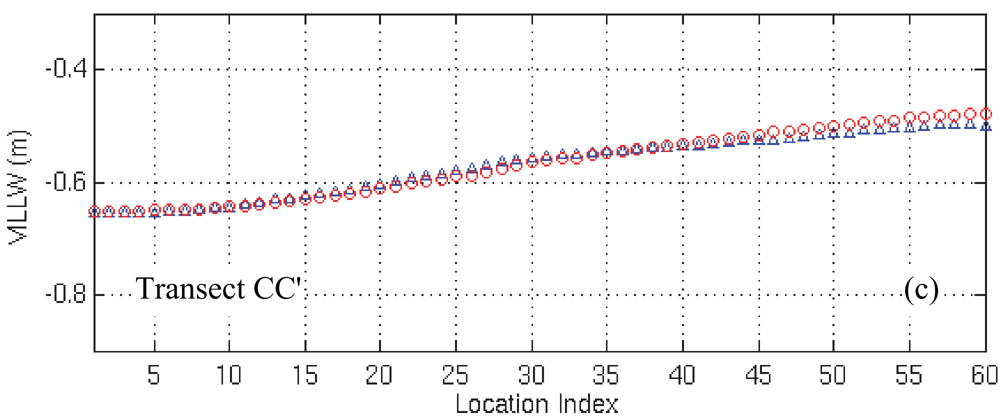


Figure 16.4. Comparisons of the LIS-NY and NYB MLLW along transects (a) AA', (b) BB', and (c) CC'. Location index represents indices of data points relative to the starting point (A, B, or C) of each transect.

5. TOPOGRAPHY OF THE SEA SURFACE

The Topography of the Sea Surface (TSS) is defined as the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to local mean sea level (LMSL). The TSS field is created by combining datum values at NGS benchmark locations with model results. The location of tide gauges and tidal benchmarks used in generating the TSS are illustrated in Figure 17. At each NGS benchmark location, there is a set of TBM_{datum} values, which is the elevation at the Tidal Benchmark of a datum relative to MLLW (i.e., Datum – MLLW). Table E.2 in Appendix E lists the differences for each tidal datum at NGS benchmarks. Also, from the four tidal datum grids (see Section 4), we have a set of VD_{datum} values, which are the difference between the tidal datum and MSL (i.e., Datum – MSL).

For the first step, we compute four residuals, which are defined separately for MHHW, MHW, MLW, and MLLW as:

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

Note that the VD values are interpolated to the location of the benchmark. The four residuals at the benchmark are averaged to produce the mean. Note that this mean is an estimate of the quantity MSL – NAVD88.

Next, a gridded sea surface topography field is generated. The mean residuals at all benchmarks are merged with (NAVD88-MSL) values at CO-OPS' water level stations to produce input data for contouring. A mesh covering the entire area of benchmarks and water level stations with a spatial resolution similar to that of the tidal datum marine grid is created (see Figure 18). Breaklines are inserted to represent the influence of land. A sea surface topography field is generated using the Surfer© software's minimum curvature algorithm to create a surface that honors the data as closely as possible. The maximum allowed departure value used was 0.0001 meters. To control the amount of bowing on the interior and at the edges of the grid, an internal and boundary tension value of 0.3 was utilized. Once the gridded topography field has been generated, null values are obtained from the marine tidal grids and are inserted to denote the presence of land.

Then a set of 'Delta' values are computed. Delta represents the difference between the observed tidal datum (see Table E.2 in Appendix E for a list of observation stations) and the datum as computed by the gridded fields. If S represents the value of the quantity NAVD88 – MSL obtained from the sea surface topography grid, then Delta (D) for each tidal datum is computed as:

$$-D_{datum} = TBM_{navd88} - TBM_{datum} + VD_{datum} - S$$

The averaged Delta at each benchmark should be less than 0.01 m. If it is not, the input data and grids are checked, appropriate changes are made, and the Deltas are recomputed until the criterion is met. This process resulted in the TSS field shown in Figure 18.

Tables E.1 and E.2 in Appendix E provide comparison of derived LIS TSS with observations and error analysis results, respectively.

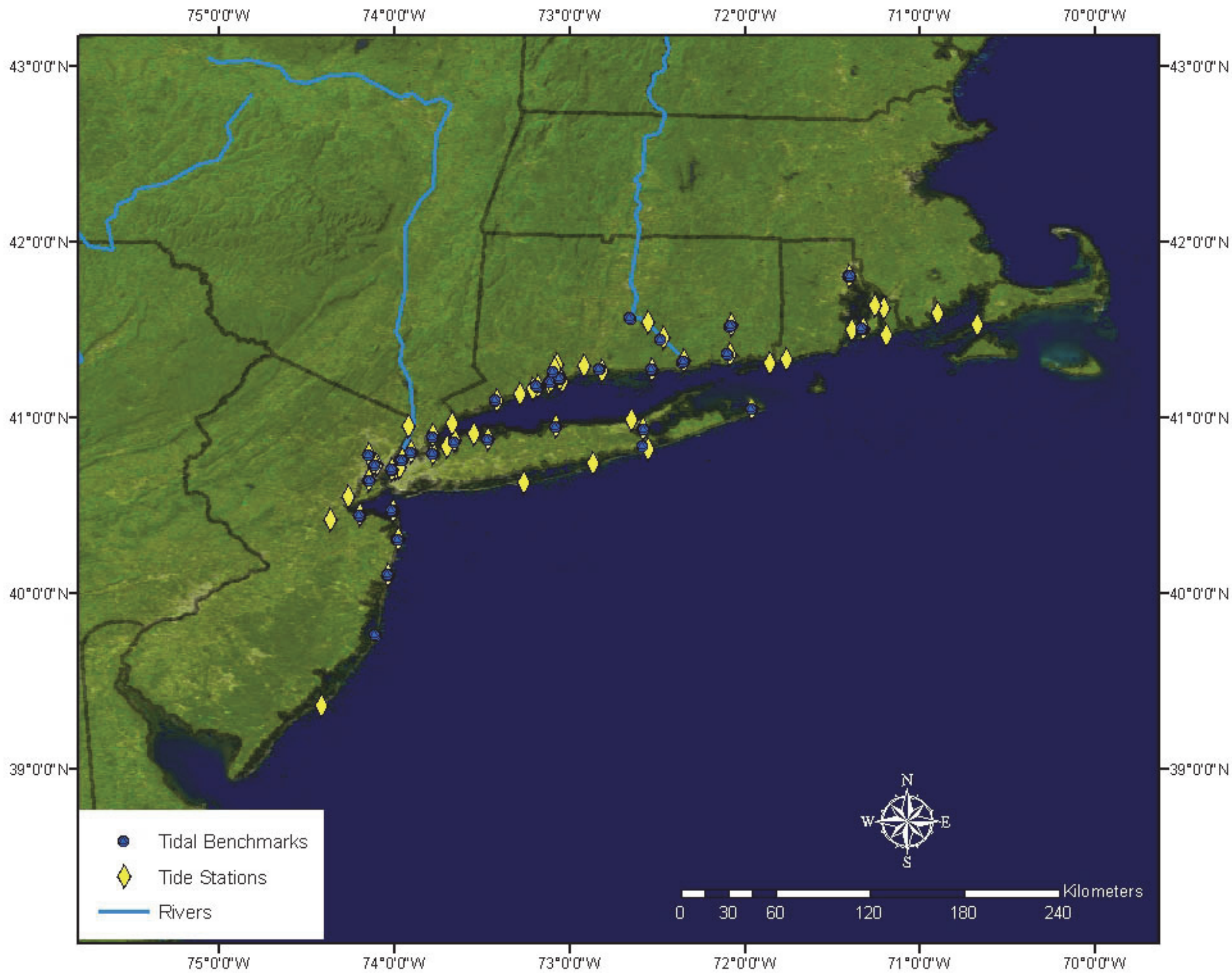


Figure 17. Location of tidal benchmarks and tide stations used to compute the TSS grid.

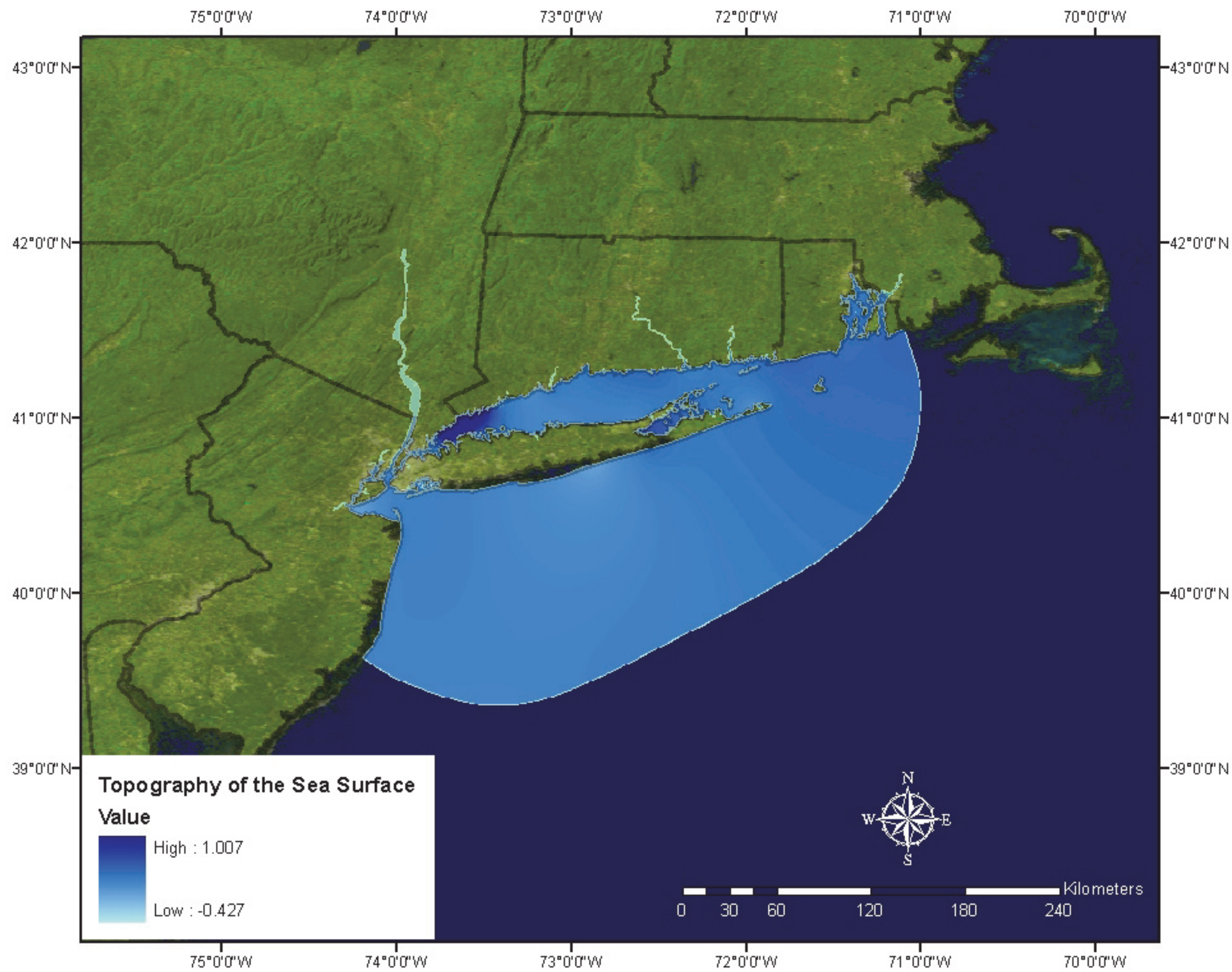


Figure 18. The TSS field withhin the VDatum domain. The TSS values are labeled in meters.

6. SUMMARY

In support of development of the national vertical datum software tool, VDatum, tidal datum and TSS fields for an area covering the Long Island Sound, Narragansett Bay, and New York Bight were developed in this study. Tidal datum fields were created by simulating tidal level time histories using the ADCIRC hydrodynamic model. The model domain was represented with an unstructured, triangular-element grid of 181,798 nodes and 333,910 elements. ADCIRC simulations were forced with harmonic constants of 7 tidal constituents on the model's open ocean boundary. At each grid node, a water level time series spanning 30 days was used to compute four tidal datums, MHHW, MHW, MLW, and MLLW.

Modeled results were verified by contrasting with observations at 123 NOAA's NOS water level stations. The average model-data discrepancy of the four datums was 3.8 cm, with a rms difference of 1.6 cm. The errors were interpolated over the whole model grid using the TCARI interpolation program. The resulting error fields were incorporated into the initial model results to derive the error-corrected tidal datum fields.

A regular VDatum marine grid was created to conform with the VDatum software tool. Tidal datums defined on the unstructured grid were interpolated onto the regular, marine grid to form the final datums as input to the VDatum tool. To compromise with the limitation of the VDatum software in handling large-size array, the whole marine grid was divided into four sections.

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

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APPENDIX A. SPECIFICATIONS OF BATHYMETRIC DATA

Table A.1. Sources and accuracy of bathymetry used for VDatum.

Source	Horizontal Resolution	Reported Horizontal Accuracy	Vertical Resolution	Reported Vertical Accuracy	Horizon tal Datum	Vertical Datum
Soundings from USACE surveys of channels, rivers, canals, and dredged areas	1:1200 to 1:48,000 usually	2 – 5 m [1]	coarser than 1 m [1]	0.25 – 1.0 ft at depths less than 15 ft 1.0 – 2.0 ft at depths greater than 15 ft [1]	NAD 83	by survey MLLW MLW, MLG, MLT
Soundings from the NOAA NOS Hydrographic Survey Data Base	1:5000 to 1:80,000 [2]	IHO and U.S. standards [3]	variable by survey	IHO and U.S. standards [3]	transfor med to NAD 83	by survey MLLW, MLW, usually
Soundings digitized from NOAA Navigational Charts or ENC	subsampled from survey source	less accurate than survey source	~0.1 m reported	less accurate than survey source	NAD 83 WGS 84	MLLW on charts after 1980 [4]

1 Table 3-1, U.S. Army Corps of Engineers Hydrographic Survey Manual, 2002.
2 1 cm spacing between sounding lines and 5-6 mm sounding density along lines at the scale of the survey. Soundings are twice as dense along lines than across lines.
3 See Table 3.2 below.
4 Original MLW and other tidal datums are designated as MLLW on NOAA navigational charts.
5 Depth values that were used to generate the CRM were non-uniformly georeferenced.
6 Smith, W.H.F. and D.T. Sandwell, 1997, Global Sea Floor Topography from Satellite Altimetry and Ship Depth Soundings, *Science* 277 (5334), p.1956-1962.

Table A.2. Minimum Accuracy Standards for Depth Measurements of NOAA Surveys.

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. Tidal and orthometric datums (meters) relative to mean sea level for NOS water level stations in Long Island Sound, New York Harbor, and Narragansett Bay area. The 'N/A's in the table denote missing values.

No.	Station ID #	Latitude (°N)	Longitude (°W)	MHHW (m)	MHW (m)	MLW (m)	MLLW (m)	NAVD88 (m)	Epoch Year
1	8447281	41.74	-71.1317	0.814	0.738	-0.634	-0.69	N/A	1983-2001
2	8447386	41.705	-71.1633	0.785	0.711	-0.618	-0.671	N/A	1983-2001
3	8447387	41.705	-71.1733	0.807	0.71	-0.625	-0.677	N/A	1960-1978
4	8450768	41.465	-71.1933	0.593	0.514	-0.453	-0.489	0.106	1983-2001
5	8450898	41.6517	-71.21	0.755	0.677	-0.593	-0.639	N/A	1983-2001
6	8450948	41.6383	-71.2117	0.699	0.617	-0.527	-0.581	N/A	1983-2001
7	8451301	41.5583	-71.2367	0.645	0.557	-0.479	-0.523	N/A	1983-2001
8	8451351	41.4867	-71.2383	0.589	0.518	-0.434	-0.474	N/A	1983-2001
9	8451552	41.6367	-71.255	0.752	0.676	-0.566	-0.616	N/A	1983-2001
10	8451929	41.6683	-71.28	0.719	0.634	-0.634	-0.683	N/A	1960-1978
11	8452154	41.6967	-71.2933	0.722	0.646	-0.646	-0.698	N/A	1960-1978
12	8452555	41.58	-71.3217	0.69	0.617	-0.522	-0.569	N/A	1960-1978
13	8452660	41.505	-71.3267	0.645	0.57	-0.487	-0.529	0.093	1983-2001
14	8452944	41.7167	-71.3433	0.756	0.68	-0.59	-0.639	N/A	N/A
15	8453033	41.7517	-71.3683	0.759	0.684	-0.61	-0.663	N/A	1983-2001
16	8453201	41.4633	-71.3617	0.611	0.537	-0.453	-0.497	N/A	1983-2001
17	8453465	41.5733	-71.3717	0.661	0.576	-0.573	-0.619	N/A	1960-1978
18	8453572	41.6667	-71.3783	0.72	0.64	-0.556	-0.602	N/A	1960-1978
19	8453733	41.7667	-71.3867	0.755	0.676	-0.677	-0.735	N/A	1960-1978
20	8453742	41.4967	-71.3867	0.639	0.567	-0.485	-0.529	N/A	1983-2001
21	8453999	41.4517	-71.4017	0.552	0.472	-0.546	-0.603	N/A	1983-2001
22	8454000	41.8067	-71.4017	0.79	0.715	-0.631	-0.686	0.068	1983-2001
23	8454049	41.585	-71.4083	0.683	0.609	-0.52	-0.567	N/A	1983-2001
24	8454341	41.46	-71.4283	0.625	0.548	-0.464	-0.502	N/A	1983-2001
25	8454658	41.4217	-71.455	0.576	0.497	-0.493	-0.533	N/A	1960-1978
26	8455083	41.3633	-71.49	0.562	0.485	-0.43	-0.468	N/A	1983-2001
27	8458022	41.3233	-71.7533	0.458	0.392	-0.378	-0.418	0.114	1983-2001
28	8458694	41.305	-71.86	0.457	0.374	-0.412	-0.457	0.096	1983-2001
29	8459338	41.1733	-71.5567	0.535	0.459	-0.411	-0.446	N/A	1983-2001
30	8459681	41.1583	-71.6133	0.482	0.408	-0.383	-0.418	N/A	1983-2001
31	8460469	41.335	-71.9117	0.521	0.427	-0.396	-0.46	N/A	N/A
32	8461392	41.5233	-72.0783	0.524	0.426	-0.497	-0.568	0.035	1983-2001
33	8461467	41.43	-72.0933	0.488	0.395	-0.438	-0.502	N/A	1983-2001
34	8461490	41.355	-72.0867	0.462	0.372	-0.409	-0.468	0.092	1983-2001
35	8461491	41.36	-72.0917	0.467	0.375	-0.411	-0.472	N/A	1960-1978
36	8461925	41.325	-72.1867	0.472	0.386	-0.398	-0.446	N/A	1983-2001
37	8462764	41.32	-72.3517	0.59	0.506	-0.503	-0.557	N/A	1983-2001
38	8463348	41.4517	-72.465	0.488	0.413	-0.412	-0.443	N/A	1983-2001
39	8463701	41.2683	-72.5317	0.801	0.709	-0.679	-0.751	0.103	1983-2001
40	8464041	41.27	-72.59	0.847	0.753	-0.756	-0.826	N/A	1960-1978
41	8464445	41.2717	-72.6667	0.887	0.792	-0.79	-0.86	N/A	1983-2001
42	8465233	41.2617	-72.8183	0.992	0.896	-0.886	-0.956	0.086	1983-2001
43	8465692	41.2517	-72.905	1.035	0.934	-0.93	-1.001	N/A	1983-2001
44	8465705	41.2833	-72.9083	1.034	0.936	-0.939	-1.013	N/A	1983-2001
45	8465748	41.2933	-72.9167	1.046	0.945	-0.948	-1.021	0.076	1983-2001

46	8466375	41.205	-73.0417	1.058	0.96	-0.957	-1.034	0.074	1983-2001
47	8466442	41.2183	-73.055	1.062	0.962	-0.964	-1.039	0.071	1983-2001
48	8466664	41.275	-73.0883	1.202	1.1	-0.987	-1.062	0.02	1983-2001
49	8466791	41.1867	-73.1133	1.091	0.991	-0.97	-1.043	0.185	1983-2001
50	8466797	41.2033	-73.1117	1.115	1.013	-0.993	-1.067	0.054	1983-2001
51	8467150	41.1733	-73.1817	1.127	1.025	-1.03	-1.104	0.067	1983-2001
52	8467373	41.1567	-73.2133	1.13	1.027	-1.031	-1.107	N/A	1983-2001
53	8467726	41.1333	-73.2833	1.143	1.041	-1.043	-1.117	0.051	1983-2001
54	8468448	41.0967	-73.415	1.174	1.07	-1.084	-1.163	0.05	1983-2001
55	8468609	41.065	-73.445	1.181	1.076	-1.086	-1.164	N/A	1983-2001
56	8468799	41.0383	-73.48	1.2	1.092	-1.091	-1.162	N/A	1983-2001
57	8469549	41.0167	-73.5967	1.214	1.095	-1.094	-1.173	N/A	1960-1978
58	8510321	41.07	-71.8583	0.442	0.365	-0.397	-0.427	N/A	1960-1978
59	8510448	41.0733	-71.935	0.393	0.306	-0.305	-0.357	N/A	1983-2001
60	8510560	41.0483	-71.96	0.393	0.306	-0.325	-0.377	0.02	1983-2001
61	8510719	41.2567	-72.03	0.427	0.338	-0.373	-0.434	N/A	1983-2001
62	8511171	41.035	-72.19	0.469	0.378	-0.378	-0.439	N/A	1960-1978
63	8511236	41.1717	-72.205	0.491	0.396	-0.396	-0.457	N/A	1960-1978
64	8512354	40.8367	-72.48	0.559	0.475	-0.535	-0.58	N/A	1983-2001
65	8512668	41.015	-72.5617	0.876	0.784	-0.77	-0.836	N/A	1983-2001
66	8512735	40.935	-72.5817	0.501	0.411	-0.438	-0.492	N/A	1983-2001
67	8512987	40.9817	-72.645	0.914	0.82	-0.812	-0.878	N/A	1983-2001
68	8514422	40.965	-73.0433	1.086	0.988	-0.976	-1.045	N/A	1983-2001
69	8514560	40.95	-73.0767	1.108	1.01	-1.005	-1.073	0.059	1983-2001
70	8515586	40.9	-73.3533	1.212	1.105	-1.111	-1.18	N/A	1983-2001
71	8515921	40.91	-73.4317	1.175	1.066	-1.078	-1.143	N/A	1983-2001
72	8516061	40.8733	-73.47	1.22	1.109	-1.114	-1.182	N/A	1983-2001
73	8516274	40.885	-73.5317	1.24	1.127	-1.098	-1.18	N/A	N/A
74	8516287	40.8833	-73.545	1.24	1.127	-1.098	-1.18	N/A	N/A
75	8516299	40.9033	-73.55	1.242	1.132	-1.122	-1.2	N/A	1983-2001
76	8516614	40.8633	-73.655	1.217	1.106	-1.11	-1.181	0.084	1983-2001
77	8516761	40.8317	-73.7033	1.212	1.103	-1.121	-1.203	N/A	1983-2001
78	8516945	40.81	-73.765	1.191	1.081	-1.1	-1.185	N/A	1983-2001
79	8516990	40.7933	-73.7817	1.191	1.08	-1.098	-1.182	0.058	1983-2001
80	8517125	40.7983	-73.8133	1.195	1.086	-1.082	-1.173	N/A	1960-1978
81	8517276	40.7833	-73.8567	1.14	1.03	-1.034	-1.119	N/A	1960-1978
82	8517667	40.7617	-73.9467	0.804	0.701	-0.671	-0.738	N/A	N/A
83	8517732	40.7067	-73.9733	0.756	0.653	-0.652	-0.722	N/A	1960-1978
84	8517811	40.59	-73.9983	0.826	0.723	-0.722	-0.792	N/A	1960-1978
85	8517921	40.665	-74.0133	0.823	0.72	-0.722	-0.786	N/A	1960-1978
86	8518051	41	-73.66	1.219	1.097	-1.098	-1.189	N/A	N/A
87	8518091	40.9617	-73.6717	1.222	1.112	-1.11	-1.183	N/A	1960-1978
88	8518490	40.8917	-73.7817	1.216	1.107	-1.115	-1.194	0.084	1983-2001
89	8518621	40.8	-73.8733	1.164	1.055	-1.055	-1.143	N/A	1960-1978
90	8518639	40.8017	-73.9067	1.059	0.952	-0.949	-1.03	0.043	1983-2001
91	8518643	40.8	-73.9283	0.805	0.704	-0.704	-0.777	N/A	1960-1978
92	8518668	40.7767	-73.9417	0.808	0.713	-0.714	-0.772	N/A	1960-1978
93	8518687	40.7583	-73.9583	0.751	0.65	-0.669	-0.733	0.061	1983-2001
94	8518695	40.7467	-73.9683	0.758	0.655	-0.659	-0.732	N/A	1960-1978
95	8518699	40.7117	-73.9683	0.719	0.62	-0.667	-0.727	0.066	1983-2001
96	8518750	40.7	-74.015	0.758	0.66	-0.72	-0.783	0.064	1983-2001
97	8518903	40.8783	-73.925	0.68	0.588	-0.585	-0.643	N/A	1960-1978

98	8518905	40.9033	-73.9167	0.68	0.588	-0.588	-0.649	N/A	1960-1978
99	8518924	41.2183	-73.9633	0.57	0.485	-0.498	-0.55	N/A	1960-1978
100	8519024	40.6067	-74.055	0.795	0.692	-0.695	-0.759	N/A	1960-1978
101	8519200	40.645	-74.18	0.85	0.747	-0.808	-0.878	N/A	1960-1978
102	8519436	40.5433	-74.14	0.805	0.702	-0.731	-0.792	N/A	N/A
103	8519483	40.64	-74.1467	0.834	0.736	-0.782	-0.846	0.054	1983-2001
104	8519789	40.5567	-74.2233	0.899	0.795	-0.796	-0.881	N/A	1960-1978
105	8530095	40.945	-73.9183	0.62	0.543	-0.6	-0.658	-0.022	1983-2001
106	8530505	40.8133	-73.9783	0.732	0.646	-0.646	-0.71	N/A	1960-1978
107	8530645	40.7667	-74.0183	0.759	0.667	-0.665	-0.735	N/A	1960-1978
108	8530696	40.7517	-74.0967	0.841	0.752	-0.855	-0.926	N/A	1983-2001
109	8530743	40.7317	-74.1167	0.866	0.771	-0.816	-0.884	N/A	1983-2001
110	8530772	40.7283	-74.1033	0.862	0.762	-0.827	-0.901	0.039	1983-2001
111	8530802	40.7167	-74.0317	0.762	0.67	-0.671	-0.732	N/A	N/A
112	8530882	40.6733	-74.14	0.848	0.744	-0.794	-0.856	N/A	1983-2001
113	8530986	40.655	-74.085	0.793	0.692	-0.719	-0.789	N/A	1960-1978
114	8531232	40.4917	-74.2817	0.859	0.755	-0.796	-0.863	N/A	1960-1978
115	8531262	40.5083	-74.3117	0.879	0.777	-0.812	-0.87	N/A	1983-2001
116	8531390	40.4783	-74.3567	0.898	0.798	-0.858	-0.929	N/A	1960-1978
117	8531545	40.44	-74.1983	0.842	0.741	-0.798	-0.863	0.031	1983-2001
118	8531592	40.4483	-74.1433	0.805	0.704	-0.704	-0.753	N/A	1960-1978
119	8531662	40.4183	-74.035	0.808	0.705	-0.731	-0.792	N/A	1960-1978
120	8531680	40.4667	-74.01	0.807	0.707	-0.727	-0.785	0.073	1983-2001
121	8531991	40.3033	-73.9767	0.76	0.655	-0.686	-0.744	0.075	1983-2001
122	8532337	40.185	-74.0083	0.765	0.658	-0.692	-0.744	N/A	1960-1978
123	8532591	40.1017	-74.035	0.706	0.605	-0.621	-0.676	0.063	1983-2001

Table B.2. NOS Water Level Station Names

No.	Station ID #	Station Name
1	8447281	STEEPBROOK
2	8447386	FALL RIVER HOPE BAY
3	8447387	BORDEN FLATS LIGHT MT
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 RIV
23	8454049	QUONSET POINT
24	8454341	BOSTON NECK
25	8454658	NARRAGANSETT PIER RI
26	8455083	POINT JUDITH HARBOR OF R
27	8458022	WEEKAPAUG POINT BLOCK ISL
28	8458694	WATCH HILL POINT
29	8459338	BLOCK ISLAND HARBOR OLD
30	8459681	BLOCK ISLAND SW END BLOCK
31	8460469	STONINGTON STONINGTON HBR
32	8461392	NORWICH THAMES RIVER CT
33	8461467	YALE BOATHOUSE THAMES RI
34	8461490	NEW LONDON THAMES RIVER C
35	8461491	NEW LONDON (BACKUP) CT
36	8461925	NIANTIC NIANTIC RIVER CT
37	8462764	LYME HWY BR CT RIVER CT
38	8463348	TYLERVILLE CONNECTICUT R
39	8463701	CLINTON CLINTON HARBOR
40	8464041	MADISON BEACH CLUB LONG I
41	8464445	GUILFORD GUILFORD HARBOR
42	8465233	BRANFORD BRANFORD RIVER C
43	8465692	LIGHTHOUSE POINT NEW HAV

44	8465705	NEW HAVEN NEW HAVEN HARB
45	8465748	NEW HAVEN
46	8466375	GULF BEACH
47	8466442	MILFORD HARBOR CT
48	8466664	MURPHY'S BOAT YARD HOUSAT
49	8466791	SNIFFENS POINT HOUSATONIC
50	8466797	I-95 BRIDGE HOUSATONIC RI
51	8467150	BRIDGEPORT BRIDGEPORT HAR
52	8467373	BLACK ROCK HARBOR CEDAR
53	8467726	SOUTHPORT SOUTHPORT HARB
54	8468448	SOUTH NORWALK NORWALK RI
55	8468609	ROWAYTON FIVEMILE RIVER C
56	8468799	LONG NECK PT LONG ISLAND
57	8469549	COSCOB HARBOR CT
58	8510321	MONTAUK POINT LIGHT NY
59	8510448	U S COAST GUARD STATION L
60	8510560	MONTAUK FORT POND BAY
61	8510719	SILVER EEL POND FISHERS
62	8511171	THREEMILE HARBOR ENTRANCE
63	8511236	PLUM ISLAND PLUM GUT HARB
64	8512354	SHINNECOCK INLET
65	8512668	MATTITUCK INLET LONG ISL
66	8512735	SOUTH JAMESPORT GREAT PE
67	8512987	NORTHVILLE FUEL DOCK LONG
68	8514422	CEDAR BEACH NY
69	8514560	PORT JEFFERSON NY
70	8515586	NORTHPORT NORTHPORT BAY N
71	8515921	LLOYD HARBOR LIGHTHOUSE
72	8516061	COLD SPRINGS HARBOR NY
73	8516274	FRIEDMAN PIER SITE #4 NY
74	8516287	GILMORE PIER SITE #4 NY
75	8516299	BAYVILLE BRIDGE OYSTER B
76	8516614	GLEN COVE YACHT CLUB LON
77	8516761	PORT WASHINGTON MANHASSS
78	8516945	KINGS POINT LONG ISLAND
79	8516990	WILLETS POINT LITTLE BAY
80	8517125	WHITESTONE NY
81	8517276	COLLEGE PT FT OF 110TH ST
82	8517667	CON EDISON DOCK 37TH AVE
83	8517732	WALLABOUT BAY BKLN NAVY Y
84	8517811	GRAVESEND BAY NORTON PT B
85	8517921	GOWANUS BAY NY
86	8518051	PORT CHESTER NY
87	8518091	RYE BEACH AMUSEMENT PARK
88	8518490	NEW ROCHELLE NY
89	8518621	HUNTS PT NY
90	8518639	PORT MORRIS EAST 138TH S

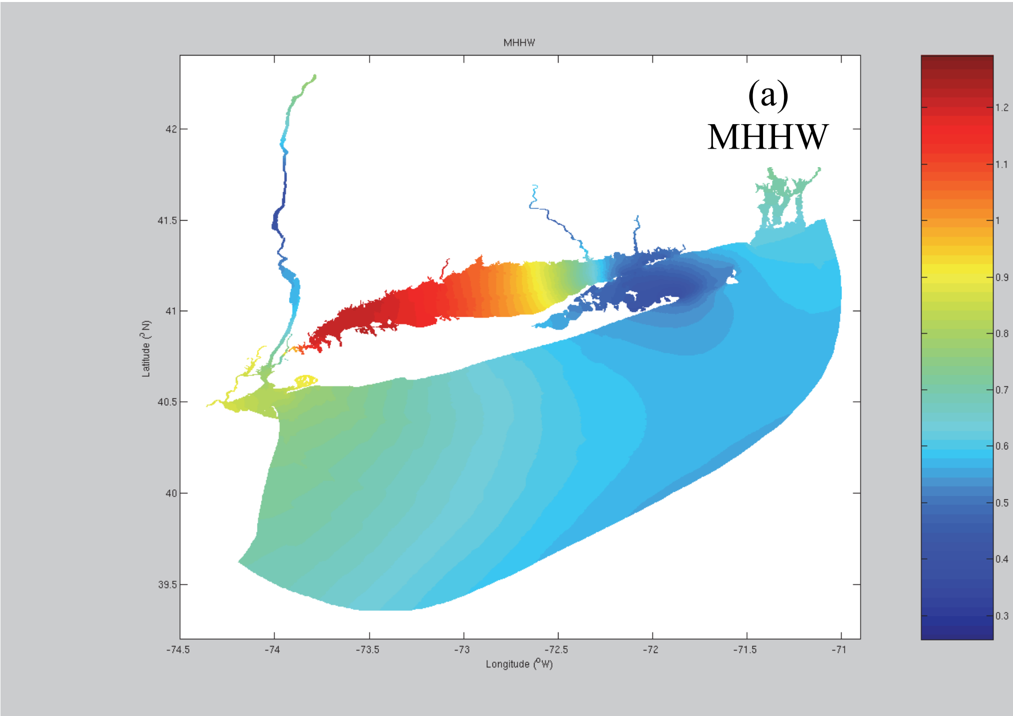
91	8518643	RANDALLS IS NY
92	8518668	HORNS HOOK E. 90TH STREE
93	8518687	QUEENSBORO BRIDGE EAST RI
94	8518695	EAST 41ST STREET PIER NY
95	8518699	WILLIAMSBURG BRIDGE
96	8518750	THE BATTERY NEW YORK HAR
97	8518903	SPUYTEN DUYVIL CK ENT HUD
98	8518905	RIVERDALE HUDSON RIVER NY
99	8518924	HAVERSTRAW BAY
100	8519024	FORT WADSWORTH STATEN ISL
101	8519200	PORT IVORY ARTHUR KILL NY
102	8519436	GREAT KILLS HARBOR NY
103	8519483	BERGEN POINT WEST REACH K
104	8519789	ROSSVILLE STATEN ISLAND N
105	8530095	ALPINE HUDSON RIVER
106	8530505	EDGEWATER HUDSON RIVER NJ
107	8530645	UNION CITY HUDSON RIVER N
108	8530696	BELLEVILLE TPKE HACKENSA
109	8530743	POINT NO POINT PASSAIC R
110	8530772	KEARNY POINT HACKENSACK R
111	8530802	JERSEY CITY PA-RR FERRY N
112	8530882	PORT ELIZABETH NEWARK BA
113	8530986	CONSTABLE HOOK UPPER BAY
114	8531232	SOUTH AMBOY RARITAN RIVER
115	8531262	KEASBEY RARITAN RIVER
116	8531390	SAYREVILLE RARITAN RIVER
117	8531545	KEYPORT RARITAN BAY
118	8531592	WAACKAACK CK RARITAN BAY
119	8531662	ATLANTIC HIGHLANDS SANDY
120	8531680	SANDY HOOK
121	8531991	LONG BRANCH FISHING PIER
122	8532337	BELMAR OUTSIDE NJ
123	8532591	MANASQUAN INLET NJ

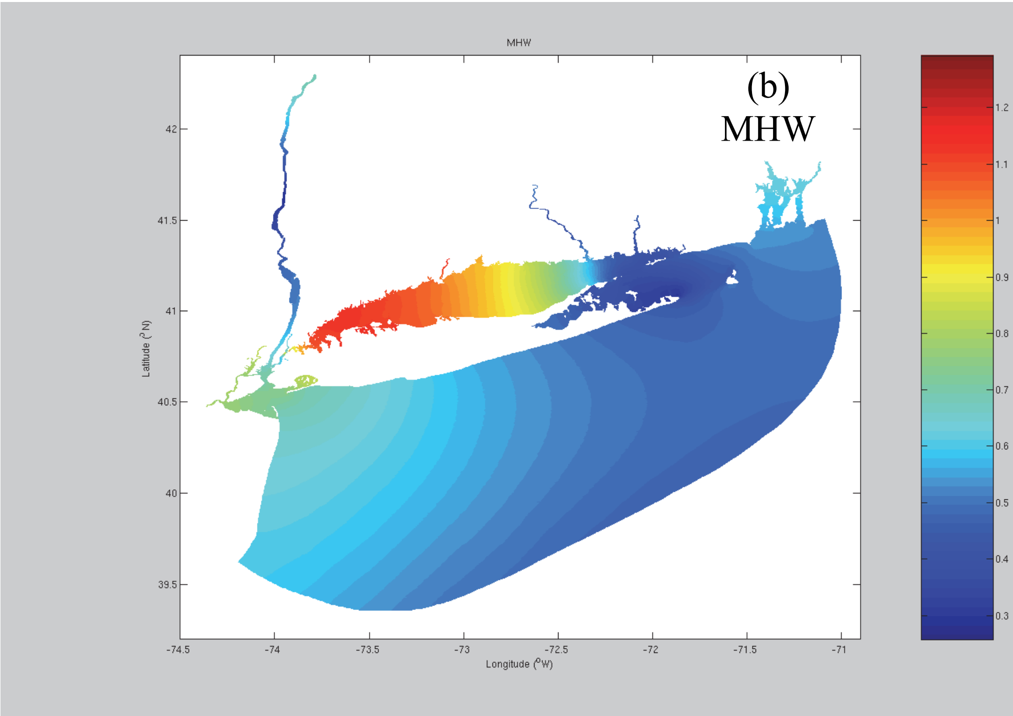
Table B.3. Comparisons of tidal range at stations updated from the 1960-1978 National Tidal Datum Epoch (NTDE) to the 1983-2001 NTDE.

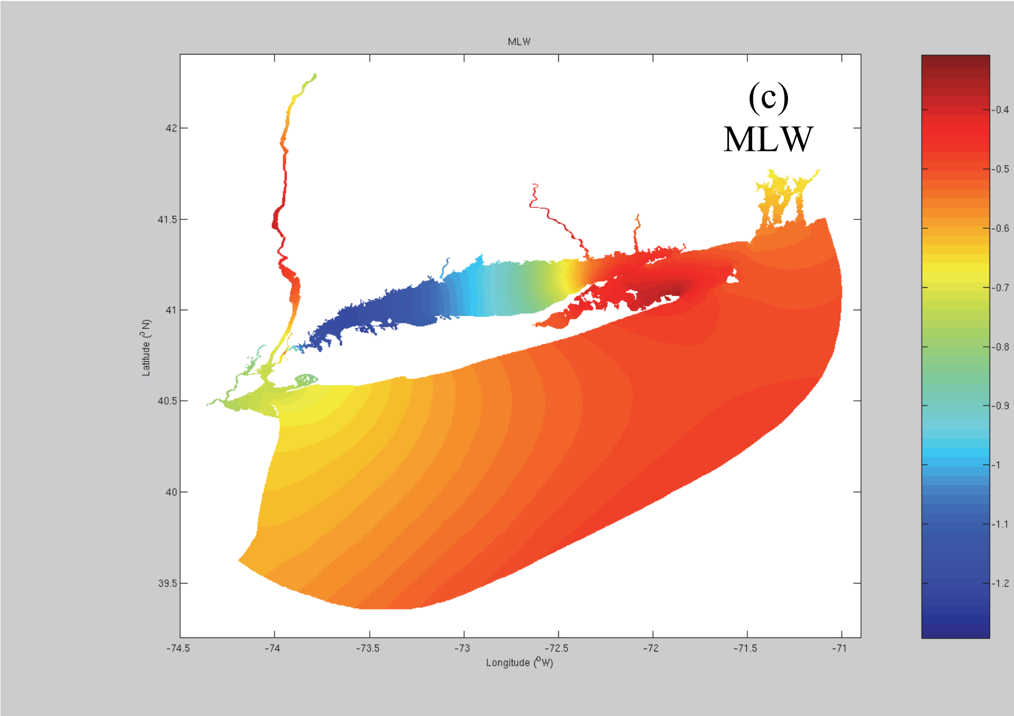
No.	Station ID	Range (m) 1960-1978	Range (m) 1983-2001	Ratio (%)	Difference (m)	Percentage (%)
1	8447281	1.542	1.504	0.975	-0.038	2.514
2	8447386	1.494	1.456	0.975	-0.038	2.544
3	8450768	1.106	1.082	0.978	-0.024	2.232
4	8450898	1.42	1.394	0.981	-0.026	1.874
5	8450948	1.311	1.28	0.977	-0.031	2.365
6	8451301	1.189	1.168	0.983	-0.021	1.758
7	8451351	1.082	1.063	0.982	-0.019	1.775
8	8451552	1.402	1.368	0.976	-0.034	2.461
9	8452660	1.195	1.174	0.983	-0.021	1.757
10	8453033	1.453	1.422	0.979	-0.031	2.157
11	8453201	1.125	1.108	0.985	-0.017	1.497
12	8453742	1.189	1.168	0.983	-0.021	1.758
13	8453999	1.173	1.155	0.984	-0.018	1.587
14	8454000	1.512	1.476	0.976	-0.036	2.397
15	8454049	1.275	1.25	0.98	-0.025	1.98
16	8454341	1.146	1.127	0.983	-0.019	1.676
17	8455083	1.049	1.03	0.982	-0.019	1.781
18	8458022	0.892	0.876	0.982	-0.016	1.81
19	8458694	0.92	0.914	0.993	-0.006	0.708
20	8459338	1	0.981	0.981	-0.019	1.893
21	8459681	0.916	0.9	0.983	-0.016	1.762
22	8461392	1.1	1.092	0.992	-0.008	0.76
23	8461467	1	0.99	0.99	-0.01	0.979
24	8461490	0.939	0.93	0.991	-0.009	0.94
25	8461925	0.933	0.918	0.984	-0.015	1.621
26	8462764	1.155	1.147	0.993	-0.008	0.712
27	8463348	0.939	0.931	0.992	-0.008	0.833
28	8464445	1.743	1.747	1.002	0.004	0.229
29	8465233	1.951	1.948	0.999	-0.003	0.14
30	8465692	2.039	2.036	0.998	-0.003	0.153
31	8465705	2.049	2.047	0.999	-0.002	0.098
32	8465748	2.067	2.067	1	0	0.022
33	8466375	2.094	2.092	0.999	-0.002	0.094
34	8466442	2.103	2.101	0.999	-0.002	0.101
35	8466664	2.268	2.264	0.998	-0.004	0.177
36	8466791	2.136	2.134	0.999	-0.002	0.094
37	8466797	2.184	2.182	0.999	-0.002	0.092
38	8467150	2.234	2.231	0.999	-0.003	0.143
39	8468609	2.35	2.345	0.998	-0.005	0.213
40	8468799	2.356	2.362	1.003	0.006	0.25
41	8510448	0.771	0.75	0.973	-0.021	2.761
42	8510560	0.789	0.77	0.975	-0.019	2.492
43	8510719	0.863	0.861	0.998	-0.002	0.184

44	8512354	1.152	1.139	0.989	-0.013	1.147
45	8512735	1.027	0.993	0.967	-0.034	3.383
46	8512987	1.814	1.792	0.988	-0.022	1.196
47	8514422	2.137	2.131	0.997	-0.006	0.265
48	8514560	2.185	2.181	0.998	-0.004	0.202
49	8515586	2.39	2.392	1.001	0.002	0.099
50	8515921	2.316	2.318	1.001	0.002	0.066
51	8516061	2.396	2.402	1.003	0.006	0.261
52	8516299	2.435	2.442	1.003	0.007	0.273
53	8516614	2.393	2.398	1.002	0.005	0.222
54	8516761	2.411	2.415	1.002	0.004	0.167
55	8516945	2.373	2.376	1.001	0.003	0.126
56	8516990	2.371	2.373	1.001	0.002	0.084
57	8518490	2.405	2.41	1.002	0.005	0.213
58	8518639	2.087	2.089	1.001	0.002	0.096
59	8518687	1.496	1.484	0.992	-0.012	0.805
60	8518699	1.466	1.446	0.986	-0.02	1.374
61	8518750	1.561	1.541	0.987	-0.02	1.289
62	8519483	1.695	1.68	0.991	-0.015	0.889
63	8530095	1.292	1.278	0.989	-0.014	1.117
64	8530696	1.783	1.767	0.991	-0.016	0.906
65	8530743	1.771	1.75	0.988	-0.021	1.187
66	8530772	1.786	1.763	0.987	-0.023	1.296
67	8530882	1.719	1.704	0.991	-0.015	0.881
68	8531262	1.747	1.749	1.001	0.002	0.143
69	8531545	1.695	1.705	1.006	0.01	0.607
70	8531680	1.585	1.592	1.004	0.007	0.441
71	8531991	1.5	1.504	1.003	0.004	0.266
72	8532591	1.375	1.382	1.005	0.007	0.533

APPENDIX C. TCARI-CORRECTED TIDAL FIELDS ON THE UNSTRUCTURED MODEL GRID







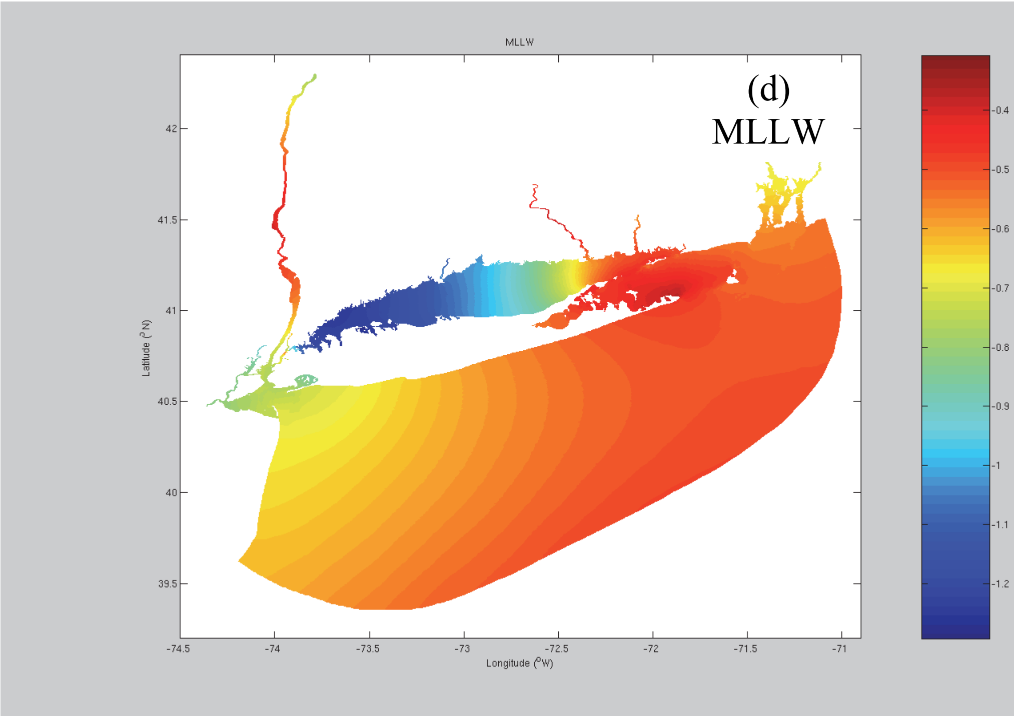


Figure C.1. Corrected tidal datum fields on the unstructured grid, (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW, relative to MSL. Color bars are in meters.

APPENDIX D. TIDAL GAUGE AND BENCHMARKS DATA USED TO CREATE THE TSS

Table D.1. Derived NAVD 88-to-LMSL values for each tidal datum at NGS benchmarks from the Long Island Sound Tidal Grids.

Bench-mark	Latitude	Longitude	From MLLW (m)	From MLW (m)	From MHW (m)	From MHHW (m)	Average (m)	Std. Dev. (m)
LW0832	41.04722	-71.9583	0.0177	0.0185	0.0149	0.0129	0.0160	0.0026
LW0831	41.04805	-71.9572	0.0629	0.0636	0.0598	0.0577	0.0610	0.0028
LW0833	41.05138	-71.9578	0.1038	0.1045	0.0988	0.0967	0.1010	0.0038
LX0101	41.31777	-72.3503	0.0808	0.0808	0.0658	0.0676	0.0738	0.0082
LX0102	41.32111	-72.3511	0.0569	0.0565	0.0451	0.0485	0.0518	0.0059
LX0157	41.35944	-72.0911	0.0938	0.0961	0.0952	0.0977	0.0957	0.0016
AH9447	41.505	-71.3267	0.089	0.0902	0.098	0.0973	0.0936	0.0047
AH9448	41.505	-71.3267	0.089	0.0902	0.098	0.0973	0.0936	0.0047
LW0491	41.50611	-71.3278	0.0862	0.0886	0.1044	0.1041	0.0958	0.0098
LW0493	41.50666	-71.3272	0.0872	0.0888	0.0994	0.0988	0.0936	0.0064
LW0489	41.5075	-71.3286	0.0788	0.0814	0.0999	0.0996	0.0899	0.0114
LX3397	41.52083	-72.0811	0.0392	0.04	0.0386	0.0386	0.0391	0.0007
LX3226	41.52388	-72.08	0.0326	0.0335	0.0328	0.0328	0.0329	0.0004
LW5205	41.80638	-71.4011	0.0677	0.0687	0.0662	0.0683	0.0677	0.0011
LW0150	41.80666	-71.4014	0.0647	0.0657	0.0632	0.0653	0.0647	0.0011
LW0152	41.80694	-71.4019	0.0645	0.0655	0.0629	0.0651	0.0645	0.0011
LW0154	41.80722	-71.3992	0.0638	0.0649	0.0621	0.0643	0.0638	0.0012
AH9453	41.8075	-71.4	0.0641	0.0651	0.0624	0.0646	0.0641	0.0012
KU1594	40.86277	-73.6544	0.0822	0.0838	0.0838	0.0827	0.0831	0.0008
KU1595	40.86277	-73.6539	0.0891	0.0907	0.0908	0.0897	0.0901	0.0008
KU1593	40.86305	-73.6544	0.0853	0.0868	0.0868	0.0858	0.0862	0.0007
KU0432	40.87555	-73.4692	0.0607	0.0627	0.0596	0.0616	0.0612	0.0013
KU0373	40.93416	-72.5769	0.1366	0.1369	0.1436	0.1427	0.1400	0.0037
KU0505	40.94777	-73.075	0.0453	0.0468	0.0462	0.0434	0.0454	0.0015
KU0506	40.95083	-73.0775	0.0636	0.065	0.0641	0.0612	0.0635	0.0016
AI1725	41.17333	-73.1817	0.0692	0.0701	0.0707	0.0686	0.0697	0.0009
LX2344	41.17555	-73.18	0.0663	0.0671	0.0675	0.0654	0.0666	0.0009
LX0885	41.20472	-73.1117	0.0619	0.0629	0.0642	0.0618	0.0627	0.0011
LX0470	41.27	-72.5283	0.1058	0.1041	0.106	0.1059	0.1055	0.0009
AI8467	40.44	-74.1961	0.0434	0.0441	0.0288	0.0309	0.0368	0.0081
KV0714	40.46111	-74.0042	0.0758	0.0783	0.075	0.0748	0.0760	0.0016
AB6711	40.4675	-74.01	0.0733	0.0747	0.0723	0.0715	0.0730	0.0014
KV3521	40.46777	-74.0089	0.0753	0.0765	0.0756	0.0747	0.0755	0.0008
KV0707	40.46805	-74.0083	0.0755	0.0767	0.0755	0.0747	0.0756	0.0008
KV0709	40.46805	-74.0086	0.0754	0.0766	0.0755	0.0747	0.0756	0.0008
KV3519	40.46833	-74.0069	0.0729	0.0741	0.0724	0.0716	0.0728	0.0010
AB6710	40.46861	-74.0103	0.08	0.0811	0.0744	0.074	0.0774	0.0037
KV0701	40.47111	-74.0119	0.0857	0.0862	0.0772	0.0767	0.0815	0.0052
KV2864	40.63777	-74.1464	0.0579	0.0581	0.0567	0.0571	0.0575	0.0007
KV0442	40.63833	-74.1444	0.0624	0.0627	0.0591	0.0599	0.0610	0.0018
KV0441	40.63861	-74.1431	0.0577	0.0581	0.0536	0.0545	0.0560	0.0023
AB6736	40.7	-74.015	0.0706	0.0694	0.063	0.0614	0.0661	0.0046
AB6737	40.7	-74.015	0.0736	0.0724	0.066	0.0644	0.0691	0.0046
KV0587	40.70083	-74.0156	0.0681	0.0673	0.0757	0.0727	0.0709	0.0040

KV0579	40.70333	-74.0142	0.0726	0.0718	0.0788	0.0764	0.0749	0.0033
KV0584	40.70416	-74.0158	0.074	0.0744	0.0814	0.0752	0.0762	0.0035
KU1418	40.75972	-73.9583	0.0687	0.0688	0.0774	0.0756	0.0726	0.0045
KU0976	40.79333	-73.7811	0.062	0.0611	0.0621	0.0599	0.0613	0.0010
KU0978	40.79416	-73.7811	0.0595	0.0587	0.059	0.0567	0.0585	0.0012
KU0979	40.79416	-73.7814	0.0597	0.0589	0.0591	0.0568	0.0586	0.0013
KU1012	40.80166	-73.9064	0.0525	0.0518	0.0472	0.0473	0.0497	0.0028
KU1013	40.80166	-73.9064	0.0435	0.0428	0.0382	0.0383	0.0407	0.0028
KU1726	40.89055	-73.7822	0.0874	0.0874	0.0899	0.0914	0.0890	0.0020
KU1724	40.89166	-73.7825	0.088	0.088	0.0895	0.0905	0.0890	0.0012

Table D.2. Location and elevation information for NOAA tide gauges used to create the TSS. Tidal datums and NAVD88 are relative to MLLW. Data are from CO-OPS. Station numbers marked with an asterisk have NAVD 88 elevations computed from NGS.

Bench-Mark	Latitude (deg)	Longitude (deg)	MLLW (m)	MLW (m)	MSL (m)	MHW (m)	MHHW (m)	NAVD88 (m)
8461392	41.52333	-72.07833	0.00	0.07	0.56	0.99	1.09	0.60
8461490	41.35500	-72.08667	0.00	0.05	0.46	0.84	0.93	0.56
8462764*	41.32167	-72.35000	0.00	0.05	0.55	1.06	1.14	0.61
8463348*	41.45167	-72.46500	0.00	0.03	0.44	0.85	0.93	0.38
8463701	41.26833	-72.53167	0.00	0.07	0.75	1.46	1.55	0.85
8463827*	41.54167	-72.55167	0.00	0.03	0.40	0.76	0.84	0.29
8465233	41.26167	-72.81833	0.00	0.07	0.95	1.85	1.94	1.04
8465748	41.29333	-72.91667	0.00	0.07	1.02	1.96	2.06	1.09
8466375	41.20500	-73.04167	0.00	0.07	1.03	1.99	2.09	1.10
8466442	41.21833	-73.05500	0.00	0.07	1.03	2.00	2.10	1.11
8466573	41.30167	-73.07167	0.00	0.07	1.08	2.20	2.31	1.10
8466664	41.27500	-73.08833	0.00	0.07	1.06	2.16	2.26	1.08
8466791	41.18667	-73.11333	0.00	0.07	1.04	2.03	2.13	1.22
8466797	41.20333	-73.11167	0.00	0.07	1.06	2.08	2.18	1.12
8467150	41.17333	-73.18167	0.00	0.07	1.10	2.12	2.23	1.17
8467373*	41.15667	-73.21333	0.00	0.07	1.10	2.13	2.23	1.16
8467726	41.13333	-73.28333	0.00	0.07	1.11	2.15	2.26	1.16
8468448	41.09667	-73.41500	0.00	0.07	1.16	2.23	2.33	1.21
8447930	41.52333	-70.67167	0.00	0.04	0.30	0.58	0.67	0.41
8447712*	41.59333	-70.90000	0.00	0.04	0.51	1.13	1.20	0.60
8534720	39.35500	-74.41833	0.00	0.05	0.67	1.27	1.40	0.79
8532591	40.10167	-74.03500	0.00	0.05	0.67	1.28	1.38	0.73
8531991	40.30333	-73.97667	0.00	0.05	0.74	1.39	1.50	0.81
8531680	40.46667	-74.01000	0.00	0.05	0.78	1.49	1.59	0.85
8531545	40.44000	-74.19833	0.00	0.06	0.86	1.60	1.70	0.89
8531369*	40.41667	-74.36333	0.00	0.06	0.94	1.76	1.86	0.95
8531156*	40.54500	-74.26500	0.00	0.05	0.88	1.64	1.73	0.91
8530772	40.72833	-74.10333	0.00	0.07	0.90	1.66	1.76	0.94
8530743*	40.73167	-74.11667	0.00	0.06	0.88	1.65	1.75	0.91
8530591	40.78667	-74.14667	0.00	0.07	0.93	1.78	1.88	0.95
8530095	40.94500	-73.91833	0.00	0.05	0.65	1.20	1.27	0.63
8510560	41.04833	-71.96000	0.00	0.05	0.37	0.68	0.77	0.39
8512735*	40.93500	-72.58167	0.00	0.05	0.49	0.90	0.99	0.63
8512769*	40.81833	-72.55333	0.00	0.03	0.40	0.80	0.88	0.50
8513825*	40.73833	-72.86833	0.00	0.03	0.22	0.39	0.44	0.24
8514560	40.95000	-73.07667	0.00	0.06	1.07	2.08	2.18	1.13
8515186	40.62667	-73.26000	0.00	0.04	0.34	0.64	0.70	0.40
8516061*	40.87333	-73.47000	0.00	0.06	1.18	2.29	2.40	1.24
8516299*	40.90333	-73.55000	0.00	0.07	1.20	2.33	2.44	1.27
8516614	40.86333	-73.65500	0.00	0.07	1.18	2.28	2.39	1.26
8516761*	40.83167	-73.70333	0.00	0.08	1.20	2.30	2.41	1.34
8516990	40.79333	-73.78167	0.00	0.08	1.18	2.26	2.37	1.24
8517847	40.70333	-73.99500	0.00	0.06	0.78	1.43	1.55	0.89
8518091	40.96167	-73.67167	0.00	0.07	1.18	2.29	2.40	2.19
8518490	40.89333	-73.78167	0.00	0.07	1.19	2.30	2.41	1.27
8518639	40.80167	-73.90667	0.00	0.08	1.03	1.98	2.08	1.07
8518687	40.75833	-73.95833	0.00	0.06	0.73	1.38	1.48	0.79

8518699	40.71167	-73.96833	0.00	0.06	0.72	1.34	1.44	0.79
8518750	40.70000	-74.01500	0.00	0.06	0.78	1.44	1.54	0.84
8519483	40.64000	-74.14667	0.00	0.06	0.84	1.58	1.68	0.90
8512987	40.98167	-72.64500	0.00	0.06	0.87	1.69	1.79	0.93
8450768	41.46500	-71.19333	0.00	0.03	0.48	1.00	1.08	0.59
8450954*	41.61833	-71.20333	0.00	0.04	0.53	1.11	1.20	0.59
8451552*	41.63667	-71.25500	0.00	0.05	0.61	1.29	1.36	0.70
8452660	41.50500	-71.32667	0.00	0.04	0.52	1.09	1.17	0.62
8453742*	41.49667	-71.38667	0.00	0.04	0.52	1.09	1.16	0.61
8454000	41.80667	-71.40167	0.00	0.05	0.68	1.40	1.47	0.75
8458022	41.32833	-71.76167	0.00	0.04	0.41	0.81	0.87	0.53
8458694	41.30500	-71.86000	0.00	0.04	0.45	0.83	0.91	0.55

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

Table E.1. QA/QC Residuals from the Long Island Sound TSS Grid.

PID	Latitude (deg)	Longitude (deg)	MHHW Res. (m)	MHW Res. (m)	MLW Res. (m)	MLLW Res. (m)	Avg. (m)	Std. Dev. (m)
LW0832	41.04722	-71.95833	-0.0043	-0.0035	-0.0071	-0.0091	-0.0060	0.0026
LW0831	41.04805	-71.95722	0.0067	0.0074	0.0036	0.0016	0.0048	0.0027
LW0833	41.05138	-71.95777	0.0174	0.0181	0.0124	0.0103	0.0146	0.0038
LX0101	41.31777	-72.35027	0.0107	0.0106	-0.0048	-0.0029	0.0034	0.0084
LX0102	41.32111	-72.35111	0.0025	0.0021	-0.0093	-0.0059	-0.0027	0.0059
LX0157	41.35944	-72.09111	-0.0018	0.0006	-0.0003	0.0021	0.0001	0.0016
AH9447	41.50500	-71.32666	-0.0052	-0.0039	0.0038	0.0032	-0.0005	0.0047
AH9448	41.50500	-71.32666	-0.0052	-0.0039	0.0038	0.0032	-0.0005	0.0047
LW0491	41.50611	-71.32777	-0.0090	-0.0067	0.0087	0.0083	0.0003	0.0095
LW0493	41.50666	-71.32722	-0.0048	-0.0036	0.0048	0.0042	0.0001	0.0051
LW0489	41.50750	-71.32861	-0.0149	-0.0123	0.0062	0.0059	-0.0038	0.0114
LX3397	41.52083	-72.08111	0.0001	0.0009	-0.0005	-0.0005	0.0000	0.0007
LX3226	41.52388	-72.08000	-0.0016	-0.0008	-0.0015	-0.0015	-0.0014	0.0004
LW5205	41.80638	-71.40111	0.0015	0.0025	0.0000	0.0021	0.0015	0.0011
LW0150	41.80666	-71.40138	-0.0015	-0.0005	-0.0030	-0.0009	-0.0015	0.0011
LW0152	41.80694	-71.40194	-0.0016	-0.0005	-0.0031	-0.0010	-0.0016	0.0011
LW0154	41.80722	-71.39916	-0.0001	0.0009	-0.0019	0.0003	-0.0002	0.0012
AH9453	41.80750	-71.40000	-0.0006	0.0004	-0.0023	-0.0001	-0.0007	0.0012
KU1594	40.86277	73.65444	-0.0039	-0.0022	-0.0022	-0.0033	-0.0029	0.0008
KU1595	40.86277	73.65388	0.0019	0.0036	0.0037	0.0026	0.0029	0.0009
KU1593	40.86305	73.65444	-0.0007	0.0008	0.0008	-0.0002	0.0002	0.0008
KU1726	40.89055	73.78222	-0.0023	-0.0022	0.0002	0.0018	-0.0006	0.0020
KU1724	40.89166	73.78250	-0.0011	-0.0010	0.0010	0.0023	0.0003	0.0016
KU0432	40.87555	-73.46916	-0.0009	0.0011	-0.0019	0.0000	-0.0004	0.0013
KU0373	40.93416	-72.57694	-0.0032	-0.0029	0.0038	0.0029	0.0001	0.0037
KU0505	40.94777	-73.07500	-0.0001	0.0014	0.0008	-0.0020	0.0000	0.0015
KU0506	40.95083	-73.07750	0.0017	0.0031	0.0022	-0.0007	0.0016	0.0016
AI1725	41.17333	-73.18166	0.0013	0.0022	0.0028	0.0007	0.0018	0.0009
LX2344	41.17555	-73.18000	-0.0006	0.0002	0.0006	-0.0015	-0.0003	0.0009
LX0885	41.20472	-73.11166	-0.0002	0.0008	0.0020	-0.0003	0.0006	0.0011
LX0470	41.27000	-72.52833	0.0003	-0.0013	0.0006	0.0005	0.0000	0.0009
AI8467	40.44000	-74.19611	0.0120	0.0127	-0.0027	-0.0006	0.0053	0.0081
KV0714	40.46111	-74.00416	0.0038	0.0063	0.0031	0.0028	0.0040	0.0016
AB6711	40.46750	-74.01000	0.0003	0.0018	-0.0006	-0.0014	0.0000	0.0014
KV3521	40.46777	-74.00888	0.0024	0.0036	0.0027	0.0018	0.0026	0.0007
KV0707	40.46805	-74.00833	0.0027	0.0039	0.0027	0.0019	0.0028	0.0008
KV0709	40.46805	-74.00861	0.0026	0.0038	0.0027	0.0019	0.0027	0.0008
KV3519	40.46833	-74.00694	0.0002	0.0014	-0.0003	-0.0011	0.0000	0.0010
AB6710	40.46861	-74.01027	0.0073	0.0084	0.0017	0.0013	0.0047	0.0037
KV0701	40.47111	-74.01194	0.0137	0.0142	0.0052	0.0047	0.0094	0.0052
KV2864	40.63777	-74.14638	0.0042	0.0045	0.0030	0.0035	0.0038	0.0007
KV0442	40.63833	-74.14444	0.0088	0.0091	0.0055	0.0062	0.0074	0.0018
KV0441	40.63861	-74.14305	0.0044	0.0048	0.0002	0.0011	0.0026	0.0023
AB6736	40.70000	-74.01500	0.0051	0.0040	0.0015	-0.0004	0.0025	0.0025
AB6737	40.70000	-74.01500	0.0081	0.0070	0.0045	0.0026	0.0055	0.0025
KV0587	40.70083	-74.01555	0.0046	0.0038	0.0104	0.0076	0.0066	0.0030

KV0579	40.70333	-74.01416	0.0094	0.0089	0.0252	0.0215	0.0163	0.0083
KV0584	40.70416	-74.01583	0.0117	0.0115	0.0233	0.0184	0.0162	0.0057
KU1418	40.75972	-73.95833	0.0081	0.0082	0.0168	0.0150	0.0120	0.0045
KU0976	40.79333	-73.78111	0.0040	0.0031	0.0040	0.0019	0.0033	0.0010
KU0978	40.79416	-73.78111	0.0008	0.0000	0.0003	-0.0020	-0.0002	0.0012
KU0979	40.79416	-73.78138	0.0010	0.0002	0.0004	-0.0019	-0.0001	0.0013
KU1012	40.80166	-73.90638	0.0091	0.0084	0.0039	0.0039	0.0063	0.0028
KU1013	40.80166	-73.90638	0.0001	-0.0006	-0.0051	-0.0051	-0.0027	0.0028

Table E.2. Long Island Sound TSS Comparison to Tide Gauges and Tidal Benchmarks.

PID	Latitude (deg)	Longitude (deg)	NAVD 88 to MSL (m)	TSS Derived Value (m)	Delta (m)
8461392	41.52333	-72.07833	0.0350	0.0348	0.0002
8461490	41.35500	-72.08667	0.0920	0.0923	-0.0003
8462764	41.32167	-72.35000	0.0620	0.0602	0.0018
8463348	41.45167	-72.46500	-0.0620	-0.0619	-0.0001
8463701	41.26833	-72.53167	0.1030	0.1030	0.0000
8463827	41.54167	-72.55167	-0.1090	-0.1089	-0.0001
8465233	41.26167	-72.81833	0.0860	0.0863	-0.0003
8465748	41.29333	-72.91667	0.0760	0.0760	0.0000
8466375	41.20500	-73.04167	0.0740	0.0740	0.0000
8466442	41.21833	-73.05500	0.0710	0.0711	-0.0001
8466664	41.27500	-73.08833	0.0200	0.0203	-0.0003
8466791	41.18667	-73.11333	0.1850	0.1825	0.0025
8466797	41.20333	-73.11167	0.0540	0.0545	-0.0005
8467150	41.17333	-73.18167	0.0670	0.0679	-0.0009
8467373	41.15667	-73.21333	0.0560	0.0561	-0.0001
8467726	41.13333	-73.28333	0.0510	0.0511	-0.0001
8468448	41.09667	-73.41500	0.0500	0.0527	-0.0027
8532591	40.10167	-74.03500	0.0630	0.0630	0.0000
8531991	40.30333	-73.97667	0.0750	0.0750	0.0000
8531680	40.46667	-74.01000	0.0730	0.0729	0.0001
8531545	40.44000	-74.19833	0.0310	0.0310	0.0000
8530772	40.72833	-74.10333	0.0390	0.0385	0.0005
8530743	40.73167	-74.11667	0.0260	0.0262	-0.0002
8530095	40.94500	-73.91833	-0.0220	-0.0219	-0.0001
8510560	41.04833	-71.96000	0.0200	0.0226	-0.0026
8512735	40.93500	-72.58167	0.1380	0.1378	0.0002
8512769	40.81833	-72.55333	0.0970	0.0967	0.0003
8514560	40.95000	-73.07667	0.0590	0.0570	0.0020
8516061	40.87333	-73.47000	0.0580	0.0580	0.0000
8516299	40.90333	-73.55000	0.0760	0.0770	-0.0010
8516614	40.86333	-73.65500	0.0840	0.0846	-0.0006
8516761	40.83167	-73.70333	0.1410	0.1416	-0.0006
8516990	40.79333	-73.78167	0.0580	0.0582	-0.0002
8517847	40.70333	-73.99500	0.1100	0.1099	0.0001
8518091	40.96167	-73.67167	1.0070	0.9973	0.0097
8518490	40.89333	-73.78167	0.0840	0.0852	-0.0012
8518639	40.80167	-73.90667	0.0430	0.0432	-0.0002
8518687	40.75833	-73.95833	0.0610	0.0610	0.0000
8518699	40.71167	-73.96833	0.0660	0.0662	-0.0002
8518750	40.70000	-74.01500	0.0640	0.0645	-0.0005
8519483	40.64000	-74.14667	0.0540	0.0539	0.0001
8512987	40.98167	-72.64500	0.0580	0.0581	-0.0001
8450768	41.46500	-71.19333	0.1060	0.1060	0.0000
8451552	41.63667	-71.25500	0.0910	0.0910	0.0000
8452660	41.50500	-71.32667	0.0930	0.0942	-0.0012
8453742	41.49667	-71.38667	0.0860	0.0861	-0.0001
8454000	41.80667	-71.40167	0.0680	0.0662	0.0018
8458022	41.32833	-71.76167	0.1140	0.1138	0.0002

8458694	41.30500	-71.86000	0.0960	0.0960	0.0000
LW0832	41.04722	-71.95833	0.0160	0.0220	-0.0060
LW0831	41.04805	-71.95722	0.0610	0.0562	0.0048
LW0833	41.05138	-71.95777	0.1010	0.0864	0.0146
LX0101	41.31777	-72.35027	0.0738	0.0705	0.0033
LX0102	41.32111	-72.35111	0.0518	0.0544	-0.0027
LX0157	41.35944	-72.09111	0.0957	0.0955	0.0002
AH9447	41.50500	-71.32666	0.0936	0.0942	-0.0006
AH9448	41.50500	-71.32666	0.0936	0.0942	-0.0006
LW0491	41.50611	-71.32777	0.0958	0.0955	0.0003
LW0493	41.50666	-71.32722	0.0936	0.0937	-0.0002
LW0489	41.50750	-71.32861	0.0899	0.0937	-0.0038
LX3397	41.52083	-72.08111	0.0391	0.0391	0.0000
LX3226	41.52388	-72.08000	0.0329	0.0342	-0.0013
LW5205	41.80638	-71.40111	0.0677	0.0662	0.0015
LW0150	41.80666	-71.40138	0.0647	0.0662	-0.0015
LW0152	41.80694	-71.40194	0.0645	0.0661	-0.0016
LW0154	41.80722	-71.39916	0.0638	0.0640	-0.0002
AH9453	41.80750	-71.40000	0.0641	0.0647	-0.0006
KU1594	40.86277	-73.65444	0.0831	0.0860	-0.0029
KU1595	40.86277	-73.65388	0.0901	0.0871	0.0030
KU1593	40.86305	-73.65444	0.0862	0.0860	0.0002
KU0432	40.87555	-73.46916	0.0612	0.0615	-0.0003
KU0373	40.93416	-72.57694	0.1400	0.1398	0.0001
KU0505	40.94777	-73.07500	0.0454	0.0454	0.0000
KU0506	40.95083	-73.07750	0.0635	0.0619	0.0016
AI1725	41.17333	-73.18166	0.0697	0.0679	0.0018
LX2344	41.17555	-73.18000	0.0666	0.0669	-0.0003
LX0885	41.20472	-73.11166	0.0627	0.0622	0.0005
LX0470	41.27000	-72.52833	0.1055	0.1054	0.0001
AI8467	40.44000	-74.19611	0.0368	0.0315	0.0053
KV0714	40.46111	-74.00416	0.0760	0.0720	0.0040
AB6711	40.46750	-74.01000	0.0730	0.0729	0.0000
KV3521	40.46777	-74.00888	0.0755	0.0728	0.0027
KV0707	40.46805	-74.00833	0.0756	0.0728	0.0028
KV0709	40.46805	-74.00861	0.0756	0.0728	0.0028
KV3519	40.46833	-74.00694	0.0728	0.0727	0.0000
AB6710	40.46861	-74.01027	0.0774	0.0727	0.0047
KV0701	40.47111	-74.01194	0.0815	0.0720	0.0095
KV2864	40.63777	-74.14638	0.0575	0.0537	0.0038
KV0442	40.63833	-74.14444	0.0610	0.0536	0.0074
KV0441	40.63861	-74.14305	0.0560	0.0535	0.0025
AB6736	40.70000	-74.01500	0.0661	0.0645	0.0016
AB6737	40.70000	-74.01500	0.0691	0.0645	0.0046
KV0587	40.70083	-74.01555	0.0710	0.0640	0.0070
KV0579	40.70333	-74.01416	0.0749	0.0636	0.0113
KV0584	40.70416	-74.01583	0.0763	0.0623	0.0140
KU1418	40.75972	-73.95833	0.0726	0.0606	0.0120
KU0976	40.79333	-73.78111	0.0613	0.0581	0.0032
KU0978	40.79416	-73.78111	0.0585	0.0587	-0.0002
KU0979	40.79416	-73.78138	0.0586	0.0587	-0.0001
KU1012	40.80166	-73.90638	0.0497	0.0434	0.0063
KU1013	40.80166	-73.90638	0.0407	0.0434	-0.0027
KU1726	40.89055	-73.78222	0.0890	0.0896	-0.0006

KU1724	**40.89166**	**-73.78250**	**0.0890**	**0.0887**	**0.0003**