NOAA Technical Memorandum NOS CS 49

UPDATE VDATUM FOR THE NEW YORK BIGHT, NEW YORK HARBOR, HUDSON RIVER, LONG ISLAND SOUND, AND NARRAGANSETT BAY: TIDAL DATUMS AND THEIR ASSOCIATED SPATIALLY VARYING UNCERTAINTIES, AND SEA SURFACE TOPOGRAPHY

Silver Spring, Maryland
July 2022

noaa **National Oceanic and Atmospheric Administration**

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

Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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NOTICE

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ABSTRACT

This technical memorandum documents the update of the tide model and modeled tidal datums, the calculation of tidal datum spatially varying uncertainties, and the creation of the topography of sea surface (TSS) field and TSS spatially varying uncertainty field in the New York Bight, New York Harbor, Hudson River, Long Island Sound, and Narragansett Bay. The initial development and application of a tidal datum model in this region was made in 2001 (Hess 2001), and the previous update of the tidal datum model in this region was done in 2008 (Yang et al., 2008).

The current work is to support the development of NOAA's vertical datum transformation software tool (VDatum), which has been widely used to transform geospatial vertical data among a variety of three-dimensional ellipsoidal, orthometric and tidal datum reference systems. Three primary goals of the current work include: (1) developing an updated tidal datum model by using the most recent shoreline, bathymetry, and tide station data; (2) implementing a Spatially Varying Uncertainty (SVU) statistical interpolation method (Shi and Myers, 2016) for interpolating modeled tidal datums and estimating tidal datum spatially varying uncertainties; (3) updating the TSS field and its associated spatially varying uncertainty field.

A two-dimensional depth-integrated barotropic version of the ADvanced CIRCulation (ADCIRC) hydrodynamic model was used in this work: ADCIRC version 51.52.34, released in January 2016. Model domain was first extended to incorporate most recent shoreline data and include new tide stations. The new tide model includes 448,219 unstructured triangular finite elements with a total of 250,569 mesh nodes. Additionally, the bathymetry in the model domain was updated with the most recent data available.

The ADCIRC-based tide model was then used to generate 6-minute water level time series at each model mesh node by using the open ocean boundary forcing which equals the sum of the water elevations of the nine tidal harmonic constituents (K1, O1, P1, Q1, M2, S2, N2, K2, and M4) from the EC2015 tidal database (Szpilka et al., 2016). The model run time was 60 days. Modeled water level time series of the last 50 days were used for computing modeled tidal datums, including mean higher high water (MHHW), mean high water (MHW), mean low water (MLW), mean lower low water (MLLW), diurnal tidal level (DTL), and mean tidal level (MTL).

The modeled tidal datums were first compared to observed tidal datums at 174 tide stations. The initial presence of large model errors (> 0.20 m) as shown at 20 tide stations were reduced by refining bathymetry assignment and by adjusting bottom friction setting in the regions with large model errors. The modeled tidal datums were then corrected by using the SVU statistical interpolation method. The SVU correction procedure is used to limit the interpolated tidal datums to within a user-defined model error (0.01 m in this work) at each tide station and produce a spatially varying uncertainty field for each interpolated tidal datum field. The final step is to generate four bounding polygons to cover the model domain, create marine grids within each bounding polygon, and then populate modeled tidal datums and associated spatially varying uncertainties onto the marine grids to form the regularly-sampled products which constitute what is known as the "marine grid" VDatum.

Finally, the TSS field, defined as the elevation of the North American Vertical Datum of 1988 relative to local mean sea level, was updated by the NOAA NOS National

Geodetic Survey (NGS) by interpolating orthometric-to-MSL relationships which were obtained through the calculation of the NAVD88-to-MSL values at NOAA tide stations. The TSS spatially varying uncertainty filed was generated by using a rigorous error propagation approach. Observed TSS values and their corresponding standard deviations at 137 tide stations were used in generating the TSS field and its associated spatially varying uncertainty field.

Key Words: Coastal and estuarine modeling, ADCIRC, shoreline, bathymetry, water level time series, VDatum, tidal datums, spatially varying uncertainty, marine grid population, the topography of the sea surface, New York Bight, New York Harbor, Hudson River, Long Island Sound, and Narragansett Bay.

1. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) maintains a software tool called VDatum, which allows users to transform geospatial data among a variety of three-dimensional ellipsoidal, orthometric, and tidal datum reference systems (Gill and Schultz 2001; Hess, 2001; Hess et al., 2012; Hess et al. 2003; Hess et al. 2005; Hess and White 2004; Mibert and Hess 2001; Milbert 2002; Myers 2005; Myers et al., 2005; Myers and Hess 2006; Parker et al. 2003; Parker 2002; Spargo et al. 2006; Hess et al., 2016; White et al., 2016). A total of 48 vertical datums are currently included in VDatum. VDatum is crucial to coastal applications that rely on vertical accuracy among bathymetric, topographic, and coastline datasets (Myers, 2005; Myers et al., 2007).

The goal of NOAA's VDatum project is to continually develop and maintain a seamless nationwide product and service to facilitate more effective sharing of national elevation and shoreline databases (Myers, 2005; Myers et al., 2007). VDatum is currently available in the coastal regions covering the continental United States, Southeast Alaska, Puerto Rico, and the U.S. Virgin Islands (https://vdatum.noaa.gov/). Several regions are undergoing model upgrades in concert with foundational geodetic and tidal datum data updates. The national VDatum program will eventually include base coverage of all of the U.S. coastal waters from the landward navigable reaches of estuaries and charted embayments to the offshore extent of the U.S. Exclusive Economic Zone (EEZ). For the current VDatum update, the VDatum program requirement is to develop VDatum products for the coastal waters from the coastline to approximately 75 nautical miles offshore. NOAA's VDatum supports transformations between ellipsoidal, geoidal (orthometric), and tidal datums.

Knowledge of the spatial distributions of tidal datums is essential to ensure the accuracy of VDatum for applications such as marine geodesy (Mibert and Hess 2001). Tidal datums, including mean higher high water (MHHW), mean high water (MHW), mean low water (MLW), mean lower low water (MLLW), diurnal tide level (DTL), mean tide level (MTL), and local mean sea level (LMSL), can be computed either using observed water level time series from tide stations or using modeled water level time series from hydrodynamic models. The latter has an advantage of being capable of computing tidal datums in the areas without tide stations.

A VDatum tidal datum model was initially developed in 2001 for the coastal region from the New York Harbor east to Montauk, New York (-71^o 50') and south to Cape May, New Jersey (38^o 55') (Hess 2001). That tidal datum model was conducted by running a hydrodynamic circulation model to generate 6-minute water level time series for 80 days, followed by an analysis to compute tidal datums throughout the domain. A spatially-varying correction field was generated based on modeled mean tide range. The initial tidal datum modeling was crucial to: 1) understanding the important role of a hydrodynamic model in generating accurate tidal datum products; 2) gaining fundamental understanding about the characteristics of tidal datums in this model domain.

The NOAA modeled tidal datums and uncertainty products of this region were updated in 2008 by using an advanced hydrodynamic model, with an expanded domain that included the New York Bight, New York Harbor, Hudson River, Long Island Sound, and Narragansett Bay (Yang et al. 2008). Specifically, the 2008 modeling work included:

(1) creating unstructured triangular model mesh with bathymetry assigned; (2) running a two-dimensional barotropic version of the ADvanced Circulation (ADCIRC) hydrodynamic model; (3) calculating and analyzing tidal datums using modeled water level time series; (4) analyzing and correcting the model errors by comparing modeled tidal datums with observations; (5) producing structured grids for sampling the modeled tidal datums into final VDatum products; and (6) creating the VDatum TSS structured grid product using spatial interpolation techniques.

It has been more than a decade since the previous update of the VDatum modeling in 2008. Changes in the shoreline and bathymetry are significant due to severe weather events and other environmental changes. The availability of new and improved data from shoreline mapping, bathymetric surveys, and tide station updates makes it necessary to upgrade the tidal datum modeling.

Figure 1 shows an example of shoreline changes that have occurred since the prior tidal datum modeling effort: A new opening at (72.90 ºW, 40.72 ºN) in the Fire Island of the south shore of Long Island, New York was created by 2012 Hurricane Sandy. We incorporated this change in the current tide model update.

Figure 1. A new opening at (72.90 ºW, 40.72 ºN) in the Fire Island of the south shore of Long Island, New York, which was created by 2012 Hurricane Sandy.

Figure 2 shows a general map of the updated model domain mesh, with the 2008 model domain mesh shown as an inset in the lower right corner for comparison. VDatum products from the current update cover the coastal waters to approximately 75 nautical miles offshore from the Long Island south shore. Detailed geographic coverages of the updated VDatum products will be shown in Figure 24.

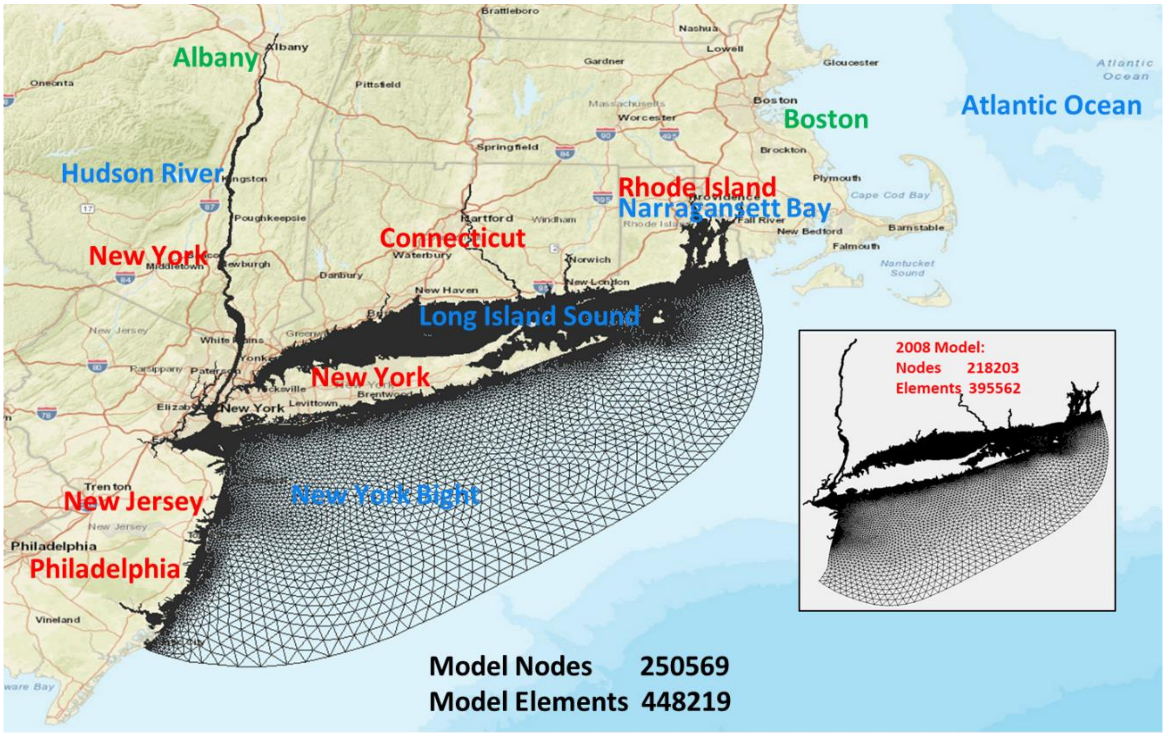

Figure 2. A map showing the updated model domain mesh (main/left) versus the 2008 model domain mesh (inset/right). VDatum products were developed for the coastal waters from the coastline to approximately 75 nautical miles offshore. The geographic coverages of VDatum products will be shown in Figure 24.

The goals of this work include: (1) developing an updated tide model and modeled tidal datums (i.e., MHHW, MHW, MLW, MLLW, DTL, and MTL in reference to LMSL) by using a 2016 version of ADCIRC hydrodynamic model (version 51.52.34, released in January 2016) and incorporating the most recently available shoreline, bathymetry, and tide station data; (2) implementing a Spatially Varying Uncertainty (SVU) statistical interpolation method (Shi and Myers 2016) to interpolate the modeled tidal datums and estimate their associated spatially varying uncertainties; (3) creating the TSS field by interpolating orthometric-to-MSL relationships and the TSS associated spatially varying uncertainty field by using an error propagation approach. The TSS field and its associated spatially varying uncertainty field were created by the NOAA NOS National Geodetic Survey (NGS).

We first extended the model domain to include new tide stations, and incorporated the contemporary shoreline and bathymetry data. We then ran the updated tide model by using a 2016 version of ADCIRC model to obtain 6-minute modeled water level time series at each node of the model mesh. The modeled water level time series were then used to compute modeled tidal datums. Modeled tidal datums were validated by using observed tidal datums at 174 tide station (point) locations. Large (>0.20 m) model biases were reduced by refining model bathymetry and adjusting bottom friction. After that, we implemented the SVU statistical interpolation method to interpolate the modeled tidal datums and estimate associated spatially varying uncertainties. Four (4) bounding polygons were generated and then used to partition the model domain into regularly-sampled marine grids. We then populated the SVU-interpolated modeled tidal datums and their associated spatially varying uncertainties onto the marine grids as final modeled tidal datum products. Finally, the TSS field and its associated spatially varying uncertainty filed were created by using observed TSS values and their corresponding standard deviations at 137 tide stations.

The remainder of the technical report is organized as follows: Section 2 describes the shoreline, bathymetry, and tide station data which were used for updating the tide model, validating and improving modeled tidal datums. Section 3 introduces the updated tide model and its configuration. Section 4 shows the modeled tidal datums, validations of modeled tidal datums, model improvements for reducing model errors, and implementing the SVU statistical interpolation method to interpolate modeled tidal datums and compute their associated spatially varying uncertainties. Section 5 details the creation of bounding polygons and the regularly structured marine grids, and the marine grid population of the SVU-interpolated modeled tidal datums and their associated spatially varying uncertainties. Section 6 outlines the creation of the TSS field and its associated spatially varying uncertainty field. Section 7 gives a brief summary.

2. DATA DESCRIPTION

The shoreline, bathymetry, and tide station data, which were used to update the VDatum tidal datum model in the New York Bight, New York Harbor, Hudson River, Long Island Sound, and Narragansett Bay, are described below.

2.1. NOAA's Continually Updated Shoreline Product (CUSP)

NOAA's Continually Updated Shoreline Product (CUSP) provides an accurate, consistent, and contemporary national shoreline representation of the U.S. and its territories (https://www.ngs.noaa.gov/CUSP). The CUSP includes frequent updates to support various applications, including VDatum.

The CUSP references a MHW shoreline based on vertical modeling or image interpretation, leveraging both water level stations and other applicable shoreline indicators. At the time of this work, the CUSP included comprehensive coverage of the continental U.S., as well as portions of Hawaii, the Pacific Islands, Alaska, Puerto Rico, and the U.S. Virgin Islands. The CUSP dataset was particularly valuable in our work for: (1) updating the model's coastlines in the regions of New Jersey and the south shore of Long Island, New York, and (2) extending the shoreline-bounded model domain.

2.2. Bathymetric Data

We used the most recently available bathymetry data to update model bathymetry at model grid points. The data sources used for the bathymetry update are listed below by priority of use, according to dataset age and reliability.

Priority 1 bathymetry consisted of data from the U.S. Army Corps of Engineers (USACE) hydrographic surveys in Hudson River, Connecticut River, Seekonk River, and Housatonic River. The data are available at https://navigation.usace.army.mil/Survey/Hydro. Figure 3 shows the distributions of the bathymetry data and the survey years of the USACE data used for the model update. Figure 3 (a) to (c) illustrate the USACE data used in the initial model bathymetry update, and (d) to (g) show the USACE data used in the refinement step to reduce modeling errors.

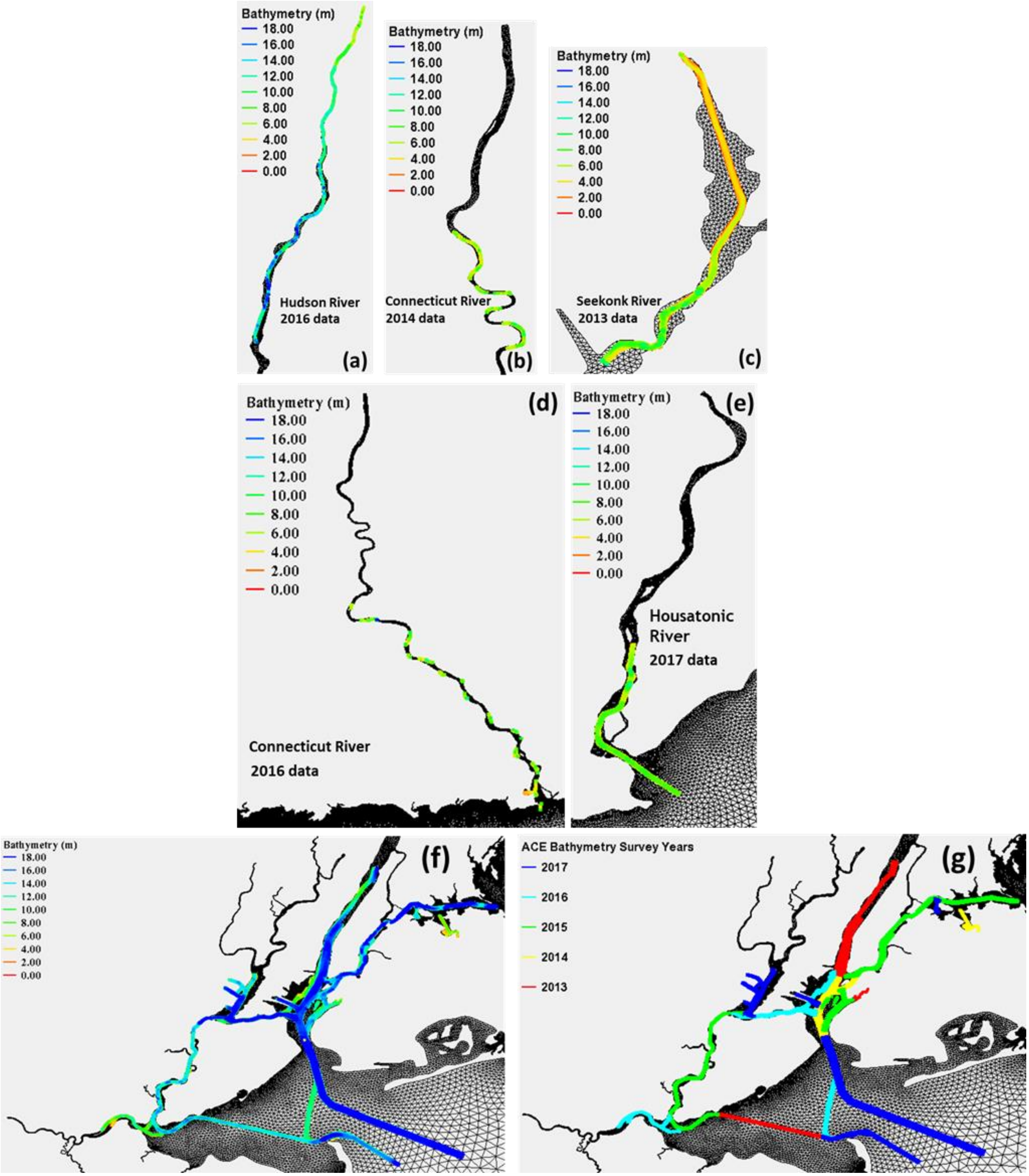

Figure 3. The locations, bathymetry (in reference to LMSL), and years of the USACE survey bathymetry data used for the model update. The USACE data (a) to (c) were used for initial model bathymetry update, and the USACE data (d) to (g) were used for refining model bathymetry for reducing model errors.

Priority 2 bathymetry data consisted of the most recently available NOAA NOS hydrographic survey data, dating from 2000 to 2017, as assembled by the Coast Survey Development Laboratory. Figure 4 shows the distributions of the bathymetry data (a) and the survey years (b).

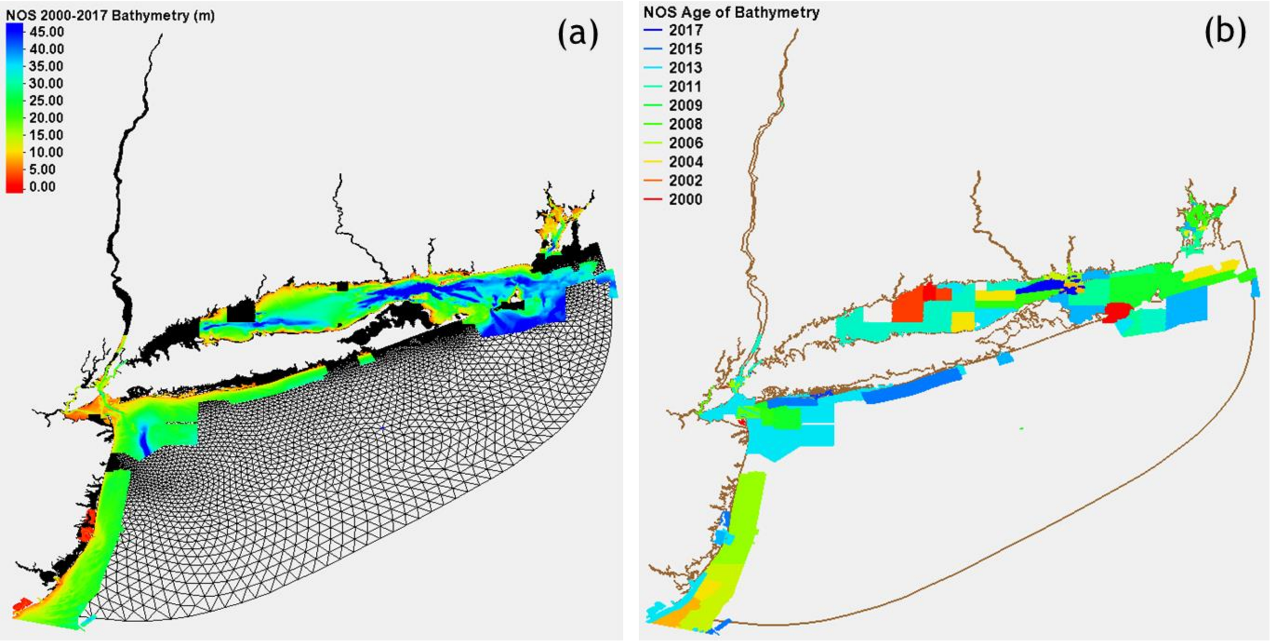

Figure 4. The locations, bathymetry (in reference to LMSL) (a), and survey years (b) of the NOAA NOS bathymetry data used for the model update.

Priority 3 bathymetry data was assembled from the NOAA Electronic Navigational Chart (ENC). ENC Charts #12343 and #12347 data were used for refining model bathymetry in part of the Hudson River for reducing model errors (Figure 5). The Chart #12343 (the corrected version on August 21, 2018) was available at http://www.charts.noaa.gov/OnLineViewer/12343.shtml and the Chart #12347 (the corrected version on May 4, 2018) was available at http://www.charts.noaa.gov/OnLineViewer/12347.shtml.

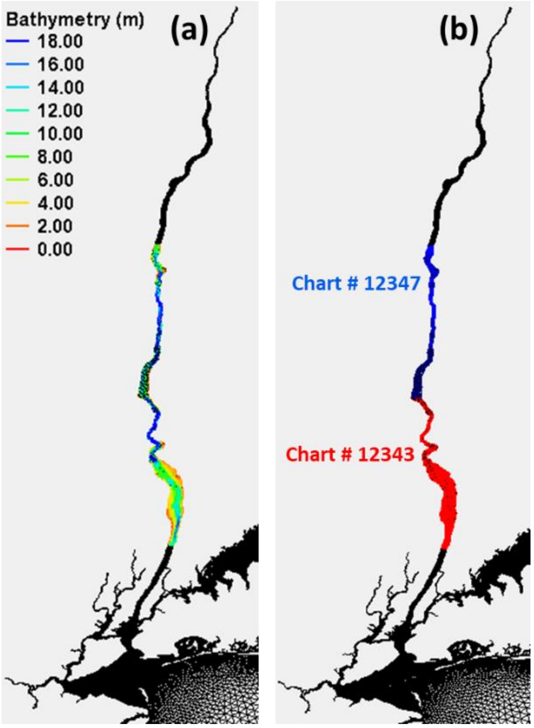

Figure 5. The bathymetry (in reference to LMSL) (a) and the locations (b) of NOAA ENC Charts #12343 and #12347 which were used for refining model bathymetry in part of Hudson River for reducing model errors.

Priority 4 bathymetry data was sourced from the NOAA National Centers for Environmental Information (NCEI) suite of digital elevation model (DEM) tiles developed for the U.S. Atlantic Coast impacted by Hurricane Sandy. Data utilized in the NCEI DEM creation came from multiple sources, including NOS partners OCS, NGS, and Office for Coastal Management, the U.S. Geological Survey, and the USACE. A total of 42 DEM tiles gridded at 1/9 arc-second were used for initial model bathymetry update in the coastal water areas with no bathymetry data available from Priority 1-3. The 42 DEM data files were available at https://www.ngdc.noaa.gov/mgg/inundation/sandy/sandy_geoc.html. Figure 6 shows the Priority 4 bathymetry data: the DEM data geographic coverage (a) and the bathymetry data within the model domain (b).

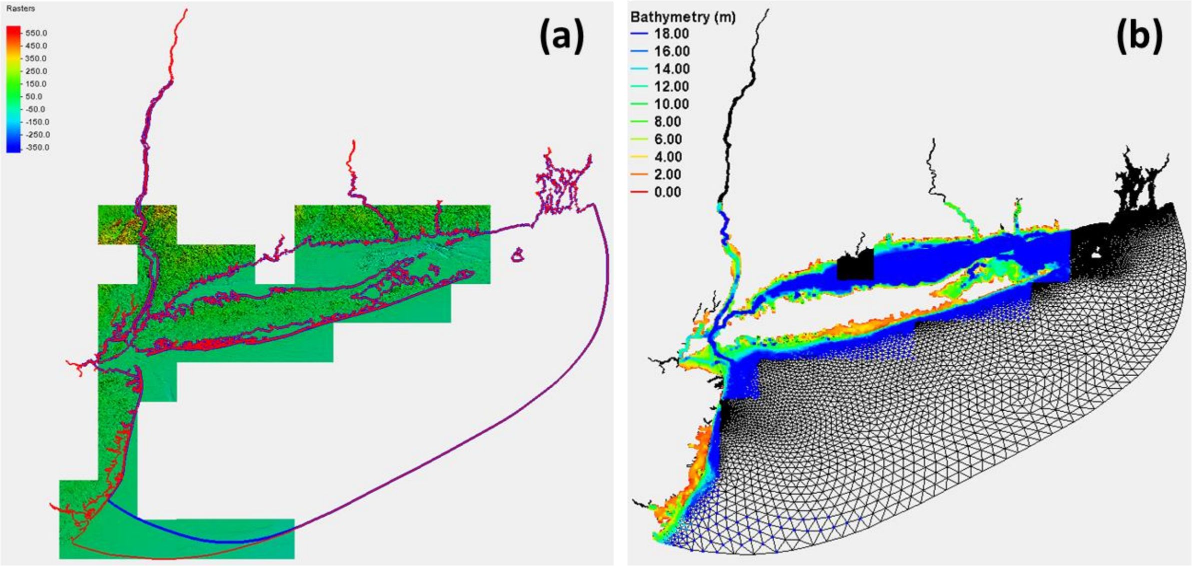

Figure 6. The geographic coverage (a) and the bathymetry (in reference to LMSL) (b) of the NCEI DEM data which were used for initial model bathymetry update in the coastal water areas where higher-priority bathymetry data (see Figures 3, 4, and 5) were unavailable. Note: In the left panel (a), the current model boundary is marked in red and the 2008 model boundary is marked in blue, and overlapping bounds appear in magenta.

Priority 5 bathymetry data: The 2008 model depth data (Yang et al. 2008) used to round out the bathymetry coverage in the areas outside the abovementioned updates (Priority levels 1-4, Figures 3-6) for initial model bathymetry assignment is shown in Figure 7. The 2008 model bathymetry was created by using NOAA NOS hydrographic survey data from 1930 to 2000, and NOAA NOS ENCs (2004 editions) for Sabine Lake and southern Laguna Madre.

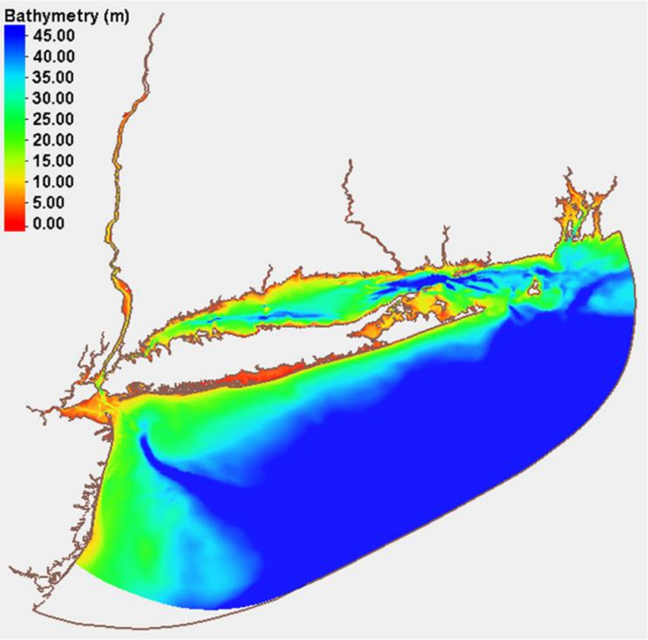

Figure 7. The 2008 model bathymetry data used to round out the bathymetry coverage in the areas outside the abovementioned updates (Priority levels 1-4, Figures 3-6) for initial model bathymetry assignment. Bathymetry data are relative to LMSL in units of meters, and the current model boundary is marked in brown.

It is worthwhile to mention that the bathymetry in some new areas (such as extended bay areas and rivers) were assigned by using an averaged bathymetry of the model grid points closest to the area, if without any bathymetry available or the available DEM bathymetry is not representing NOS or USACE survey data in the nearest areas.

2.3. Observed Tidal Datums and Station Root-Mean-Square (RMS) Errors

The observed tidal datums (MHHW, MHW, MLW, and MLLW) and station root mean square (RMS) errors at a total of 174 tide stations were used in this work. The observed tidal datums were used for validating and improving ADCIRC modeled tidal datums. Both the observed tidal datums and station RMS errors were used for conducting the SVU statistical interpolation of ADCIRC modeled tidal datums.

The observed tidal datums were computed using collected 6-minute water level time series from tide stations, maintained by NOAA NOS Center for Operational Oceanographic Products and Services (CO-OPS). Detailed computational techniques can be found in NOAA publications (Gill et al. 2014; Gill, Hubbard, and Dingle 1995; Gill and Schultz 2001; Parker 2007). The observed tidal datums used in this work were computed in reference to the current tidal epoch of 1983–2001 National Tidal Datum Epoch (NTDE).

The observed MHHW, MHW, MLW, and MLLW heights relative to LMSL at the 174 tide stations are shown in Figure 8. The maximum value of the observed tidal datums in the model domain is less than 1.24 m (MHHW). The largest values of the observed tidal datums are situated in the western half of Long Island Sound. The eastern half of Long

Island Sound, the coastal areas surrounding the eastern Long Island, and the coastal areas of New Jersey and Philadelphia exhibit the smallest tidal datum values.

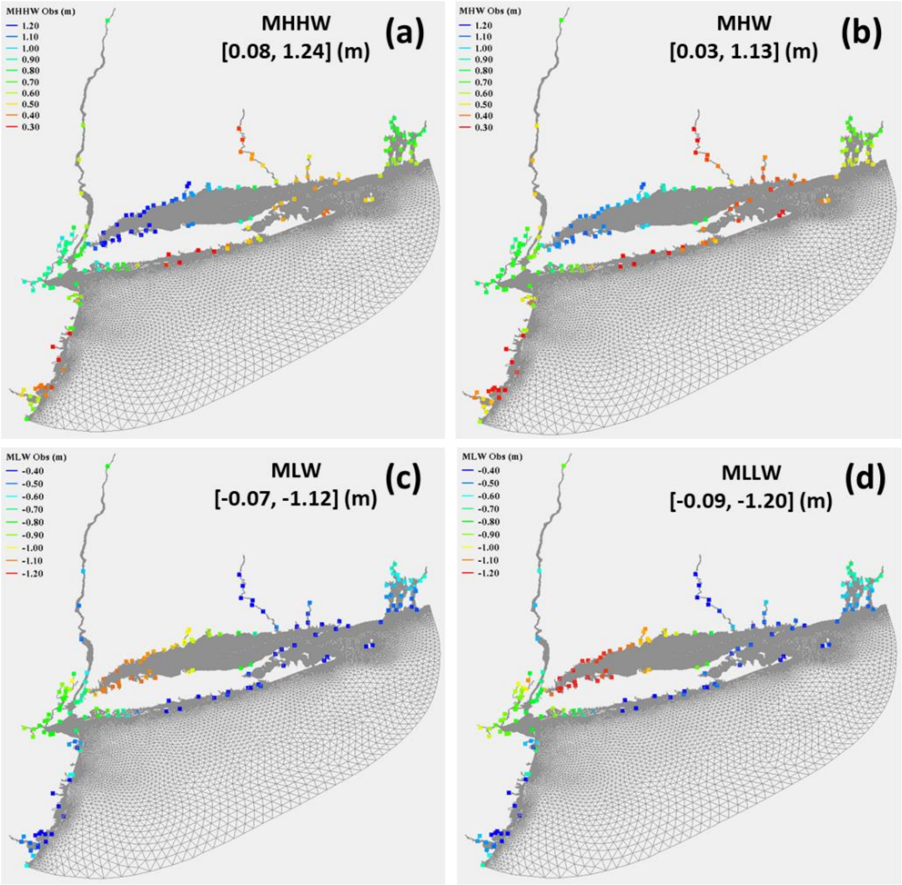

Figure 8. Observed tidal datums (MHHW, MHW, MLW, and MLLW) relative to LMSL at 174 tide stations; minimum and maximum values shown in brackets.

3. TIDAL DATUM SIMULATION

This section briefly introduces the ADCIRC hydrodynamic model which was used for generating modeled 6-minute water level time series as well as model grids, bathymetry, and model configurations respectively.

3.1. Hydrodynamic Model

ADCIRC is an advanced hydrodynamic model which has been developed since the early 1990s (Luettich, Westerink, and Scheffner 1992; Westerink, Luettich, and Scheffner 1993; Westerink et al. 1994). The model has been demonstrated to be effective in modeling ocean, coastal, and estuarine processes such as tides (Luettich et al. 1999; Mukai et al. 2002; Myers 2005) and thus has been widely used in the modeling community. In this work, we used a two-dimensional, depth-integrated barotropic version of the ADCIRC hydrodynamic model (version 51.52.34, released in January 2016, http://adcirc.org/) to simulate tidal water levels and compute tidal datums.

3.2. Model Domain Extension, Model Boundary Update, and Model Grid Creation

ADCIRC utilizes unstructured triangular model mesh grids. Model domain from the 2008 model (Yang et al. 2008) was first extended to include new tide stations, by using a commercial software package of Surface-water Modeling System© (SMS, https://www.aquaveo.com/software/sms-surface-water-modeling-system-introduction). Figure 9 shows a comparison of model boundary between the 2008 model (the blue line) and the current updated model (the red line). As shown in Figure 9, the model boundary was significantly extended in almost all the coastal areas of the model domain. Major extension and adjustments were made in Hudson River, New York Harbor, Connecticut River, the South Shore of Long Island, and the coastal water areas of New Jersey and Philadelphia.

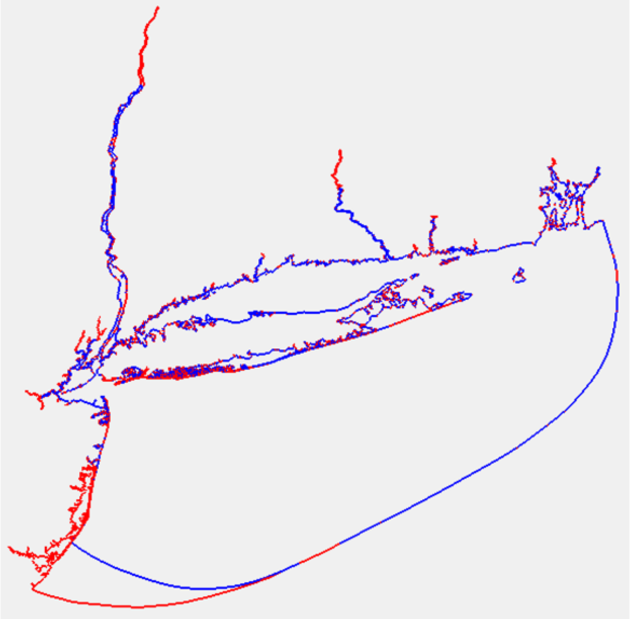

Figure 9. A comparison of model boundary between the 2008 model (blue lines) and the current updated model (red lines).

Figure 10 shows the triangular model mesh grids (a) and the model grid spacing (b) after the model update. The spatial resolution of model grids ranges from 7.55 m in the coastal region to 12.48 km near the open ocean boundary. The updated tide model includes a total of 250,569 nodes and 448,219 elements. Model grid resolution increases from the open ocean to the coasts, embayments, and rivers to represent the complexity in the shorelines for better resolving shallow water tidal dynamics.

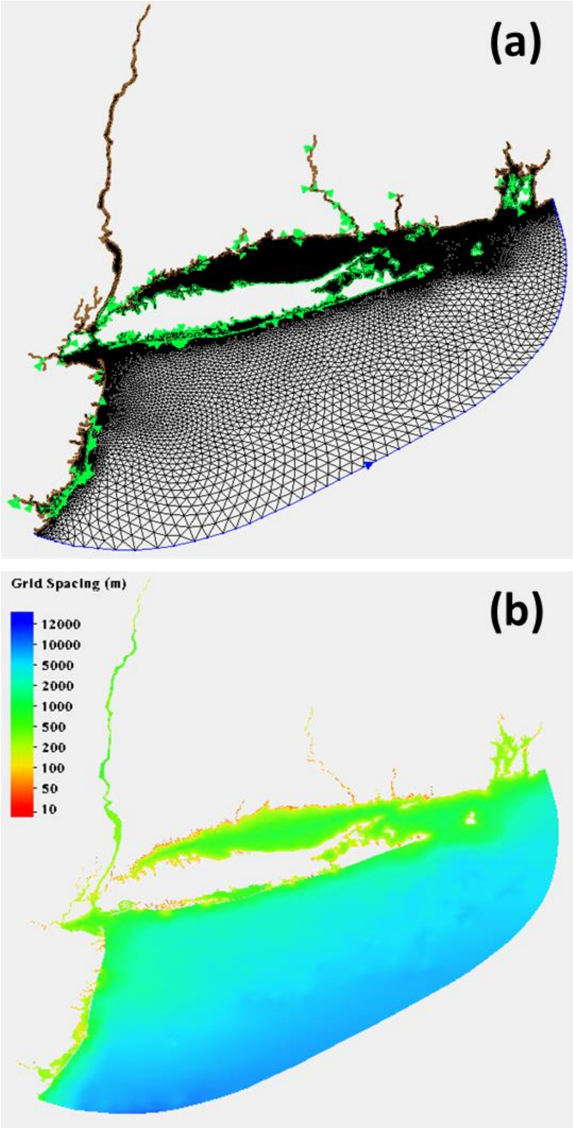

Figure 10. (a) The triangular model mesh grids after the current update. The blue line denotes the model's open ocean boundary, the brown line denotes land boundary, and the green lines denote island boundaries. (b) The grid spacing in the updated model domain.

3.3. Bathymetry on the Model Grids

The current updated model leverages bathymetry from USACE survey data, NOAA NOS survey data, NOAA NOS ENC data, NCEI DEM data, and the 2008 model bathymetry data. As introduced in Section 2.2, prioritization of overlapping bathymetric sources was assigned according to data reliability and recentness of survey.

In evaluating ADCIRC modeled tidal datum errors and for improving model performance, the most recently available USACE survey bathymetry data in Hudson River, New York Harbor, Connecticut River, and Housatonic River as well as two ENC Charts' bathymetry data in Hudson River [(d) to (g) in Figure 3] were used to refine the initially assigned model bathymetry.

The updated model bathymetry ranges from 0.41 m to 101.42 m in reference to LMSL. The shallowest bathymetry (0.41 m) occurs in the coast of New Jersey and in the south shore of Long Island, as marked by the two black circles in Figure 11 (a). Bathymetry generally increases from the coasts toward the open ocean boundary; however, the deepest model bathymetry (101.42 m) occurs in the east end of Long Island Sound as marked by the black triangle in Figure 11 (a).

The black rectangle in Figure 11 (a) is enlarged into the panel (c) on the right, for showing the change of the model mesh structure and bathymetry in comparison to the 2008 model as shown in (b). As discussed in Section 1 and shown in Figure 1, the shoreline at the Fire Island on the south shore of Long Island, New York included significant changes. Note the new opening in the shoreline (marked in a black circle) which was created by 2012 Hurricane Sandy, as well as the localized shoreline and bathymetry changes in comparing Figure 11 (b) and (c).

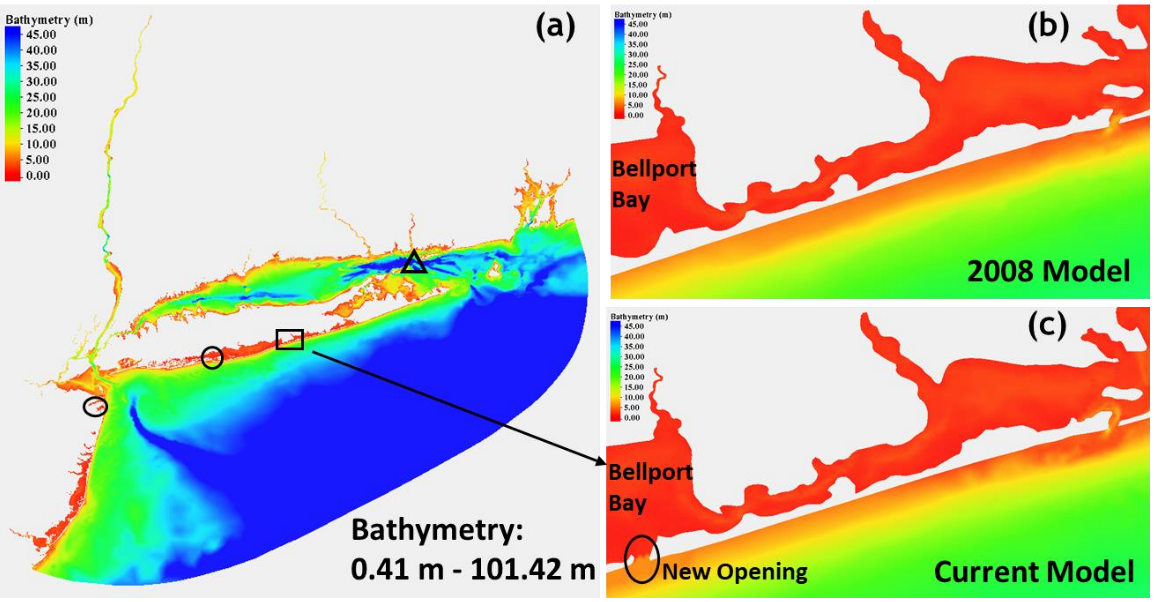

Figure 11. The updated model bathymetry (a). The black rectangle in panel (a) is enlarged into the panel (c) to the right to highlight some updates to model mesh structure and bathymetry in comparing to the 2008 model (b), including a new opening (marked in a black circle) in the shoreline which connects Bellport Bay to the open ocean. In the panel (a): The two black circles mark the locations with the shallowest bathymetry (0.41 m), and the black triangle marks the location with the deepest bathymetry (101.42 m).

3.4. Model Configuration

ADCIRC key model parameter settings in the update are similar to that used in the 2008 model, with slight variations in the bottom friction and the open ocean boundary forcing setting. The model parameter settings include:

(1) Nonlinear quadratic bottom friction with a spatially constant bottom friction coefficient of 0.0025, except for the Hudson River where the bottom friction coefficient quasi-linearly decreases from 0.0025 to zero right at Spuyten Duyvil Creek toward the North (Figure 12).

The reason of setting the Hudson River's bottom friction coefficient as zero is that the modeled tidal datums in Hudson River were heavily influenced by bottom friction setting in ADCIRC, and by setting zero bottom friction in Hudson River the modeled tidal datum errors were significantly reduced. The largest reduction in error of modeled versus observed datums occurred at the tide station situated near the northern extent of the model domain in Hudson River, dropping from 45 cm to 7 cm.

This bottom-friction influence was probably induced by the naturally tilted topographic structure of the long river included in the model, with a total length of more than 250 km within the model domain. The two-dimensional hydrodynamic model (ADCIRC) does not count the natural topographic impact. For a long river like Hudson, zero bottom friction setting is effective to fix this issue. However, zero bottom friction is not real.

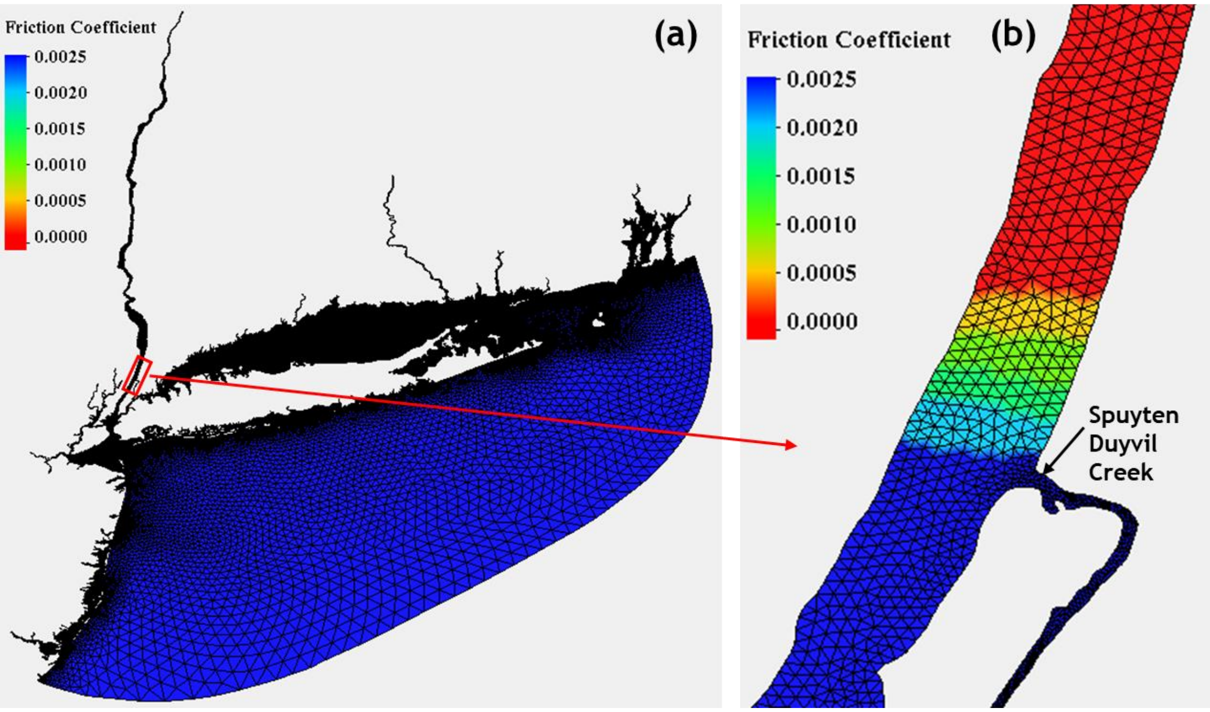

Figure 12. The updated model nonlinear quadratic bottom friction (a) with a spatially constant bottom friction coefficient of 0.0025, except for the Hudson River where the bottom friction coefficient linearly decreases from 0.0025 to zero right at Spuyten Duyvil Creek toward the North. A zoomed view of the Hudson River area delineated by the red box in panel (a) is shown in panel (b), showing the quasi-linear transition of the bottom friction setting.

The 2008 model used a quadratic friction scheme with a spatially varying bottom-friction coefficient setting. The spatially varying bottom-friction coefficient setting in the 2008 model was obtained by conducting sensitivity tests to mitigate model-data discrepancy of tidal datums (Yang et al. 2008).

(2) A spatially constant horizontal eddy viscosity of 6.0 m^2/s for the momentum equations;
(3) Wetting and drying process enabled with a minimum water depth of 0.05 m as a wet node/element criterion;
(4) A spatially uniform Generalized Wave-Continuity Equation (GWCE) weighting factor of 0.005;
(5) Advective terms were included;
(6) No atmospheric forcing and no river flow were imposed;
(7) Tidal potential body force of the nine principal tidal constituents (K1, O1, P1, Q1, M2, S2, N2, K2, and M4) was included;
(8) A total of 60 days as the ADCIRC model run time which uses a time step of 1 second. A hyperbolic tangent ramp function was specified, and the beginning 10 days were used to ramp up ADCIRC forcing from zero. The output from the ADCIRC model run consists of 6-minute water level time series at each model grid point from the final 50 days of the simulation. Modeled tidal datums were computed using the modeled 6-minute water level time series at each model grid point.

The updated tide model used the open ocean boundary forcing which equals the sum of the elevations of the nine tidal harmonic constituents (K1, O1, P1, Q1, M2, S2, N2, K2, and M4). The nine tidal harmonic constituents were extracted from the EC2015 tidal database (Szpilka et al. 2016), available at http://adcirc.org/products/adcirc-tidal-databases/. In contrast, the 2008 tide model calculated its open ocean boundary forcing by using the harmonic constants of seven astronomical tidal constituents (K1, O1, Q1, M2, S2, N2, and K2) (Yang et al. 2008).

4. MODEL RESULTS, VALIDATION, and STATISTICAL INTERPOLATION

4.1. Model Results and Validation

ADCIRC simulated water level time series at 6-minute intervals were used to compute modeled tidal datums in reference to LMSL: MHHW, MHW, MLW, MLLW, DTL, and MTL. Tidal datums were resolved using mean values associated with the semi-diurnal water level time series extrema using Coast Survey Development Laboratory FORTRAN software program lv8j.f; lv8j.f is an improved version of the initial code developed in early 2000s (Hess 2001). The six modeled tidal datums (MHHW, MHW, MLW, MLLW, DTL, and MTL) after deducting the model derived LMSL (shown in Figure 13) were first validated by using the observed tidal datums at the 174 tide stations (Figure 14a). Model grid points with large model errors (>0.20 m) were identified which were located in Hudson River, New York Harbor, Connecticut River, and Housatonic River. The criteria of 0.20 m was determined by considering the model domain's tidal range based on observations and the 2008 tide model, and the magnitude of the observed tidal datum's RMS errors in the model domain.

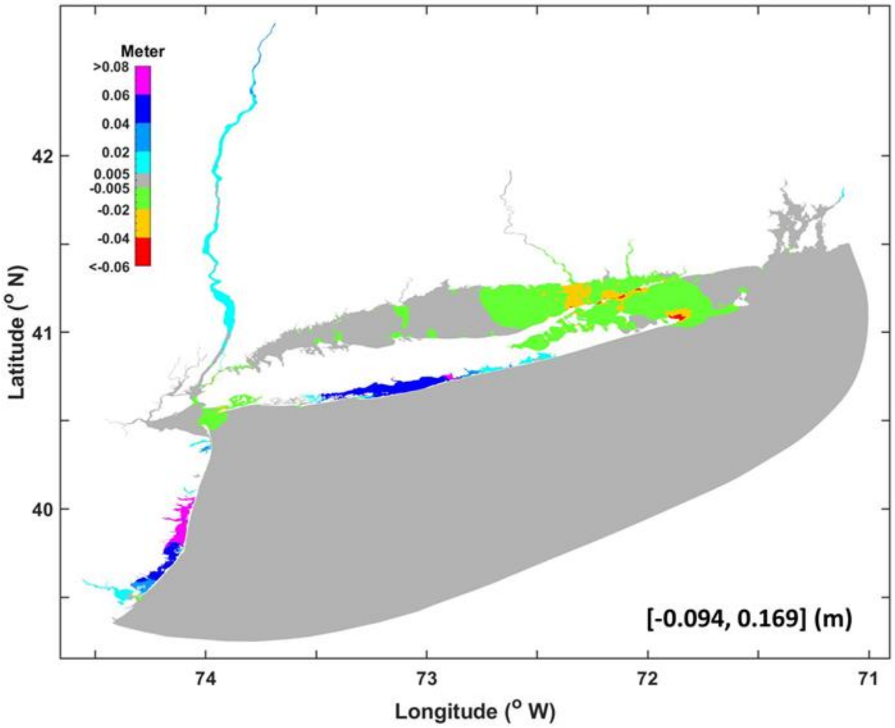

Figure 13. The correction in the LMSL resulting from the ADCIRC hydrodynamic simulation of water level height.

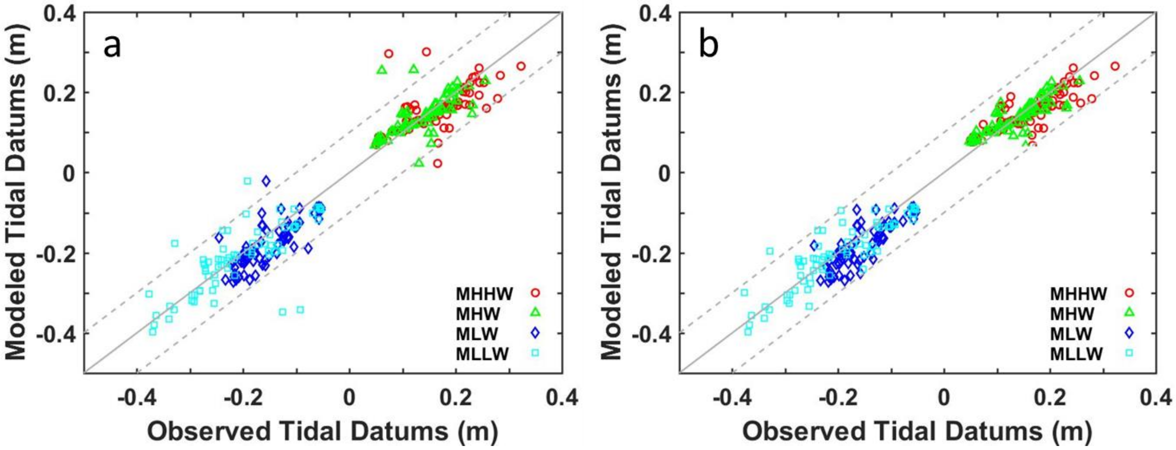

Figure 14. Modeled tidal datums vs observed tidal datums at 174 tide station locations, before (a) and after (b) model adjustments. The dashed lines represent 0.20 m error limits.

The quality of bathymetry data initially assigned in the four identified areas with large model errors (>0.20 m) was investigated, prompting the refinements using the bathymetry sources outlined in Section 2.2. We found that the bathymetry data initially assigned in the prior model differed from the most recently available USACE survey data [Figure 4(d)-(g)] in the four problematic areas (Connecticut River, Housatonic River, Hudson River, and New York Harbor). The previously assigned bathymetry in part of Hudson River also exhibited differences in comparison with the NOAA charted bathymetry [Figure 5(a)-(b)]. So, the most recently available USACE survey data in the four areas and the two ENCs' bathymetry data were used to refine the initial bathymetry assignments and then re-run the ADCIRC model. The errors in modeled tidal datums were significantly reduced after refining the bathymetry in the four areas, except that two tide stations in the northern extent of Hudson River still showed large errors.

To mitigate the large errors in the northern region of Hudson River, we adjusted the bottom friction setting in Hudson River by using the quasi-linear transition of the bottom friction coefficient setting from 0.0025 to zero right at Spuyten Duyvil Creek toward the North as shown in Figure 12. The purpose of zero bottom friction setting in Hudson River is to lessen the negative impact of the naturally tilted topographic structure of the long river on the performance of the ADCIRC hydrodynamic model as mentioned in Section 3.4. Figure 14b shows that the modeled tidal datum errors were significantly reduced after refining the model bathymetry and adjusting model bottom friction.

Figure 15 shows a representative example of the geographic distributions of ADCIRC model errors in MHHW before (a) and after (b) the model improvement as discussed above. The model errors in the other three major tidal datums (MHW, MLW, and MLLW) have similar situations. The large ADCIRC model errors (> 0.20 m) were reduced significantly after the model improvement, with most of the model errors less than 0.15 m. However, there was a remaining tide station in Hudson River with a model error greater than 0.20 cm. One contributing factor to this is likely due to the fact that no recent bathymetry data were available in this region.

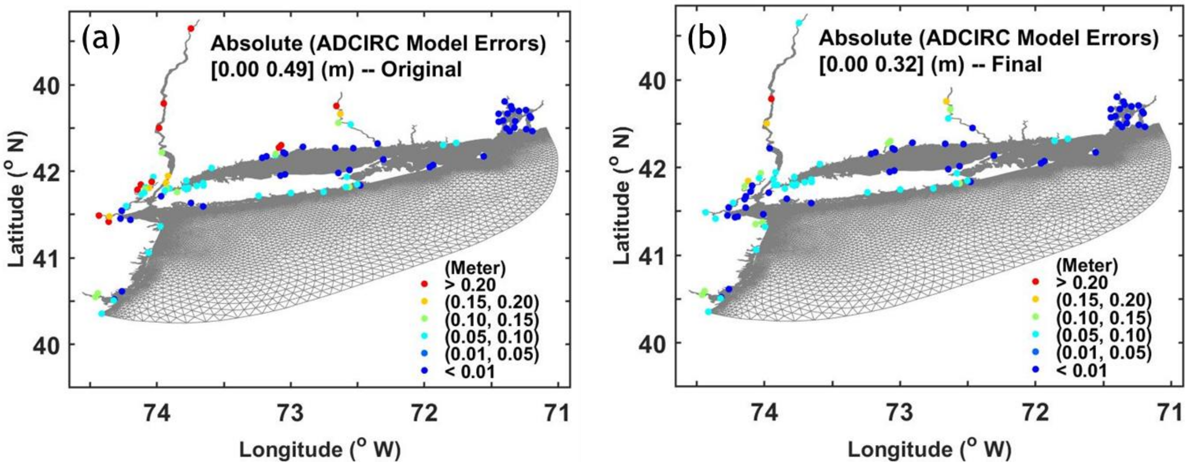

Figure 15. The geographic distributions of the absolute values of ADCIRC model errors in MHHW before (a) and after (b) the model improvement. The model error refers to modeled MHHW minus observed MHHW.

Accurate bathymetry data are indeed crucial to model performance. For example, Figure 16 shows the errors in ADCIRC modeled MHHW before (a) and after (b) using the most recently available USACE bathymetry survey data (collected in December 2017), showing that good-quality bathymetry data can significantly reduce model errors and therefore enhance model performance.

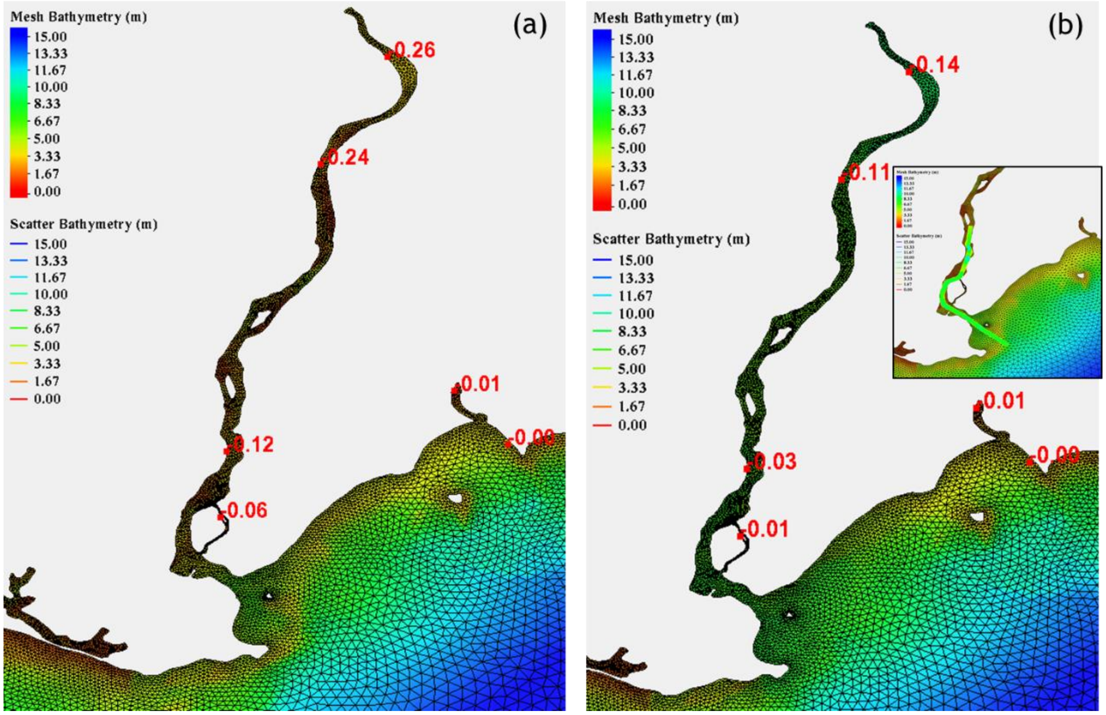

Figure 16. The errors in the ADCIRC modeled MHHW (scatter numbers in red: modeled MHHW minus observed MHHW) before (a) and after (b) using the most

recently available USACE bathymetry survey data collected in the Housatonic River [scatter dots in the plot embedded in (b)].

The modeled four major tidal datums (MHHW, MHW, MLW, and MLLW) from the current updated tide model and from the 2008 tide model are shown in Figure 17 and Figure 18, respectively. The general patterns of the modeled tidal datums from the current model and from the 2008 model look similar in Long Island Sound, New York Bight, and New York Harbor. In those regions, the magnitude of the modeled tidal datums generally increases from the east to the west, which is also consistent with the results shown even in the earlier tidal datum modeling (Hess, 2001). The magnitude of the modeled tidal datums in Hudson River decreases from New York Harbor northward for two-thirds of the river length in the model domain, followed by an increase proceeding further upriver. The magnitude of the modeled tidal datums in Connecticut River decreases from the river entrance to the upstream. Tidal datums in Narragansett Bay show a slight increase in magnitude from the entrance toward the bay interior. The largest magnitude in the tidal datums is seen in the western area of Long Island Sound. The smallest tidal datum magnitudes are in the eastern area of Long Island Sound, the coastal water areas of the eastern and southern Long Island, and the coastal water areas of New Jersey and Philadelphia.

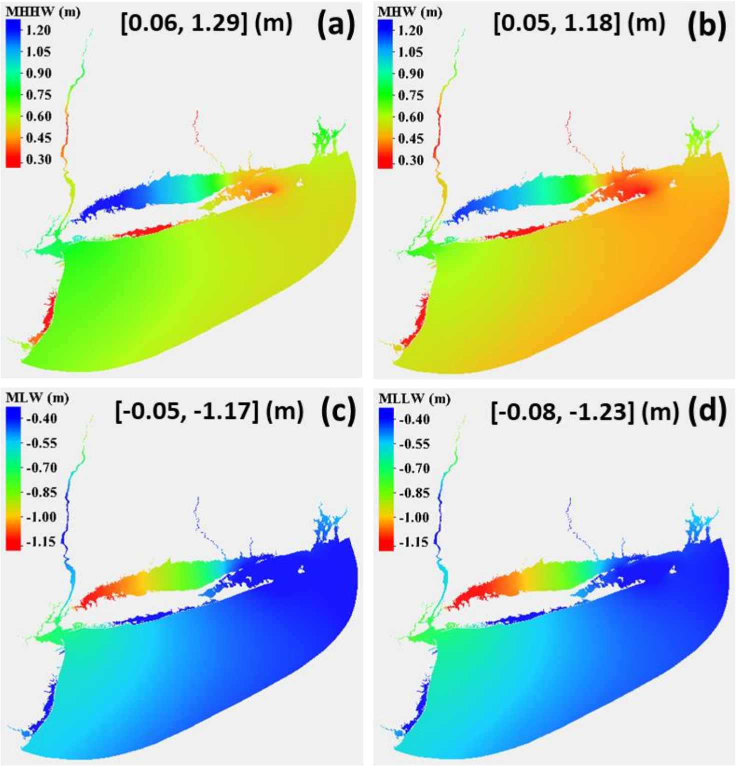

Figure 17. ADCIRC tidal datum model results from the current updated model; height, in meters: (a) MHHW-LMSL, (b) MHW-LMSL, (c) MLW-LMSL, and (d) MLLW-LMSL. Minimum and maximum values are shown in brackets.

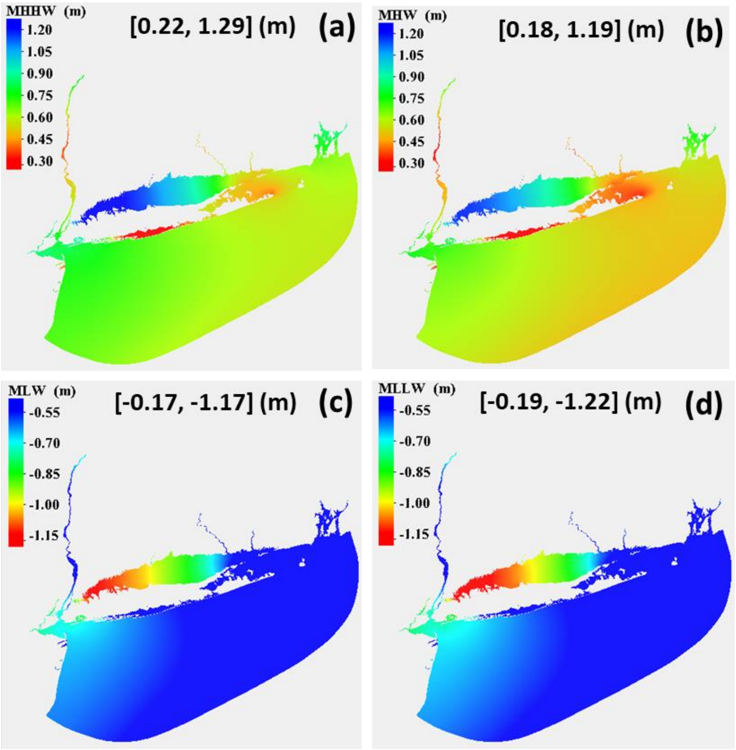

Figure 18. ADCIRC tidal datum model results from the 2008 model; height, in meters: (a) MHHW-LMSL, (b) MHW-LMSL, (c) MLW-LMSL, and (d) MLLW-LMSL. Minimum and maximum values are shown in brackets.

Figure 19 shows the differences of the modeled four major tidal datums between the current updated tide model and the 2008 tide model in their common model areas. The largest difference is up to 0.40 m for MHHW, 0.38 m for MHW, 0.50 m for MLW, and 0.55 m for MLLW. Most areas show small differences (< 0.10 m). The large differences (> 0.10 m) tend to occur in rivers and coastal embayments.

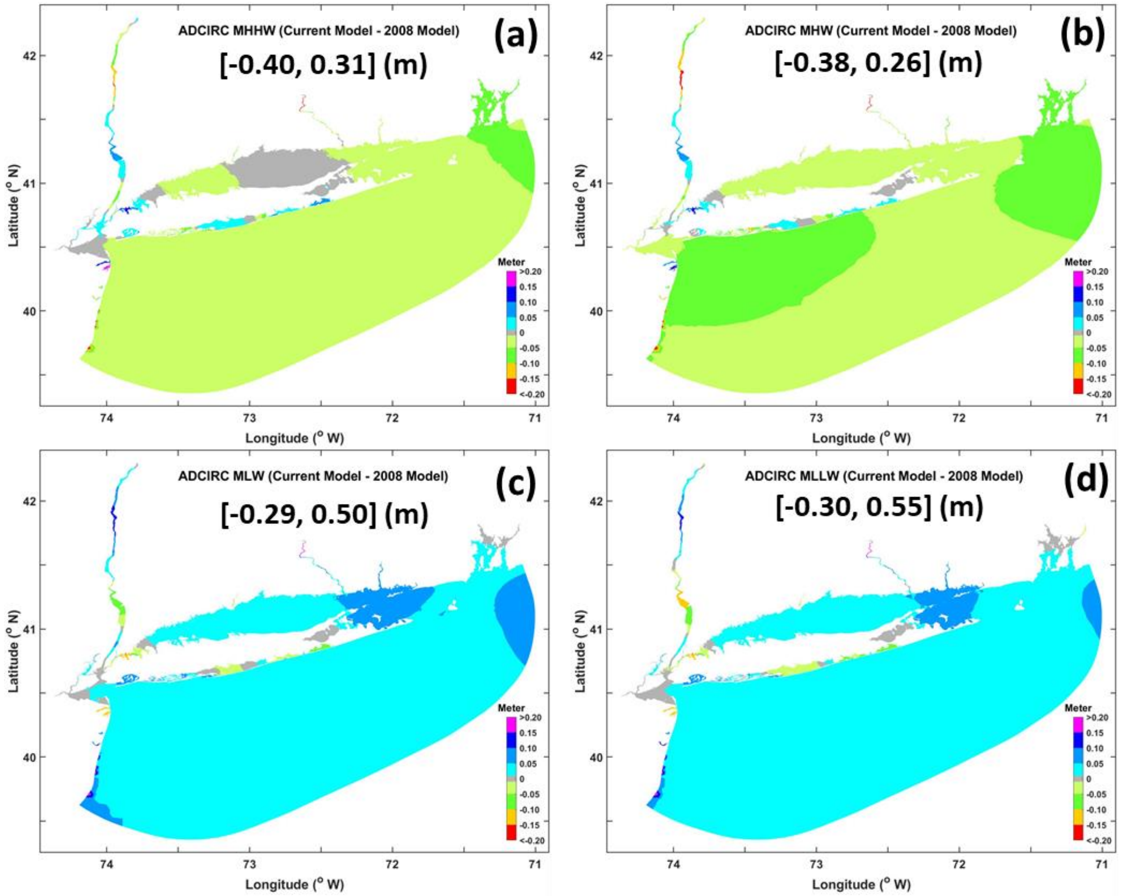

Figure 19. Differences of the ADCIRC modeled tidal datums (tidal datums from the current updated tide model minus those from the 2008 tide model): (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW. The minimum and maximum differences are shown in brackets. Grey areas represent small differences within ±0.01 m.

4.2. Statistical Interpolation and Spatially Varying Uncertainty (SVU)

After the errors in the ADCIRC modeled tidal datums were reduced, the ADCIRC modeled tidal datums were interpolated by using observed tidal datums and their RMS errors via a statistical interpolation SVU method (Shi and Myers 2016).

Shi and Myers (2016) showed that the SVU statistical interpolation method was developed based on the variational principle. First, a cost function was constructed according to the error covariance of the observed and modeled tidal datums. Then, a blended tidal datum field was derived by optimizing the cost function. The associated uncertainty was calculated for the blended tidal datum field as an auxiliary product. As stated in Shi and Myers (2016), the statistical interpolation has a few advantages over the traditional deterministic correction method: 1) It provides a spatially varying uncertainty throughout the domain; 2) It provides a framework to assimilate future data streams within a user-defined model error to improve the quality of the final tidal datum products; and 3) It reduces model bias, maximum absolute model error, mean absolute model error, and RMS of the model errors in comparison with the traditional deterministic approach which was based on the application of Laplace's Equation (Hess et al., 1999; Hess et al., 2012; Hess 2002; Hess 2003).

ADCIRC modeled tidal datums, and the modeled tidal datums after the SVU statistical interpolation and their associated spatially varying uncertainties of MHHW/MHW, MLW/MLLW, and DTL/MTL are shown in Figures 20, 21, and 22 respectively.

Similar to the observed tidal datums (Figure 8) and the 2008 modeled tidal datums (Figure 18), the current updated modeled four major tidal datums (MHHW, MHW, MLW, and MLLW) showed an overall trend of magnitude increase from the eastern model region to the western model region. The large values of the modeled tidal datums (> 1.00 m) occur in the western area of Long Island Sound, and the smallest values occur in New Jersey coastal embayment, the middle part of Hudson River, the extent of the Connecticut River, the east end of Long Island Sound, and in the middle area of Long Island south shore.

The spatially varying uncertainty of the modeled four major tidal datums computed by the SVU statistical interpolation method showed the largest for MLLW (up to 0.063 m), the second largest for MLW (0.056 m), the third largest for MHHW (0.045 m), the smallest for MHW (0.042 m). The spatially varying uncertainty was small at nodes close to the coastal lines and tide stations, and was relatively large otherwise. The largest uncertainties were located at the open ocean boundary where no tide stations existed and the distance to the available tide stations was the greatest. As explained in (Wu et al. 2019), since the RMS errors of the observed tidal datums at each tide station were the same for all the tidal datums, the differences among tidal datums' spatially varying uncertainties were mainly determined by the differences in the model error covariance which was different for different tidal datums. Also, because the covariance was adjusted and decreases exponentially over the distance to tide stations, the greater the distance from a node to tide stations, the larger the SVU uncertainty at the node, which explains why the greatest SVU uncertainty was located near the open ocean boundary.

The current model simulated DTL and MTL showed positive, relatively large values in the eastern model domain in the Narragansett Bay and its surrounding areas, east of Long Island Sound and the coastal areas of Long Island Forks. Negative small values of DTL and MTL were located in the Hudson River, at the east end of Long Island Sound, and at the Long Island South Shore. The spatially varying uncertainty of DTL and MTL were relatively evenly distributed in comparison with the four major tidal datums (MHHW, MHW, MLW, and MLLW). Relatively large uncertainty values were located in the Hudson River and from the coastal area of Long Island South Shore to the open ocean boundary. The largest uncertainties are 0.021 m for DTL and 0.022 m for MTL, respectively.

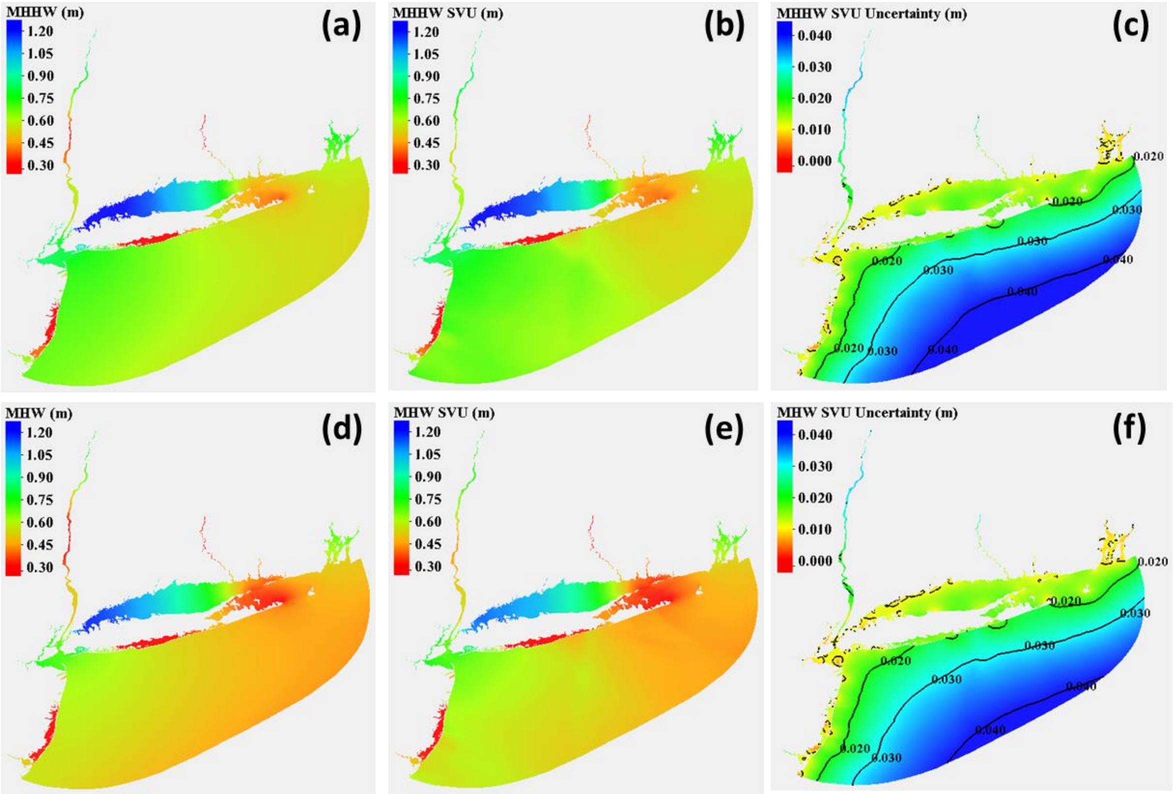

Figure 20. Modeled tidal datums: MHHW [(a) to (c)] and MHW [(d) to (f)]. The first column [(a) and (d)] shows ADCIRC modeled tidal datums; the second column [(b) and (e)] shows the tidal datums after the SVU statistical interpolation; the third column [(c) and (f)] shows the associated SVU spatially varying uncertainties.

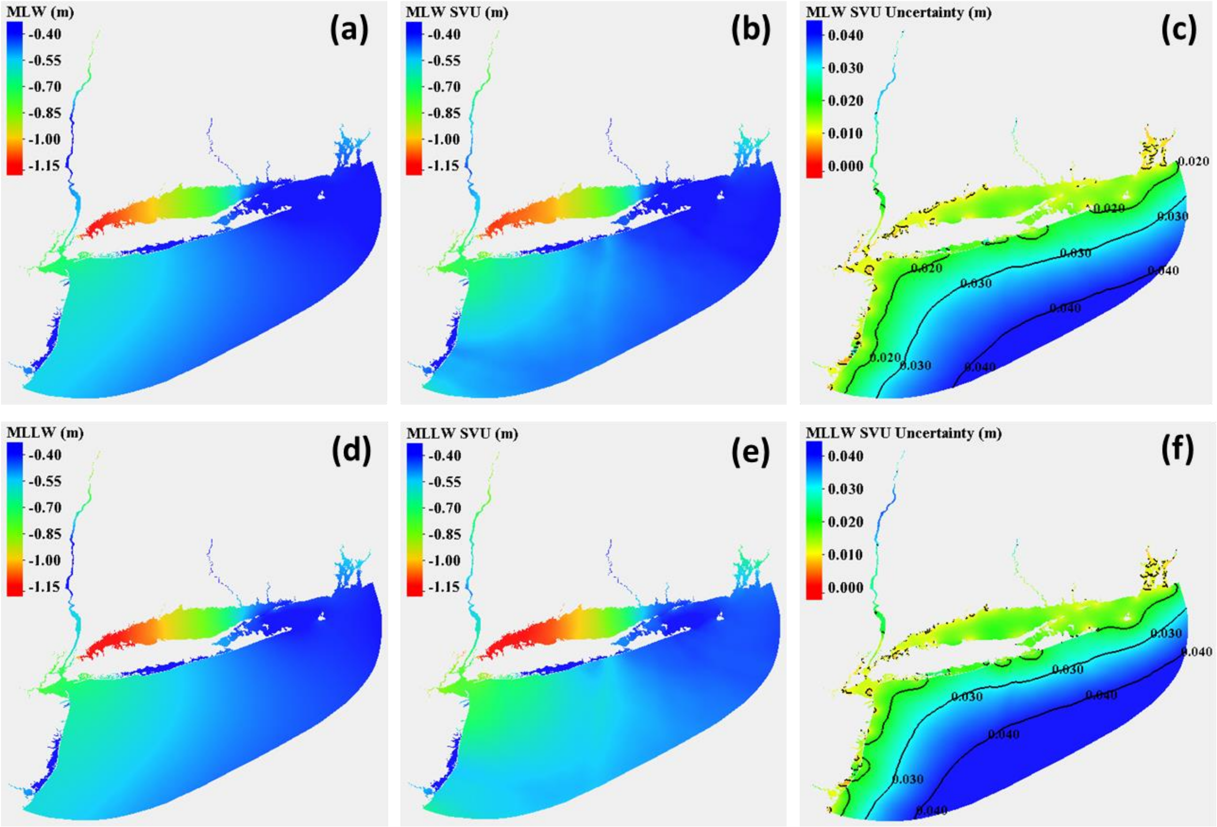

Figure 21. Modeled tidal datums: MLW [(a) to (c)] and MLLW [(d) to (f)]. The first column [(a) and (d)] shows ADCIRC modeled tidal datums; the second column [(b) and (e)] shows the tidal datums after the SVU statistical interpolation; the third column [(c) and (f)] shows the associated SVU spatially varying uncertainties.

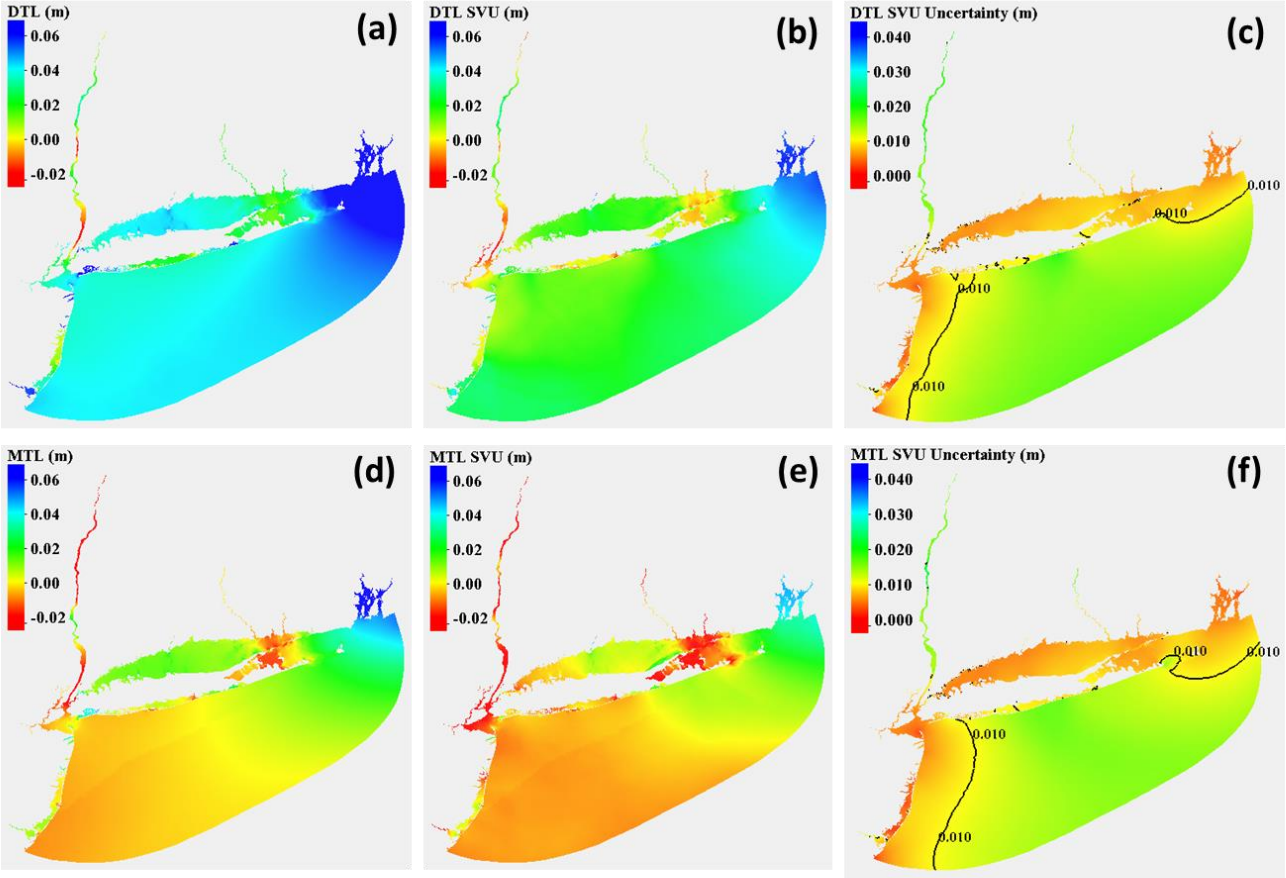

Figure 22. Modeled tidal datums: DTL [(a) to (c)] and MTL [(d) to (f)]. The first column [(a) and (d)] shows ADCIRC modeled tidal datums; the second column [(b) and (e)] shows the tidal datums after the SVU statistical interpolation; the third column [(c) and (f)] shows the associated SVU spatially varying uncertainties.

Table 1 lists the summary statistics (minimum, maximum, mean, and standard deviation) of the observed tidal datums at the 174 tide stations which were located in coastal regions within the model domain. The maximum values of the observed tidal datums are 1.24 m (MHHW), 1.13 m (MHW), -1.12 m (MLW), and -1.20 m (MLLW). The minimum values of the observed tidal datums are in the order of centimeters. The mean values of the observed tidal datums range from 0.65 m to 0.74 m. The standard deviations of the observed tidal datums are 0.28 m for MHHW and MLLW, and 0.27 for MHW and MLW.

Table 1. Statistics of observed tidal datums (in units of meters).

Statistics	MHHW	MHW	MLW	MLLW
Minimum	0.08	0.03	-0.07	-0.09
Maximum	1.24	1.13	-1.12	-1.20
Mean	0.74	0.65	-0.66	-0.71
Standard Deviation	0.28	0.27	0.27	0.28

Table 2 lists the summary statistics (minimum, maximum, mean, and standard deviation) of the ADCIRC modeled tidal datums (in the entire model domain). The magnitudes of the minimum, maximum and mean values of the ADCIRC modeled tidal datums are similar to those of the observed tidal datums at the 174 tide stations. The standard deviations of the ADCIRC modeled tidal datums show a few centimeters larger in comparison with the observations.

Table 2. Statistics of ADCIRC modeled tidal datums (in units of meters).

Statistics	MHHW	MHW	MLW	MLLW	MTL	DTL
Minimum	0.06	0.05	-0.05	-0.08	-0.06	-0.04
Maximum	1.29	1.18	-1.17	-1.22	0.17	0.23
Mean	0.75	0.66	-0.64	-0.67	0.01	0.04
Standard Deviation	0.32	0.31	0.30	0.31	0.02	0.02

Table 3 shows the summary statistics of the ADCIRC modeled tidal datum errors. The model errors are up to 0.31 m for MHHW, up to 0.31 m for MHW, up to 0.23 m for MLW, and up to 0.29 m for MLLW. The largest model errors are situated in the areas where bathymetry survey data are lacking such as Hudson River and some upstream areas near New York Harbor.

The mean values of model errors are small: 0.003 m for MHHW, -0.001 m for MHW, 0.029 m for MLW, and 0.053 m for MLLW. The mean values of absolute model error are 0.04 m for MHHW and MHW, 0.05 m for MLW, and 0.06 m for MLLW. The standard deviations of the model errors range from 0.05 m to 0.06 m. The RMS of the model errors are 0.06 m for MHHW, 0.05 m for MHW, 0.06 m for MLW, and 0.08 m for MLLW. According to Table 3, the largest model error occurs in MLLW, the next largest in MLW, and the model errors in the MHHW are comparable to but slightly larger than those in MHW.

Table 3. Statistics of the ADCIRC model errors in simulated tidal datums (in units of meters).

Statistics	MHHW	MHW	MLW	MLLW
Minimum	-0.319	-0.307	-0.090	-0.089
Maximum	0.140	0.107	0.232	0.289
Mean	0.003	-0.001	0.029	0.053
Mean of Absolute Error	0.036	0.036	0.046	0.062
Standard Deviation	0.055	0.052	0.055	0.061
RMS of Model Errors	0.055	0.052	0.062	0.080

Tables 4 lists the summary statistics of the modeled tidal datums after the SVU statistical interpolation. Table 5 summarizes the statistics of the SVU-interpolated datums' uncertainties. The modeled tidal datums after the SVU statistical interpolation are close to the observed tidal datums at all the tide stations to less than 0.010 m as constrained by the SVU methodology. The largest differences (of the minimum, maximum and mean tidal datum values) before and after the SVU statistical interpolation are: 1) 0.05 m in the minimum values of MHHW, MHW, or MLLW; 2) 0.05 m in the maximum values of MHHW and MHW; 3) 0.04 m in the mean MLLW. The standard deviations before and after the SVU statistical interpolation are the same except for MLLW which increased 0.01 m after the SVU statistical interpolation.

The minimum values of the tidal datum spatially varying uncertainties are all equal to 0.001 m. The maximum values of the tidal datum spatially varying uncertainties range from 0.021 m (DTL) to 0.063 m (MLLW). The mean values of the tidal datum spatially varying uncertainties range from 0.007 m (for MTL and DTL) to 0.014 m (for MLLW). The standard deviations of the tidal datum spatially varying uncertainties are small, ranging from 0.003 m (MTL and DTL) to 0.005 m (MLLW).

Table 4. Statistics of the SVU-statistically-interpolated modeled tidal datums (in units of meters).

Statistics	**MHHW**	**MHW**	**MLW**	**MLLW**	**MTL**	**DTL**
Minimum	0.01	0.00	-0.01	-0.03	-0.08	-0.07
Maximum	1.24	1.13	-1.13	-1.21	0.15	0.19
Mean	0.74	0.65	-0.65	-0.71	0.00	0.01
Standard Deviation	0.32	0.31	0.30	0.32	0.02	0.02

Table 5. Statistics of the spatially varying uncertainties of the SVU-statistically-interpolated modeled tidal datums (in units of meters).

Statistics	**MHHW**	**MHW**	**MLW**	**MLLW**	**MTL**	**DTL**
Minimum	0.001	0.001	0.001	0.001	0.001	0.001
Maximum	0.045	0.042	0.056	0.063	0.022	0.021
Mean	0.013	0.012	0.013	0.014	0.007	0.007
Standard Deviation	0.004	0.004	0.004	0.005	0.003	0.003

5. CREATION AND POPULATION OF VDATUM MARINE GRID

5.1. Creation of VDatum Marine Grids

Modeled tidal datum fields are sampled on a series of regular "marine grids" for use in the VDatum software. The standard spatial resolution of each marine grid is set to 0.001 degree in both zonal (longitude) and meridional (latitude) directions. Due to the large size of the model domain and the very high spatial resolution of the VDatum marine grids, four bounding polygons were created for the need of the VDatum marine grid generation (as shown in Figure 23). The bounding polygons are designed non-overlapping but sharing common borders. In the VDatum system, the bounding polygons are used to determine the appropriate marine grid regions for datum transformations at arbitrary points.

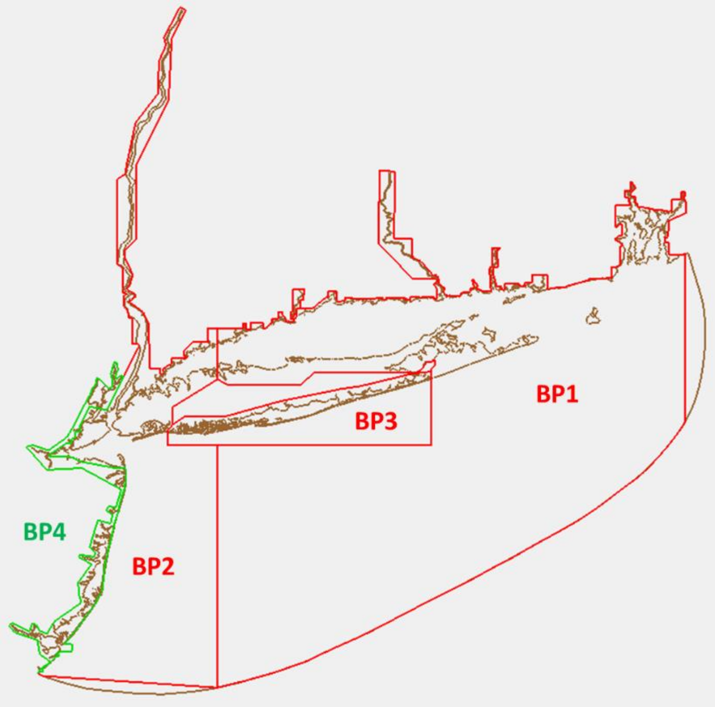

Figure 23. Four bounding polygons (the closed red lines: BP1, BP2 and BP3, and a closed green line: BP4) created for VDatum marine grid products. Brown lines are model boundaries including shorelines and open ocean boundary.

An example of the geographic structure of the generated VDatum marine grids was shown in Figure 14 in Wu et al. (2019). The generated VDatum marine grids include seven layers (Layer 1: Land, Layer 2: Water, Layers 3 to 7: Added water layers 1 to 5 landward). Each node in the marine grid field is designated as either a water node or a land node based on the high resolution shoreline data and the four bounding polygons (Figure 23). Five artificial water layers were added landward from the shoreline in the marine grid generation for extending the non-null water points over land, which allows datums to extend artificially to land for people who need the datum information. Summary information of marine grid boundary limits and grid sizes are listed in Table 6.

Table 6. VDatum marine grid information for the four VDatum regions.

VDatum Region	Longitude-Latitude Window	Zonal Spacing (deg)	Vertical Spacing (deg)	No. of Zonal Nodes	No. of Vertical Nodes
R1	[39.2813 41.9305 -73.5031 -71.1024]	0.001	0.001	2402	2651
R2	[39.2813 42.7668 -74.4293 -73.5031]	0.001	0.001	928	3487
R3	[40.5213 40.9008 -73.7605 -72.4063]	0.001	0.001	1356	381
R4	[39.4109 40.9494 -74.5721 -73.9729]	0.001	0.001	601	1540

An overview of the generated VDatum marine grid in the four VDatum regions (i.e., the geographic coverage of the current updated VDatum products) is shown in Figure 24.

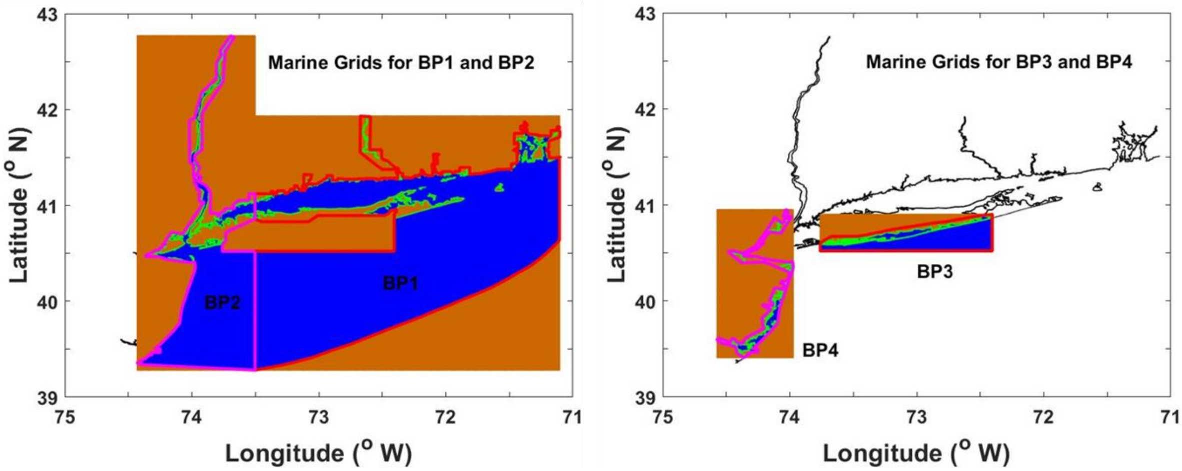

Figure 24. The generated VDatum marine grids in the four VDatum regions. Blue and green dots represent water nodes and brown dots represent land nodes. BP1, BP2, BP3, and BP4 are the four bounding polygons as shown in Figure 23.

5.2. Population onto VDatum Marine Grids with the SVU-Statistically-Interpolated Modeled Tidal Datums and Their Associated Spatially Varying Uncertainties

This section details VDatum marine grid population. The SVU-statistically-interpolated modeled tidal datums and their associated spatially varying uncertainties were populated onto the water nodes of the VDatum marine grids by average or linear interpolation. The methodology about the VDatum marine grid population can be found in Hess et al. (2012).

Figure 25 shows an example of the assembly of the SVU-statistically-interpolated modeled tidal datum (MHHW) before and after conducting the VDatum marine grid population across the four bounding polygon regions.

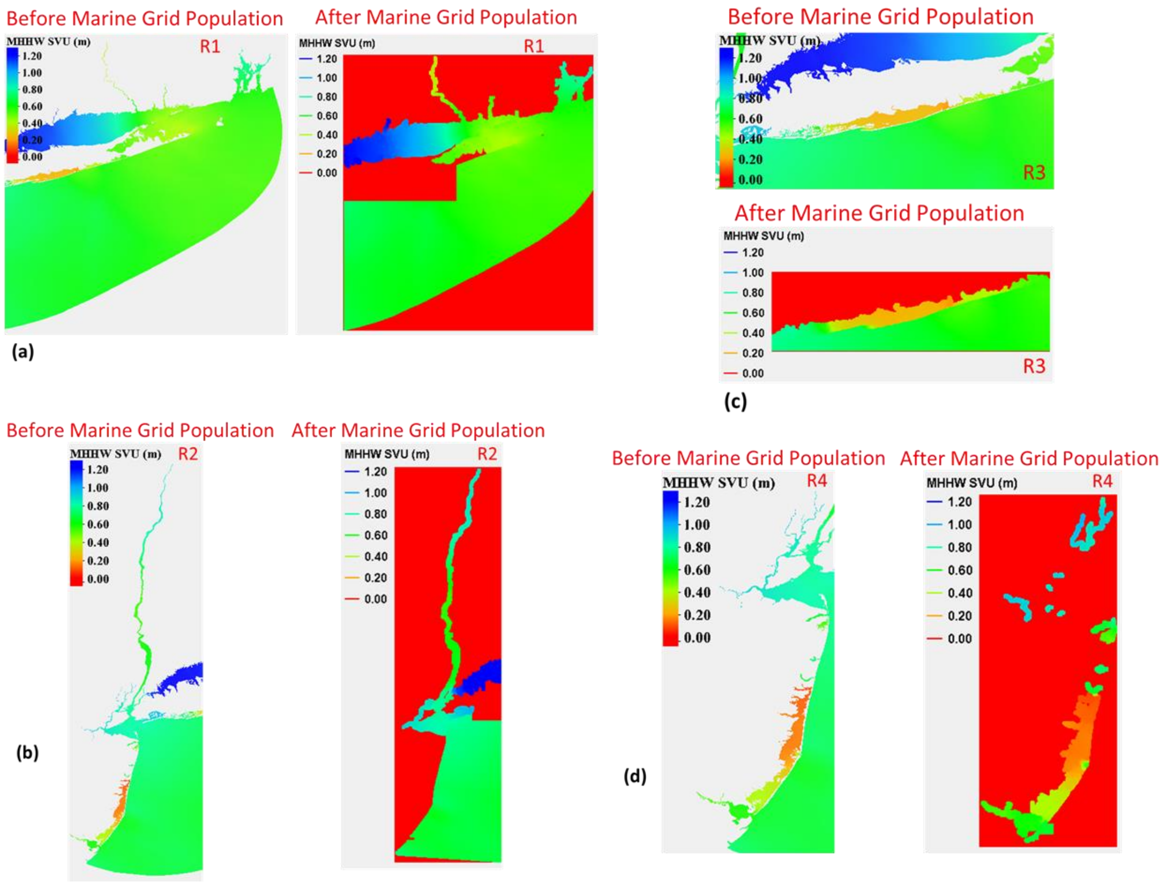

Figure 25. The SVU-statistically-interpolated modeled tidal datum (MHHW-SVU) before (left) and after (right) the VDatum marine grid population in the four VDatum marine grid regions.

The marine grid population was conducted for each of the six tidal datums in each of the four VDatum marine grid regions respectively. Tables 7 and 8 list the descriptive statistics of the SVU-statistically-interpolated modeled tidal datums and their associated spatially varying uncertainties in the four VDatum regions after the VDatum marine grid population.

Table 7. Descriptive statistics of the marine grid populated SVU-statistically-interpolated modeled tidal datums in the four designated marine grid regions. Tidal datums are relative to LMSL and in units of meters.

Region	Tidal Datum	Minimum	Maximum	Mean	Standard Deviation
R1	MHHW	0.326	1.221	0.617	0.145
R1	MHW	0.247	1.113	0.524	0.141
R1	MLW	-1.113	-0.278	-0.499	0.144
R1	MLLW	-1.184	-0.319	-0.551	0.151
R1	DTL	-0.017	0.111	0.025	0.011
R1	MTL	-0.037	0.083	0.000	0.011
R2	MHHW	0.513	1.239	0.726	0.124
R2	MHW	0.409	1.127	0.624	0.122
R2	MLW	-1.131	-0.434	-0.611	0.139
R2	MLLW	-1.210	-0.480	-0.665	0.145
R2	DTL	-0.029	0.110	0.016	0.010
R2	MTL	-0.055	0.087	-0.010	0.007
R3	MHHW	0.162	0.784	0.564	0.142
R3	MHW	0.112	0.679	0.485	0.130
R3	MLW	-0.715	-0.141	-0.480	0.130
R3	MLLW	-0.774	-0.184	-0.527	0.137
R3	DTL	-0.024	0.053	0.013	0.007
R3	MTL	-0.042	0.023	-0.004	0.005
R4	MHHW	0.022	0.979	0.433	0.272
R4	MHW	0.012	0.873	0.357	0.251
R4	MLW	-0.990	-0.006	-0.378	0.265
R4	MLLW	-1.080	-0.034	-0.413	0.283
R4	DTL	-0.069	0.061	0.010	0.021
R4	MTL	-0.075	0.030	-0.009	0.016

Table 8. Descriptive statistics of the marine grid populated spatially varying uncertainties of the SVU-statistically-interpolated modeled tidal datums in the four designated marine grid regions. All are in units of meters.

Region	Tidal Datum Uncertainty	Minimum	Maximum	Mean	Standard Deviation
R1	MHHW	0.001	0.044	0.030	0.010
R1	MHW	0.001	0.042	0.028	0.010
R1	MLW	0.001	0.043	0.030	0.010
R1	MLLW	0.001	0.049	0.032	0.011
R1	DTL	0.001	0.017	0.013	0.003
R1	MTL	0.001	0.017	0.012	0.003
R2	MHHW	0.001	0.037	0.022	0.007
R2	MHW	0.001	0.035	0.021	0.007
R2	MLW	0.001	0.051	0.022	0.007
R2	MLLW	0.001	0.058	0.025	0.008
R2	DTL	0.001	0.020	0.010	0.003
R2	MTL	0.001	0.022	0.009	0.003
R3	MHHW	0.009	0.032	0.023	0.005
R3	MHW	0.009	0.031	0.022	0.005
R3	MLW	0.009	0.048	0.022	0.004
R3	MLLW	0.010	0.057	0.023	0.005
R3	DTL	0.008	0.021	0.014	0.003
R3	MTL	0.007	0.016	0.013	0.003
R4	MHHW	0.001	0.023	0.012	0.003
R4	MHW	0.001	0.022	0.011	0.003
R4	MLW	0.001	0.037	0.013	0.005
R4	MLLW	0.001	0.042	0.013	0.004
R4	DTL	0.001	0.018	0.006	0.003
R4	MTL	0.001	0.018	0.005	0.003

6. TOPOGRAPHY OF THE SEA SURFACE (TSS)

6.1 Generation of TSS field

The topography of the sea surface (TSS) is defined as the elevation of the North American Vertical Datum of 1988 (NAVD88: an orthometric datum) relative to LMSL. The TSS field provides the spatial variations between a mean sea-level surface and the NAVD88 geopotential surface. A positive value specifies that the NAVD 88 reference value is further from the center of the Earth than the LMSL surface (Hess et al. 2012). All data are based on the most recently available National Tidal Datum Epoch (1983-2001).

A total of 137 tide stations have observed TSS values in this model domain. The observed TSS and their corresponding standard deviations are listed in Appendix C. Figure 26 shows the locations of tide stations with a color code for the observed TSS values (left plot) and their corresponding standard deviations (right plot). The magnitude of the observed TSS in this model domain ranges from -0.32 m to 0.16 m. Most stations have observed TSS greater than zero. The observed TSS in the Hudson River and the Connecticut River are negative. The standard deviation of the observed TSS ranges from 0.02 m to 0.04 m, and is less than 0.03 m at most tide stations.

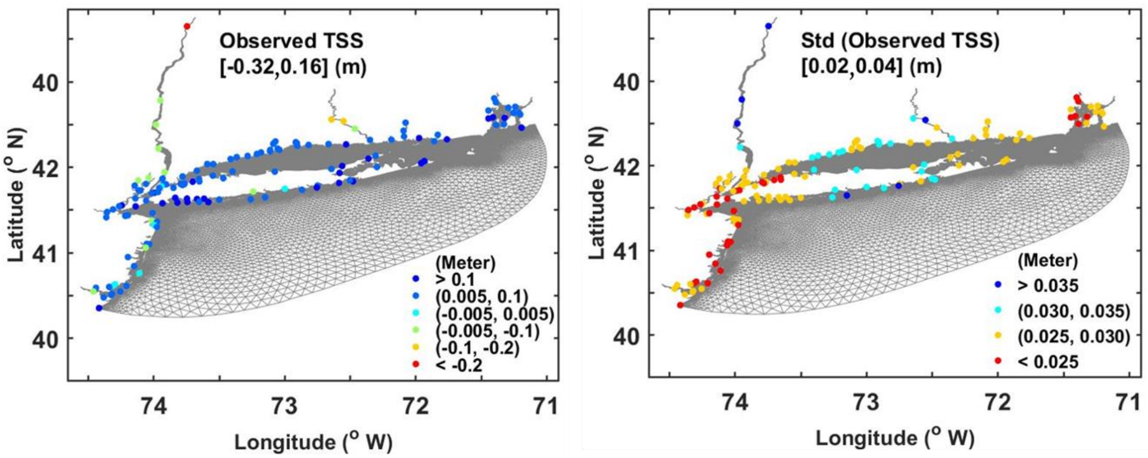

Figure 26. The observed TSS values and their corresponding standard deviations (Std) at 137 tide stations in this model domain.

The TSS field was derived by interpolating orthometric-to-MSL relationships which were obtained through the calculation of the NAVD88-to-MSL values at NOAA tide stations. Data for computing TSS values at tide stations were provided by NOAA NOS's CO-OPS and NGS. A mesh covering the entire area of benchmarks and tide stations with a spatial resolution similar to that of the tidal datum marine grids was created. Breaklines were taken into consideration in the interpolation module when generating TSS field for representing the influence of land. The TSS field was then 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 parameter value of 0.3 was utilized. Once the gridded TSS field was generated, null values representing the presence of land were obtained from the tidal datum marine grids and used to mask the TSS grid. Grid parameters for the TSS field are listed in Table 9. Note that only one TSS field (Figure 27) was created for all the four VDatum Regions in the model domain (i.e., R1, R2, R3 and R4). Along with the TSS field, its spatially varying uncertainty (SVU) filed (Figure 28) was also created using a rigorous error propagation approach. The final TSS field and its uncertainty field on the marine grids were then incorporated into the VDatum tool.

Table 9. VDatum TSS grid parameters; one TSS field covers all the four VDatum marine grid regions.

VDatum Region	Longitude-Latitude Window	Zonal Spacing (deg)	Meridional Spacing (deg)	No. of Zonal Nodes	No. of Meridional Nodes
R1, R2, R3 and R4	[39.2803 42.7663 -74.5721 -71.1021]	0.001	0.001	3471	3487

6.2 Interpolated TSS results

The interpolated TSS field (a) and its uncertainty field (b) are shown in Figure 27.

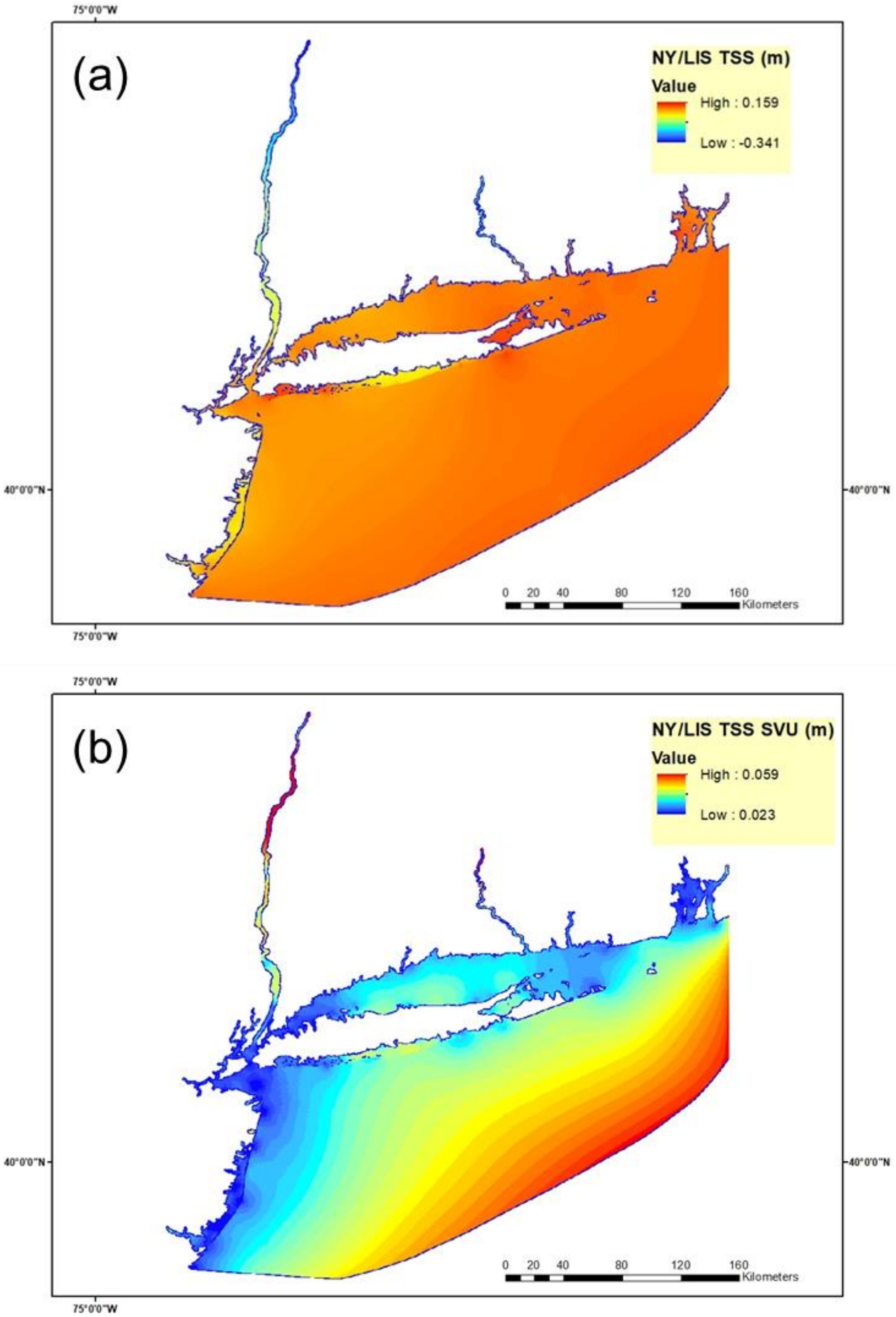

Figure 27. The interpolated TSS field (a) and its uncertainty field (b). The TSS field covers all the four VDatum regions (R1, R2, R3 and R4).

The statistical values of the interpolated TSS field and its uncertainty field are listed in Table 10.

Table 10. Statistics of the interpolated TSS field and the TSS uncertainty field (in units of meters).

Region	Field	Minimum	Maximum	Mean	Standard Deviation
R1, R2, R3 and R4	TSS	-0.341	0.159	0.086	0.033
R1, R2, R3 and R4	TSS Uncertainty	0.023	0.059	0.039	0.006

7. SUMMARY

This technical memorandum documents the modeling of the tidal datums (MHHW, MHW, MLW, MLLW, DTL, and MTL) and their associated spatially varying uncertainties in New York Bight, New York Harbor, Hudson River, Long Island Sound, and Narragansett Bay. This is an update of the previous tidal datum modeling in this model domain (Yang et al. 2008).

We first extended the previous model domain to include new tide stations and to incorporate most recently available shoreline data. Model mesh grids were generated in the updated model domain. The updated model mesh grids include 448,219 triangular finite elements and 250,569 model nodes.

A two-dimensional depth-integrated barotropic version of the ADCIRC hydrodynamic model (version 51.52.34, released in January 2016) was used to simulate 6-minute water level time series at each model grid point for 60 days. Modeled water level time series of the last 50 days were used for computing the six modeled tidal datums (MHHW, MHW, MLW, MLLW, DTL, and MTL).

Key model parameter settings include nonlinear quadratic bottom friction, spatially constant horizontal eddy viscosity, wetting and drying processes, a spatially uniform Generalized Wave-Continuity Equation (GWCE) weighting factor, advective terms, the tidal potential body force of nine principal tidal constituents (K1, O1, P1, Q1, M2, S2, N2, K2, and M4), and the open ocean boundary forcing that equals the sum of the elevations of the nine tidal harmonic constituents, extracted from the EC2015 tidal database (Szpilka et al. 2016). No atmospheric forcing and river flow were imposed.

The ADCIRC modeled tidal datums were first evaluated by comparing to observed tidal datums at 174 tide stations. The model grid locations with large (>0.20 m) model biases were identified, which were in Connecticut River, Housatonic River, New York Harbor, and Hudson River. The most recently available USACE survey bathymetry datasets and NOAA charted bathymetry data were used to refine model bathymetry to reduce model errors. Bathymetric data refinement significantly reduced errors in computed tidal datums, except for two stations situated in the northern extent of the Hudson River within the model domain.

For further reducing the large tidal datum errors happening in Hudson River, the bottom friction in Hudson River was set to zeros from the Spuyten Duyvil Creek to the north. The zero bottom friction setting in Hudson River is an effective technique used for reducing the large model errors in the northern extent of Hudson River which was probably caused by the negative impact of the naturally tilted topographic structure of the long Hudson River.

The resulting modeled tidal datums were blended with observed tidal datums using a SVU statistical interpolation method (Shi and Myers, 2016). The statistical interpolation method was developed based on the variational principle and was used to correct ADCIRC modeled tidal datums and to calculate a spatially varying uncertainty field for each SVU corrected tidal datum field. The SVU statistical interpolation method interpolated the modeled tidal datums to within a user-defined model error (0.01 m in this work) at each tide station. The produced spatially varying uncertainty field for each interpolated tidal datum field is an improvement over the previous interpolation method that only provided a single-value model uncertainty over an entire VDatum area (Shi and Myers 2016).

After that, four bounding polygons were created in this model domain for VDatum marine grid generation. The SVU-statistically-interpolated modeled tidal datums and their associated spatially varying uncertainties were interpolated onto those regularly distributed VDatum marine grids with spatial resolution of 0.001 degree in both zonal and meridional directions.

Finally, the TSS field and the TSS uncertainty field were created by NOAA NOS NGS by using observed TSS values and their corresponding standard deviations at 137 tide stations. The TSS field was created by interpolating orthometric-to-MSL relationships. The TSS uncertainty field was generated by using a rigorous error propagation approach.

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APPENDIX A. INFORMATION OF TIDE STATIONS

Below lists the information of a total of 174 tide stations used in this tidal datum modeling work in New York Bight, New York Harbor, Hudson River, Long Island Sound, and Narragansett Bay regions.

No.	Station ID	Longitude (°W)	Latitude (°N)	Station Location Name
1	8447281	-71.131700	41.740000	STEEPBROOK MASSACHUSETTS
2	8447386	-71.164100	41.704300	FALL RIVER, HOPE BAY MASSACHUSETTS
3	8450768	-71.193300	41.465000	SAKONNET RHODE ISLAND
4	8450898	-71.210000	41.651700	BAY OIL CORPORATION RHODE ISLAND
5	8450948	-71.211700	41.638300	ANTHONY POINT RHODE ISLAND
6	8450954	-71.203300	41.618300	NANNAQUAKET RHODE ISLAND
7	8451301	-71.236700	41.558300	THE GLEN,SAKONNET RIVER RI
8	8451351	-71.238300	41.486700	SACHUEST RHODE ISLAND
9	8451552	-71.255000	41.636700	BRISTOL FERRY RHODE ISLAND
10	8452154	-71.293300	41.696700	BRISTOL HIGHLANDS NARRAGENSETT BAY
11	8452555	-71.321700	41.580000	NAVY PIER, PRUDENCE ISLAND
12	8452660	-71.326700	41.505000	NEWPORT, NARRAGANSETT BAY RI
13	8452944	-71.343300	41.716700	CONIMICUT LIGHT, NARRAGANSETT BAY RI
14	8453033	-71.351700	41.751700	BAY SPRING, BULLOCK COVE RI
15	8453201	-71.361700	41.463300	CASTLE HILL RHODE ISLAND
16	8453433	-71.373300	41.840000	RUMFORD, SEEKONK RIVER RI
17	8453572	-71.378300	41.666700	WARWICK POINT
18	8453742	-71.386700	41.496700	WEST JAMESTOWN RHODE ISLAND
19	8453767	-71.388300	41.761700	PAWTUXET COVE, PROVIDENCE RIVER RI
20	8454000	-71.401200	41.807100	PROVIDENCE, PROVIDENCE RIVER RI
21	8454049	-71.411000	41.586800	QUONSET POINT RHODE ISLAND
22	8454341	-71.428300	41.460000	BOSTON NECK RHODE ISLAND
23	8454538	-71.445000	41.571700	WICKFORD, NARRAGANSETT BAY RI
24	8454578	-71.445000	41.665000	EAST GREENWICH, GREENWICH B. RI
25	8455083	-71.490000	41.363300	POINT JUDITH, HARBOR OF REFUGE RI
26	8455137	-71.241667	41.707778	KICKAMUIT RIVER RI
27	8455189	-71.832200	41.369500	WESTERLY, PAWCATUCK RIVER RI
28	8458022	-71.761700	41.328300	WEEKAPAUG POINT BLOCK IS SOUND RI
29	8458694	-71.860000	41.305000	WATCH HILL POINT RHODE ISLAND
30	8459338	-71.556700	41.173300	BLOCK ISLAND HARBOR, OLD HARBOR RI
31	8459681	-71.611400	41.163500	BLOCK ISLAND, SW END, RHODE ISLAND
32	8460751	-71.975000	41.343300	WEST MYSTIC, MYSTIC RIVER CT
33	8461392	-72.078800	41.522700	NORWICH, THAMES RIVER CONNECTICUT
34	8461467	-72.093300	41.430000	YALE BOATHOUSE, THAMES RIVER CT
35	8461490	-72.089972	41.361389	NEW LONDON, THAMES RIVER CT
36	8461925	-72.185400	41.325100	NIANTIC, NIANTIC RIVER CONNECTICUT
37	8462764	-72.350000	41.321700	LYME HWY. BR. CT. RIVER CONNECTICUT

38	8463348	-72.465000	41.451700	TYLERVILLE, CONNECTICUT RIVER
39	8463701	-72.531700	41.268300	CLINTON, CLINTON HARBOR CONNECTICUT
40	8463827	-72.551700	41.541700	MAROMAS, CONNECTICUT RIVER CT
41	8463836	-72.553300	41.503300	HIGGANUM CREEK, CONNECTICUT R. CT
42	8464255	-72.629200	41.663300	ROCKY HILL, CONNECTICUT RIVER CT
43	8464336	-72.644400	41.560700	MIDDLETOWN, CONNECTICUT RIVER CT
44	8464418	-72.658300	41.755000	SOUTH HARTFORD, CONNECTICUT RIVER
45	8464445	-72.666700	41.271700	GUILFORD, GUILFORD HARBOR CT
46	8465233	-72.818300	41.261700	BRANFORD, BRANFORD RIVER CT
47	8465692	-72.905000	41.251700	LIGHTHOUSE POINT, NEW HAVEN HBR CT
48	8465705	-72.908300	41.283300	NEW HAVEN, NEW HAVEN HARBOR CT
49	8465748	-72.916700	41.293300	NEW HAVEN CONNECTICUT
50	8466375	-73.041700	41.205000	GULF BEACH CONNECTICUT
51	8466442	-73.055000	41.218300	MILFORD HARBOR CONNECTICUT
52	8466573	-73.071700	41.301700	SHELTON, HOUSATONIC RIVER CT
53	8466664	-73.088300	41.275000	MURPHY'S BOAT YARD, HOUSATONIC R
54	8466791	-73.113300	41.186700	SNIFFENS POINT, HOUSATONIC RIVER CT
55	8466797	-73.111700	41.203300	I-95 BRIDGE, HOUSATONIC RIVER CT
56	8467150	-73.181700	41.173300	BRIDGEPORT, BRIDGEPORT HARBOR CT
57	8467373	-73.213300	41.156700	BLACK ROCK HARBOR, CEDAR CREEK CT
58	8467726	-73.282900	41.132500	SOUTHPORT, SOUTHPORT HARBOR CT
59	8468191	-73.368300	41.120000	SAUGATUCK, SAUGATUCK RIVER CT
60	8468448	-73.414500	41.097100	SOUTH NORWALK, NORWALK RIVER CT
61	8468609	-73.445000	41.065000	ROWAYTON, FIVEMILE RIVER CT
62	8468799	-73.480000	41.038300	LONG NECK PT., LONG ISLAND SND CT
63	8469057	-73.592028	41.039194	MIANUS, MIANUS RIVER CT
64	8469198	-73.544700	41.041900	STAMFORD, STAMFORD HARBOR CT
65	8510448	-71.935000	41.073300	U.S. COAST GUARD STATION LK MONTAUK
66	8510560	-71.960000	41.048300	MONTAUK, FORT POND BAY NEW YORK
67	8510719	-72.030000	41.256700	SILVER EEL POND, FISHERS IS. NEW YORK
68	8511236	-72.205000	41.171700	PLUM ISLAND PLUM GUT HARBOR
69	8511629	-72.296700	41.003300	SAG HARBOR, SHELTER IS. SOUND NY
70	8511671	-72.306700	41.136700	ORIENT, ORIENT HARBOR NEW YORK
71	8511907	-72.361167	41.101000	GREENPORT, GREENPORT HARBOR NY
72	8512354	-72.480000	40.836700	SHINNECOCK INLET NEW YORK
73	8512451	-72.503300	40.850000	PONQUOGUE POINT, SHINNECOCK BAY NY
74	8512668	-72.561700	41.015000	MATTITUCK INLET, LONG ISLAND NY
75	8512671	-72.561700	40.820000	SHINNECOCK BAY, INSIDE OUTER BAR NY
76	8512735	-72.581700	40.935000	SOUTH JAMESPORT GREAT PECONIC BAY
77	8512769	-72.586611	40.818556	SHINNECOCK YACHT CLUB PENNIMAN CK
78	8512987	-72.645000	40.981700	NORTHVILLE FUEL DOCK, LONG ISLAND NY
79	8513388	-72.750000	40.786700	MORICHES USCG STATION MORICHES B NY

80	8513398	-72.755000	40.763333	MORICHES INLET (OPEN COAST) NY
81	8513825	-72.868300	40.738300	SMITH POINT BRIDGE, NARROW BAY NY
82	8514322	-72.999100	40.750500	PATCHOGUE, PATCHOGUE RIVER NY
83	8514422	-73.043300	40.965000	CEDAR BEACH NEW YORK
84	8514560	-73.076700	40.950000	PORT JEFFERSON NEW YORK
85	8514779	-73.150611	40.649250	SEAVIEW FERRY DOCK, FIRE IS INLET NY
86	8515102	-73.240000	40.716700	BAYSHORE, LONG ISLAND NEW YORK
87	8515186	-73.260000	40.626700	FIRE ISLAND COAST GUARD STATION NY
88	8515586	-73.353300	40.900000	NORTHPORT, NORTHPORT BAY NEW YORK
89	8515786	-73.400000	40.953300	EATONS NECK, HUNTINGTON BAY NY
90	8515921	-73.431700	40.910000	LLOYD HARBOR LIGHTHOUSE NEW YORK
91	8516061	-73.470000	40.873300	COLD SPRINGS HARBOR NEW YORK
92	8516155	-73.501667	40.623333	GREEN ISLAND DRAWBRIDGE NEW YORK
93	8516299	-73.550000	40.903300	BAYVILLE BRIDGE, OYSTER BAY NEW YORK
94	8516402	-73.583972	40.593889	POINT LOOKOUT, JONES INLET NEW YORK
95	8516501	-73.616700	40.632900	BALDWIN PARSONAGE COVE HEMPSTEAD
96	8516607	-73.652417	40.834611	HARRY TAPPEN MARINA, HEMPSTEAD NY
97	8516614	-73.655000	40.863300	GLEN COVE YACHT CLUB, LONG ISLAND NY
98	8516661	-73.667500	40.628500	BAY PARK EAST ROCKAWAY HEWLETT BAY
99	8516663	-73.655000	40.595000	LONG BEACH NEW YORK
100	8516761	-73.703300	40.831700	PORT WASHINGTON MANHASSSET BAY NY
101	8516881	-73.743300	40.595000	FAR ROCKAWAY, ATLANTIC BEACH NY
102	8516891	-73.746667	40.635000	NORTON POINT, HOOK CREEK NEW YORK
103	8516945	-73.764900	40.810300	KINGS POINT, LONG ISLAND SOUND NY
104	8516990	-73.781700	40.793300	WILLETS POINT, LITTLE BAY, EAST RIVER NY
105	8517137	-73.820000	40.588300	BEACH CHANNEL CROSS B. BRIDGE NY
106	8517201	-73.836700	40.645000	NORTH CHANNEL BRIDGE, GRASSY B NY
107	8517251	-73.850361	40.761000	WORLDS FAIR MARINA, FLUSHING BAY NY
108	8517756	-73.933833	40.581250	KINGSBOROUGH CC, SHEEPSHEAD BAY NY
109	8517847	-73.995000	40.703300	BROOKLYN BRIDGE, EAST RIVER NY
110	8518091	-73.671700	40.961700	RYE BEACH, AMUSEMENT PARK NY
111	8518490	-73.781700	40.893300	NEW ROCHELLE NEW YORK
112	8518526	-73.795000	40.805000	THROGS NECK FORT SCHUYLER EAST RIVER
113	8518639	-73.905900	40.801500	PORT MORRIS, EAST 138TH ST. NEW YORK
114	8518643	-73.928300	40.800000	RANDALLS ISLAND, HARLEM RIVER NY
115	8518668	-73.941700	40.776700	HORNS HOOK, E. 90TH STREET, HELL GATE
116	8518687	-73.958300	40.758300	QUEENSBORO BRIDGE, EAST RIVER NY
117	8518699	-73.969200	40.712100	WILLIAMSBURG BRIDGE NEW YORK
118	8518750	-74.014200	40.700600	THE BATTERY, NEW YORK HARBOR NY
119	8518902	-73.933300	40.868300	NYC, DYCKMAN ST., FERRY SLIP NEW YORK

120	8518924	-73.963300	41.218300	HAVERSTRAW BAY NEW YORK
121	8518934	-73.983300	41.500000	BEACON, FLUSHKILL, HUDSON RIVER NY
122	8518951	-73.950000	41.783300	HYDE PARK, HUDSON RIVER NEW YORK
123	8518995	-73.746300	42.649700	ALBANY, HUDSON RIVER NEW YORK
124	8519050	-74.059861	40.612000	USCG STATION NY, THE NARROWS NY
125	8519436	-74.140000	40.543300	GREAT KILLS HARBOR NEW YORK
126	8519483	-74.146600	40.639900	BERGEN POINT W REACH KILL VAN KULL
127	8530095	-73.918300	40.945000	ALPINE, HUDSON RIVER NEW JERSEY
128	8530186	-74.028500	40.935100	NEW MILFORD, HACKENSACK RIVER NJ
129	8530278	-74.040000	40.880000	HACKENSACK, HACKENSACK RIVER NJ
130	8530403	-74.120900	40.846900	EAST RUTHERFORD, PASSAIC RIVER NJ
131	8530502	-74.086700	40.816700	BERRYS CREEK, NO. 7
132	8530528	-74.060000	40.806700	CARLSTADT, HACKENSACK RIVER NJ
133	8530586	-74.091700	40.793300	BERRYS CREEK #8 NEW JERSEY
134	8530591	-74.146700	40.786700	BELLEVILLE, PASSAIC RIVER NEW JERSEY
135	8530696	-74.096700	40.751700	BELLEVILLE TPKE, HACKENSACK R NJ
136	8530743	-74.116700	40.731700	POINT NO POINT, PASSAIC RIVER NJ
137	8530772	-74.103200	40.727500	KEARNY POINT, HACKENSACK RIVER NJ
138	8530882	-74.139000	40.672700	PORT ELIZABETH, NEWARK BAY NJ
139	8531077	-74.231700	40.598300	RAHWAY RIVER #1 NEW JERSEY
140	8531142	-74.245000	40.555000	PORT READING, ARTHUR KILL NEW JERSEY
141	8531156	-74.265200	40.544500	WOODBRIDGE CREEK #1 NEW JERSEY
142	8531223	-74.273700	40.453700	CHEESEQUAKE CREEK NEW JERSEY
143	8531262	-74.311700	40.508300	KEASBEY, RARITAN RIVER NEW JERSEY
144	8531369	-74.362000	40.417100	NORTH OLD BRIDGE, SOUTH RIVER NJ
145	8531390	-74.356700	40.478300	SAYREVILLE, RARITAN RIVER
146	8531463	-74.434400	40.488700	NEW BRUNSWICK RARITAN RIVER
147	8531526	-74.218300	40.433300	MATAWAN CREEK RARITAN BAY
148	8531545	-74.198300	40.440000	KEYPORT, RARITAN BAY NEW JERSEY
149	8531680	-74.009400	40.466900	SANDY HOOK NEW JERSEY
150	8531753	-74.015000	40.376700	OCEANIC, NAVESINK RIVER NEW JERSEY
151	8531804	-73.975000	40.365000	SEA BRIGHT, SHREWSBURY RIVER NJ
152	8531833	-74.065000	40.355000	RED BANK, NAVESINK RIVER NEW JERSEY
153	8531942	-73.996700	40.325000	LONG BRANCH, INSIDE NEW JERSEY
154	8531991	-73.976700	40.303300	LONG BRANCH,FISHING PIER NEW JERSEY
155	8532585	-74.054700	40.104300	POINT PLEASANT BEACH MANASQUAN R
156	8532591	-74.034800	40.102500	MANASQUAN INLET NEW JERSEY
157	8532715	-74.061700	40.061700	BEAVER DAM CREEK
158	8533051	-74.197800	39.950100	TOMS RIVER, TOMS RIVER NJ
159	8533365	-74.151700	39.845000	STOUTS CREEK, BARNEGAT BAY NJ
160	8533615	-74.111700	39.761700	BARNEGAT INLET (INSIDE) NEW JERSEY
161	8533987	-74.296400	39.632100	WEST CREEK, WESTECUNK CREEK NJ
162	8534044	-74.262800	39.613500	LONG PT, LITTLE EGG HARBOR NJ
163	8534048	-74.210000	39.613300	BEACH HAVEN CREST (INSIDE) NEW JERSEY
164	8534049	-74.309300	39.617100	PARKER RUN, LITTLE EGG HARBOR NJ

165	8534080	-74.341700	39.601700	TUCKERTON, TUCKERTONCREEK
166	8534104	-74.441700	39.591700	NEW GRETNA, BASS RIVER
167	8534208	-74.256700	39.548300	BEACH HAVEN CG STATION
168	8534212	-74.461700	39.548300	CRAMERS BOATYARD, MULLICA RIVER NJ
169	8534244	-74.386700	39.540000	GRAVELING POINT NEW JERSEY
170	8534287	-74.320000	39.521700	LITTLE SHEEPSHEAD CREEK NEW JERSEY
171	8534319	-74.325000	39.508333	GREAT BAY, TUCKERTON NEW JERSEY
172	8534393	-74.383300	39.478300	MAIN MARSH THOROFARE NEW JERSEY
173	8534496	-74.363300	39.435000	BRIGANTINE CHANNEL
174	8534720	-74.418300	39.355000	ATLANTIC CITY, ATLANTIC OCEAN NJ

APPENDIX B. OBSERVED TIDAL DATUMS AND THEIR ROOT-MEAN-SQUARE (RMS) ERRORS

Below list the observed tidal datums and their RMS errors at the 174 tide stations used in this tidal datum modeling work in New York Bight, New York Harbor, Hudson River, Long Island Sound, and Narragansett Bay regions.

No.	Station ID	Longitude (ºW)	Latitude (ºN)	MHHW (m)	MHW (m)	MLW (m)	MLLW (m)	RMS Errors (m)
1	8447281	-71.131700	41.740000	0.814	0.738	-0.634	-0.690	0.015
2	8447386	-71.164100	41.704300	0.784	0.711	-0.620	-0.672	0.001
3	8454000	-71.401200	41.807100	0.790	0.715	-0.630	-0.685	0.000
4	8455137	-71.241667	41.707778	0.770	0.696	-0.615	-0.669	0.013
5	8460751	-71.975000	41.343300	0.459	0.370	-0.392	-0.450	0.012
6	8464255	-72.629200	41.663300	0.354	0.276	-0.297	-0.335	0.024
7	8469057	-73.592028	41.039194	1.201	1.090	-1.102	-1.175	0.014
8	8513398	-72.755000	40.763333	0.483	0.415	-0.445	-0.491	0.027
9	8514779	-73.150611	40.649250	0.227	0.184	-0.174	-0.215	0.027
10	8516402	-73.583972	40.593889	0.737	0.638	-0.625	-0.681	0.015
11	8516501	-73.616700	40.632900	0.745	0.645	-0.682	-0.737	0.021
12	8516607	-73.652417	40.834611	1.216	1.107	-1.114	-1.184	0.012
13	8516661	-73.667500	40.628500	0.789	0.687	-0.724	-0.782	0.014
14	8516663	-73.655000	40.595000	0.750	0.659	-0.692	-0.745	0.016
15	8517137	-73.820000	40.588300	0.939	0.831	-0.826	-0.892	0.014
16	8517251	-73.850361	40.761000	1.132	1.022	-1.034	-1.119	0.013
17	8517756	-73.933833	40.581250	0.864	0.756	-0.745	-0.810	0.012
18	8518951	-73.950000	41.783300	0.636	0.518	-0.553	-0.614	0.026
19	8519050	-74.059861	40.612000	0.753	0.657	-0.705	-0.766	0.012
20	8531680	-74.009400	40.466900	0.808	0.707	-0.726	-0.785	0.000
21	8450768	-71.193300	41.465000	0.593	0.514	-0.453	-0.489	0.013
22	8450898	-71.210000	41.651700	0.755	0.677	-0.593	-0.639	0.014
23	8450948	-71.211700	41.638300	0.699	0.617	-0.527	-0.581	0.013
24	8450954	-71.203300	41.618300	0.661	0.576	-0.492	-0.539	0.013
25	8451301	-71.236700	41.558300	0.645	0.557	-0.479	-0.523	0.012
26	8451351	-71.238300	41.486700	0.589	0.518	-0.434	-0.474	0.012
27	8451552	-71.255000	41.636700	0.752	0.676	-0.566	-0.616	0.014
28	8452154	-71.293300	41.696700	0.747	0.674	-0.583	-0.634	0.013
29	8452555	-71.321700	41.580000	0.690	0.617	-0.522	-0.569	0.012
30	8452660	-71.326700	41.505000	0.645	0.570	-0.487	-0.529	0.016
31	8452944	-71.343300	41.716700	0.756	0.680	-0.591	-0.642	0.013
32	8453033	-71.351700	41.751700	0.759	0.684	-0.610	-0.663	0.012
33	8453201	-71.361700	41.463300	0.611	0.537	-0.453	-0.497	0.012
34	8453433	-71.373300	41.840000	0.828	0.754	-0.666	-0.722	0.011
35	8453572	-71.378300	41.666700	0.720	0.640	-0.556	-0.602	0.014
36	8453742	-71.386700	41.496700	0.639	0.567	-0.485	-0.529	0.011
37	8453767	-71.388300	41.761700	0.786	0.710	-0.616	-0.670	0.012
38	8454049	-71.411000	41.586800	0.683	0.608	-0.519	-0.566	0.012
39	8454341	-71.428300	41.460000	0.625	0.548	-0.464	-0.502	0.012
40	8454538	-71.445000	41.571700	0.692	0.613	-0.518	-0.563	0.013
41	8454578	-71.445000	41.665000	0.736	0.661	-0.576	-0.628	0.014
42	8455083	-71.490000	41.363300	0.562	0.485	-0.430	-0.468	0.014

43	8455189	-71.832200	41.369500	0.499	0.409	-0.413	-0.474	0.013
44	8458022	-71.761700	41.328300	0.458	0.392	-0.378	-0.418	0.015
45	8458694	-71.860000	41.305000	0.457	0.374	-0.412	-0.457	0.014
46	8459338	-71.556700	41.173300	0.535	0.459	-0.411	-0.446	0.016
47	8459681	-71.611400	41.163500	0.482	0.408	-0.383	-0.418	0.017
48	8461392	-72.078800	41.522700	0.524	0.426	-0.497	-0.568	0.014
49	8461467	-72.093300	41.430000	0.488	0.395	-0.438	-0.502	0.012
50	8461490	-72.089972	41.361389	0.461	0.371	-0.410	-0.468	0.016
51	8461925	-72.185400	41.325100	0.472	0.386	-0.398	-0.446	0.013
52	8462764	-72.350000	41.321700	0.590	0.506	-0.503	-0.557	0.017
53	8463348	-72.465000	41.451700	0.488	0.413	-0.412	-0.443	0.018
54	8463701	-72.531700	41.268300	0.801	0.709	-0.679	-0.751	0.018
55	8463827	-72.551700	41.541700	0.436	0.362	-0.373	-0.404	0.026
56	8463836	-72.553300	41.503300	0.432	0.362	-0.370	-0.400	0.020
57	8464336	-72.644400	41.560700	0.396	0.321	-0.341	-0.374	0.026
58	8464418	-72.658300	41.755000	0.345	0.267	-0.322	-0.354	0.025
59	8464445	-72.666700	41.271700	0.887	0.792	-0.790	-0.860	0.017
60	8465233	-72.818300	41.261700	0.992	0.896	-0.886	-0.956	0.015
61	8465692	-72.905000	41.251700	1.035	0.934	-0.930	-1.001	0.014
62	8465705	-72.908300	41.283300	1.032	0.934	-0.938	-1.012	0.014
63	8465748	-72.916700	41.293300	1.045	0.946	-0.945	-1.021	0.014
64	8466375	-73.041700	41.205000	1.058	0.960	-0.957	-1.034	0.013
65	8466442	-73.055000	41.218300	1.062	0.962	-0.964	-1.039	0.012
66	8466573	-73.071700	41.301700	1.230	1.122	-1.016	-1.087	0.014
67	8466664	-73.088300	41.275000	1.202	1.100	-0.987	-1.062	0.014
68	8466791	-73.113300	41.186700	1.091	0.991	-0.970	-1.043	0.011
69	8466797	-73.111700	41.203300	1.115	1.013	-0.993	-1.067	0.012
70	8467150	-73.181700	41.173300	1.127	1.025	-1.030	-1.104	0.017
71	8467373	-73.213300	41.156700	1.130	1.027	-1.031	-1.107	0.011
72	8467726	-73.282900	41.132500	1.143	1.041	-1.043	-1.117	0.012
73	8468191	-73.368300	41.120000	1.164	1.060	-1.071	-1.145	0.013
74	8468448	-73.414500	41.097100	1.174	1.070	-1.084	-1.163	0.013
75	8468609	-73.445000	41.065000	1.181	1.076	-1.086	-1.164	0.014
76	8468799	-73.480000	41.038300	1.200	1.092	-1.091	-1.162	0.014
77	8469198	-73.544700	41.041900	1.197	1.088	-1.098	-1.171	0.014
78	8510448	-71.935000	41.073300	0.393	0.306	-0.305	-0.357	0.011
79	8510560	-71.960000	41.048300	0.393	0.306	-0.325	-0.377	0.016
80	8510719	-72.030000	41.256700	0.428	0.339	-0.374	-0.432	0.013
81	8511236	-72.205000	41.171700	0.478	0.388	-0.404	-0.464	0.014
82	8511629	-72.296700	41.003300	0.437	0.350	-0.384	-0.435	0.016
83	8511671	-72.306700	41.136700	0.464	0.366	-0.401	-0.461	0.015
84	8511907	-72.361167	41.101000	0.444	0.358	-0.387	-0.441	0.016
85	8512354	-72.480000	40.836700	0.564	0.485	-0.453	-0.492	0.019
86	8512451	-72.503300	40.850000	0.507	0.429	-0.422	-0.460	0.019
87	8512668	-72.561700	41.015000	0.872	0.783	-0.765	-0.828	0.017
88	8512671	-72.561700	40.820000	0.458	0.381	-0.353	-0.373	0.017
89	8512735	-72.581700	40.935000	0.510	0.420	-0.444	-0.497	0.020
90	8512769	-72.586611	40.818556	0.482	0.404	-0.370	-0.403	0.017
91	8512987	-72.645000	40.981700	0.914	0.820	-0.812	-0.878	0.017
92	8513388	-72.750000	40.786700	0.400	0.330	-0.325	-0.361	0.017
93	8513825	-72.868300	40.738300	0.222	0.173	-0.188	-0.224	0.021
94	8514322	-72.999100	40.750500	0.218	0.170	-0.169	-0.200	0.024
95	8514422	-73.043300	40.965000	1.086	0.988	-0.976	-1.045	0.014

96	8514560	-73.076700	40.950000	1.108	1.010	-1.005	-1.073	0.013
97	8515102	-73.240000	40.716700	0.193	0.140	-0.161	-0.183	0.023
98	8515186	-73.260000	40.626700	0.339	0.282	-0.293	-0.336	0.020
99	8515586	-73.353300	40.900000	1.212	1.105	-1.111	-1.180	0.015
100	8515786	-73.400000	40.953300	1.193	1.087	-1.092	-1.165	0.014
101	8515921	-73.431700	40.910000	1.175	1.066	-1.078	-1.143	0.014
102	8516061	-73.470000	40.873300	1.220	1.109	-1.114	-1.182	0.014
103	8516155	-73.501667	40.623333	0.536	0.461	-0.486	-0.537	0.020
104	8516299	-73.550000	40.903300	1.242	1.132	-1.122	-1.200	0.014
105	8516614	-73.655000	40.863300	1.217	1.106	-1.110	-1.181	0.012
106	8516761	-73.703300	40.831700	1.212	1.103	-1.121	-1.203	0.011
107	8516881	-73.743300	40.595000	0.773	0.670	-0.662	-0.720	0.015
108	8516891	-73.746667	40.635000	0.955	0.851	-0.868	-0.932	0.015
109	8516945	-73.764900	40.810300	1.193	1.083	-1.101	-1.185	0.017
110	8516990	-73.781700	40.793300	1.191	1.080	-1.098	-1.182	0.010
111	8517201	-73.836700	40.645000	0.949	0.839	-0.857	-0.925	0.014
112	8517847	-73.995000	40.703300	0.769	0.655	-0.719	-0.780	0.010
113	8518091	-73.671700	40.961700	1.216	1.106	-1.116	-1.189	0.013
114	8518490	-73.781700	40.893300	1.216	1.107	-1.115	-1.194	0.012
115	8518526	-73.795000	40.805000	1.179	1.069	-1.104	-1.188	0.011
116	8518639	-73.905900	40.801500	1.059	0.952	-0.949	-1.030	0.013
117	8518643	-73.928300	40.800000	0.778	0.685	-0.704	-0.759	0.017
118	8518668	-73.941700	40.776700	0.808	0.713	-0.714	-0.772	0.014
119	8518687	-73.958300	40.758300	0.751	0.650	-0.669	-0.733	0.013
120	8518699	-73.969200	40.712100	0.719	0.620	-0.667	-0.727	0.012
121	8518750	-74.014200	40.700600	0.758	0.660	-0.720	-0.783	0.014
122	8518902	-73.933300	40.868300	0.641	0.562	-0.650	-0.702	0.015
123	8518924	-73.963300	41.218300	0.570	0.485	-0.498	-0.550	0.021
124	8518934	-73.983300	41.500000	0.565	0.458	-0.496	-0.553	0.025
125	8518995	-73.746300	42.649700	0.833	0.717	-0.802	-0.869	0.027
126	8519436	-74.140000	40.543300	0.834	0.732	-0.766	-0.832	0.012
127	8519483	-74.146600	40.639900	0.834	0.736	-0.782	-0.846	0.013
128	8530095	-73.918300	40.945000	0.620	0.543	-0.600	-0.658	0.014
129	8530186	-74.028500	40.935100	0.779	0.695	-0.755	-0.775	0.021
130	8530278	-74.040000	40.880000	0.931	0.832	-1.000	-1.088	0.019
131	8530403	-74.120900	40.846900	0.987	0.881	-0.907	-0.988	0.019
132	8530502	-74.086700	40.816700	0.840	0.748	-0.906	-0.970	0.013
133	8530528	-74.060000	40.806700	0.901	0.803	-0.936	-1.017	0.017
134	8530586	-74.091700	40.793300	0.865	0.775	-0.842	-0.906	0.013
135	8530591	-74.146700	40.786700	0.948	0.844	-0.862	-0.938	0.017
136	8530696	-74.096700	40.751700	0.841	0.752	-0.855	-0.926	0.012
137	8530743	-74.116700	40.731700	0.866	0.771	-0.816	-0.884	0.012
138	8530772	-74.103200	40.727500	0.862	0.762	-0.827	-0.901	0.014
139	8530882	-74.139000	40.672700	0.848	0.744	-0.794	-0.856	0.008
140	8531077	-74.231700	40.598300	0.911	0.808	-0.827	-0.895	0.013
141	8531142	-74.245000	40.555000	0.888	0.782	-0.831	-0.906	0.014
142	8531156	-74.265200	40.544500	0.850	0.758	-0.829	-0.886	0.013
143	8531223	-74.273700	40.453700	0.842	0.748	-0.813	-0.875	0.012
144	8531262	-74.311700	40.508300	0.879	0.777	-0.812	-0.870	0.013
145	8531369	-74.362000	40.417100	0.919	0.818	-0.882	-0.948	0.014
146	8531390	-74.356700	40.478300	0.898	0.798	-0.858	-0.929	0.013
147	8531463	-74.434400	40.488700	0.937	0.837	-0.903	-0.971	0.014
148	8531526	-74.218300	40.433300	0.846	0.742	-0.800	-0.874	0.016

149	8531545	-74.198300	40.440000	0.842	0.741	-0.798	-0.863	0.012
150	8531753	-74.015000	40.376700	0.636	0.545	-0.494	-0.530	0.014
151	8531804	-73.975000	40.365000	0.619	0.533	-0.536	-0.578	0.015
152	8531833	-74.065000	40.355000	0.637	0.547	-0.523	-0.558	0.014
153	8531942	-73.996700	40.325000	0.475	0.400	-0.392	-0.430	0.016
154	8531991	-73.976700	40.303300	0.760	0.655	-0.686	-0.744	0.006
155	8532585	-74.054700	40.104300	0.683	0.585	-0.603	-0.652	0.014
156	8532591	-74.034800	40.102500	0.706	0.605	-0.621	-0.676	0.009
157	8532715	-74.061700	40.061700	0.082	0.025	-0.066	-0.086	0.001
158	8533051	-74.197800	39.950100	0.168	0.117	-0.121	-0.148	0.001
159	8533365	-74.151700	39.845000	0.136	0.099	-0.105	-0.133	0.001
160	8533615	-74.111700	39.761700	0.410	0.339	-0.318	-0.355	0.005
161	8533987	-74.296400	39.632100	0.402	0.321	-0.313	-0.340	0.001
162	8534044	-74.262800	39.613500	0.384	0.308	-0.294	-0.320	0.001
163	8534048	-74.210000	39.613300	0.349	0.266	-0.284	-0.301	0.001
164	8534049	-74.309300	39.617100	0.395	0.319	-0.317	-0.344	0.001
165	8534080	-74.341700	39.601700	0.409	0.328	-0.314	-0.341	0.019
166	8534104	-74.441700	39.591700	0.522	0.431	-0.513	-0.557	0.017
167	8534208	-74.256700	39.548300	0.412	0.327	-0.328	-0.362	0.018
168	8534212	-74.461700	39.548300	0.494	0.413	-0.483	-0.530	0.017
169	8534244	-74.386700	39.540000	0.601	0.493	-0.477	-0.516	0.016
170	8534287	-74.320000	39.521700	0.591	0.481	-0.464	-0.503	0.016
171	8534319	-74.325000	39.508333	0.545	0.445	-0.433	-0.478	0.014
172	8534393	-74.383300	39.478300	0.602	0.497	-0.481	-0.521	0.016
173	8534496	-74.363300	39.435000	0.652	0.541	-0.564	-0.610	0.018
174	8534720	-74.418300	39.355000	0.728	0.601	-0.623	-0.675	0.000

APPENDIX C. OBSERVED TOPOGRAPHY OF THE SEA SURFACE (TSS) AND THEIR STANDARD DEVIATIONS

Below list the observed TSS values and standard deviations at the 137 tide stations used in this TSS data interpolation in New York Bight, New York Harbor, Hudson River, Long Island Sound, and Narragansett Bay regions.

No.	Station ID	Longitude (°W)	Latitude (°N)	TSS (m)	Standard Deviation (m)
1	8450768	-71.193300	41.465000	0.106	0.028
2	8450948	-71.211700	41.638300	0.050	0.026
3	8450954	-71.203300	41.618300	0.057	0.026
4	8451552	-71.255000	41.636700	0.091	0.026
5	8452154	-71.293300	41.696700	0.082	0.026
6	8452555	-71.321700	41.580000	0.109	0.024
7	8452660	-71.326700	41.505000	0.093	0.027
8	8453742	-71.386700	41.496700	0.086	0.024
9	8453767	-71.388300	41.761700	0.083	0.025
10	8454000	-71.401200	41.807100	0.068	0.022
11	8454049	-71.411000	41.586800	0.127	0.024
12	8454538	-71.445000	41.571700	0.159	0.025
13	8454578	-71.445000	41.665000	0.097	0.025
14	8455137	-71.241667	41.707778	0.085	0.026
15	8455189	-71.831700	41.381700	0.098	0.026
16	8458022	-71.761700	41.328300	0.114	0.027
17	8458694	-71.860000	41.305000	0.096	0.027
18	8460751	-71.975000	41.343300	0.115	0.027
19	8461392	-72.078300	41.523300	0.035	0.028
20	8461467	-72.093300	41.430000	0.075	0.027
21	8461490	-72.089972	41.361389	0.092	0.029
22	8461925	-72.186700	41.325000	0.093	0.029
23	8462764	-72.350000	41.321700	0.062	0.030
24	8463348	-72.465000	41.451700	-0.064	0.029
25	8463701	-72.531700	41.268300	0.103	0.029
26	8463827	-72.551700	41.541700	-0.110	0.035
27	8464336	-72.645000	41.560000	-0.188	0.035
28	8464445	-72.666700	41.271700	0.100	0.030
29	8465233	-72.818300	41.261700	0.086	0.031
30	8465692	-72.905000	41.251700	0.093	0.030
31	8465705	-72.908300	41.283300	0.090	0.030
32	8465748	-72.916700	41.293300	0.076	0.030
33	8466375	-73.041700	41.205000	0.074	0.029
34	8466442	-73.055000	41.218300	0.071	0.028
35	8466573	-73.071700	41.301700	0.022	0.029

36	8466664	-73.088300	41.275000	0.020	0.029
37	8466791	-73.113300	41.186700	0.072	0.028
38	8466797	-73.111700	41.203300	0.054	0.029
39	8467150	-73.181700	41.173300	0.067	0.032
40	8467373	-73.213300	41.156700	0.064	0.031
41	8467726	-73.283300	41.133300	0.051	0.032
42	8468191	-73.368300	41.120000	0.046	0.031
43	8468448	-73.415000	41.096700	0.050	0.031
44	8469057	-73.592028	41.039194	0.056	0.027
45	8469198	-73.546700	41.038300	0.059	0.028
46	8510448	-71.935000	41.073300	0.107	0.025
47	8510560	-71.960000	41.048300	0.101	0.028
48	8511629	-72.296700	41.003300	0.098	0.029
49	8511671	-72.306700	41.136700	0.076	0.028
50	8511907	-72.361167	41.101000	0.130	0.029
51	8512354	-72.480000	40.836700	0.142	0.032
52	8512451	-72.503300	40.850000	0.086	0.032
53	8512668	-72.561700	41.015000	0.111	0.030
54	8512735	-72.581700	40.935000	0.129	0.031
55	8512769	-72.586611	40.818556	0.106	0.030
56	8512987	-72.645000	40.981700	0.098	0.030
57	8513388	-72.750000	40.786700	0.048	0.029
58	8513398	-72.755972	40.764417	0.122	0.036
59	8513825	-72.868300	40.738300	0.011	0.032
60	8514322	-73.000000	40.750000	0.005	0.033
61	8514560	-73.076700	40.950000	0.059	0.030
62	8514779	-73.150611	40.649250	0.043	0.037
63	8515102	-73.240000	40.716700	-0.021	0.033
64	8515186	-73.260000	40.626700	0.075	0.032
65	8515786	-73.400000	40.953300	0.066	0.030
66	8516061	-73.470000	40.873300	0.058	0.027
67	8516155	-73.501700	40.623300	0.069	0.029
68	8516299	-73.550000	40.903300	0.075	0.026
69	8516402	-73.583972	40.593889	0.127	0.026
70	8516501	-73.616700	40.633300	0.124	0.030
71	8516607	-73.652417	40.834611	0.072	0.024
72	8516614	-73.655000	40.863300	0.084	0.024
73	8516661	-73.670000	40.630000	0.110	0.026
74	8516663	-73.655083	40.596333	0.072	0.027
75	8516761	-73.703300	40.831700	0.130	0.024
76	8516881	-73.743300	40.595000	0.152	0.027
77	8516891	-73.746700	40.635000	0.104	0.027
78	8516945	-73.764900	40.810300	0.071	0.028
79	8516990	-73.781700	40.793300	0.058	0.024
80	8517137	-73.820000	40.588300	0.139	0.027

81	8517201	-73.836700	40.645000	0.119	0.026
82	8517251	-73.850361	40.761000	0.050	0.026
83	8517756	-73.933833	40.581250	0.145	0.025
84	8517847	-73.995000	40.703300	0.110	0.024
85	8518091	-73.671700	40.961700	0.071	0.026
86	8518490	-73.781700	40.893300	0.085	0.026
87	8518526	-73.795000	40.805000	0.056	0.025
88	8518639	-73.906700	40.801700	0.043	0.026
89	8518643	-73.928300	40.800000	0.031	0.028
90	8518668	-73.941700	40.776700	0.000	0.026
91	8518687	-73.958300	40.758300	0.061	0.026
92	8518699	-73.968300	40.711700	0.066	0.025
93	8518750	-74.014200	40.700600	0.063	0.026
94	8518902	-73.933300	40.868300	0.029	0.027
95	8518924	-73.963300	41.218300	-0.050	0.032
96	8518934	-73.983300	41.500000	-0.083	0.036
97	8518951	-73.950000	41.783300	-0.071	0.035
98	8518995	-73.746700	42.650000	-0.319	0.036
99	8519050	-74.059861	40.612000	0.060	0.025
100	8519436	-74.140000	40.543300	0.107	0.024
101	8519483	-74.141700	40.636700	0.053	0.025
102	8530095	-73.918300	40.945000	-0.022	0.027
103	8530278	-74.040000	40.880000	-0.006	0.029
104	8530403	-74.120000	40.846700	-0.048	0.029
105	8530528	-74.060000	40.806700	0.090	0.027
106	8530591	-74.146700	40.786700	0.014	0.027
107	8530743	-74.116700	40.731700	0.026	0.024
108	8530772	-74.103300	40.728300	0.039	0.025
109	8531142	-74.245000	40.555000	0.118	0.025
110	8531156	-74.265000	40.545000	0.025	0.025
111	8531262	-74.311700	40.508300	0.075	0.025
112	8531369	-74.363300	40.416700	0.009	0.025
113	8531390	-74.356700	40.478300	0.027	0.025
114	8531526	-74.218300	40.433300	0.027	0.026
115	8531545	-74.198300	40.440000	0.031	0.024
116	8531680	-74.009400	40.466900	0.073	0.021
117	8531753	-74.015000	40.376700	-0.012	0.025
118	8531804	-73.975000	40.365000	0.073	0.026
119	8531942	-73.996700	40.325000	0.001	0.026
120	8531991	-73.976700	40.303300	0.075	0.022
121	8532585	-74.055000	40.105000	0.061	0.025
122	8532591	-74.035000	40.101700	0.063	0.023
123	8532715	-74.061700	40.061700	-0.015	0.021
124	8533051	-74.198300	39.950000	0.023	0.021
125	8533365	-74.151700	39.845000	0.020	0.022

126	8533615	-74.111700	39.761700	0.005	0.023
127	8533987	-74.296700	39.631700	0.004	0.021
128	8534048	-74.210000	39.613300	0.029	0.021
129	8534049	-74.310000	39.616700	-0.003	0.021
130	8534080	-74.341700	39.601700	0.029	0.028
131	8534104	-74.441700	39.591700	0.015	0.027
132	8534208	-74.256700	39.548300	0.052	0.028
133	8534212	-74.461700	39.548300	-0.008	0.027
134	8534287	-74.320000	39.521700	0.085	0.027
135	8534319	-74.325000	39.508300	0.075	0.026
136	8534393	-74.383300	39.478300	0.036	0.027
137	8534720	-74.418300	39.355000	0.122	0.021