NOAA Technical Memorandum NOS CS 31

VDATUM FOR THE GULF OF MAINE: TIDAL DATUMS AND THE TOPOGRAPHY OF THE SEA SURFACE

Silver Spring, Maryland
May 2013

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
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Zizang Yang and Edward P. Myers
Office of Coast Survey, Coast Survey Development Laboratory
Silver Spring, Maryland

Inseong Jeong and Stephen A. White
National Geodetic Survey, Remote Sensing Division
Silver Spring, Maryland

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U. S. DEPARTMENT OF COMMERCE Rebecca M. Blank, Acting Secretary	National Oceanic and Atmospheric Administration Dr. Kathryn D. Sullivan, Acting Under Secretary	National Ocean Service Dr. Holly A. Bamford, Assistant Administrator

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NOTICE

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ABSTRACT

A vertical datum transformation software tool, VDatum, was developed for the Gulf of Maine area. VDatum provides spatially-varying conversions between tidal, orthometric, and ellipsoid-based three-dimensional reference frames.

The tidal datum fields were derived from tidal simulations using the unstructured, two-dimensional, barotropic hydrodynamic model, the ADvanced CIRCulation model (ADCIRC). A triangular finite-element grid consisting of 167,923 nodes and 311,121 cells was created. The model was forced with nine tidal constituents (M_2, S_2, N_2, K_2, K_1, P_1, O_1, Q_1, and M_4) and run for a 55 day simulation. Various tidal datum fields, including mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and mean higher high water (MHHW), were derived using the water level time series from the final 45 days of the simulation. Model results were validated by comparing with observations at 113 water level stations maintained by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS). Discrepancies between model results and observational datums were attributed to model errors and interpolated over the whole model domain using TCARI (Tidal Constituent And Residual Interpolation), a spatial interpolation tool based on solution of Laplace's equation. The error fields were applied to the model results to derive corrected tidal datums on the model grid. These final tidal datum fields were interpolated onto a regularly structured marine grid to be used by the VDatum software.

The Topography of Sea Surface (TSS), defined as the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to mean sea level (MSL), was developed based on interpolation of bench mark data maintained by CO-OPS and the National Geodetic Survey (NGS). The NAVD88-to-MSL values were derived by fitting tidal model results to tidal bench marks leveled in NAVD88 and interpolated onto the final TSS grids.

Key Words: tides, tidal datums, Long Island Sound, Narragansett Bay, Boston Harbor, Gulf of Maine, Bay of Fundy, ADCIRC, mean sea level, bathymetry, coastline, spatial interpolation, marine grid, North American Vertical Datum of 1988

1. INTRODUCTION

NOAA's NOS has developed a software tool called VDatum to transform elevation data among approximately 30 vertical datums (Gill and Schultz, 2001; Milbert, 2002; Parker, 2002; Myers et al., 2005; Spargo et al., 2006b). Once VDatum has been established for a region, data can be incorporated into integrated bathymetric-topographic Digital Elevation Models for use in coastal GIS applications (Parker et al., 2003). VDatum allows all bathymetric and topographic data to be integrated through its inherent geoidal, ellipsoidal, and tidal relationships.

To be applicable over coastal waters, VDatum requires spatially-varying fields of the tidal datums and the Topography of Sea Surface (TSS). The former involves properties such as mean higher high water (MHHW), mean high water (MHW), mean low water (MLW), mean lower low water (MLLW), mean tide level (MTL), and diurnal tide level (DTL) as well as mean sea level (MSL). The latter refers to the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to mean sea level (MSL).

The VDatum tool software is currently available for Tampa Bay (Hess, 2001), Puget Sound (Hess and Gill, 2003; Hess and White, 2004), central/northern North Carolina (Hess et al., 2005), the Calcasieu River (Spargo and Woolard, 2005), the Strait of Juan de Fuca (Spargo et al., 2006a), Delaware and Chesapeake Bays (Yang et al., 2008a), Long Island Sound and New York Bight and Harbor (Yang et al., 2005; Yang et al., 2008b; Yang et al., 2010b), the North and Central Coasts of California (Myers and Hess, 2006), the northeast Gulf of Mexico (Dhingra et al., 2008), the southern California coastal waters (Yang et al., 2009), the eastern Louisiana and Mississippi coastal waters (Yang et al., 2010a), the Pacific Northeast region (Xu et al., 2010), and the Florida Shelf and the South Atlantic Bight (Yang et al., 2012).

This report describes the development of VDatum for the Gulf of Maine (GOM) and adjacent coastal waters surrounding Cape Cod, Nantucket Sound, and Buzzards Bay, Massachusetts. Figure 1 displays a map encompassing the eastern Long Island Sound (LIS), Narragansett Bay (NB), Buzzards Bay, Nantucket Sound, Cape Cod Bay, Gulf of Maine, and Nova Scotia (for simplicity of description, this area is referred to as GOM hereafter). U.S. water areas between the coastlines and the 25-nautical mile line represent the essential coverage of the present VDatum tool.

Development of VDatum begins with tidal simulations using a hydrodynamic model. Various tidal datum fields (MHHW, MHW, MLW, and MLLW) were derived using the simulated water level time series. The tidal datums were verified by comparing with observational data, and error corrections were made based on these comparisons. Regularly structured VDatum marine grids were created and populated with corrected tidal datums. Finally, for the same marine grid, the NAVD88-to-MSL field was derived by fitting tidal model results to tidal bench marks leveled in NAVD88.

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

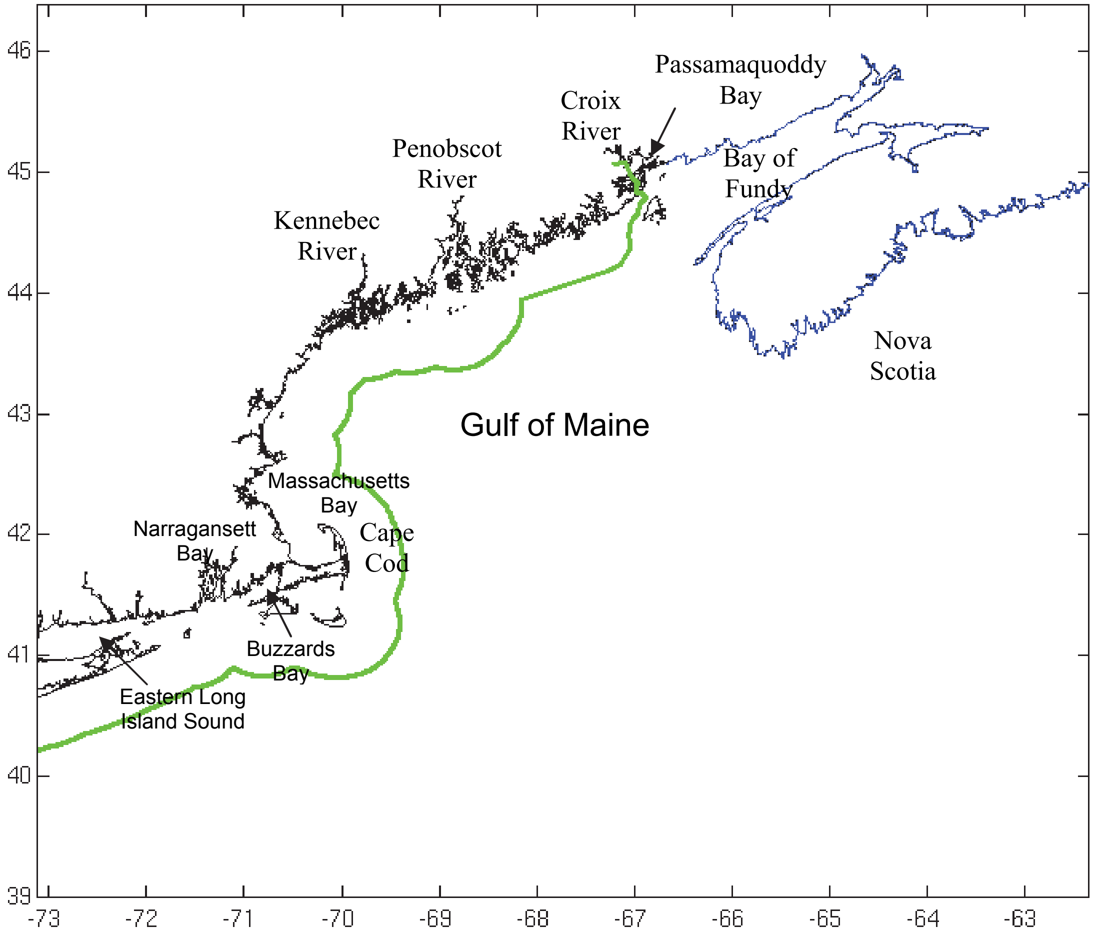

Figure 1. Map of the Gulf of Maine and adjacent waters. The MHW coastline is represented as a combination of Extracted Vector Shoreline (black lines) and World Vector Shoreline (blue lines). Green line denotes a distance 25-nautical miles offshore.

2. COASTLINE, BATHYMETRIC, AND WATER LEVEL DATA

VDatum requires an accurate representation of spatially varying tidal datum fields (Hess et al., 2003). To achieve this, VDatum applications are developed using a combination of observational data, hydrodynamic models, and spatial interpolation techniques (Spargo et al., 2006b; Yang et al., 2005, Spargo and Woolard, 2005). For this VDatum application in the Gulf of Maine area, a tide model was first set up to compute spatially varying tidal datums. The modeled tidal datums were next compared with those derived from CO-OPS observational data. Finally, spatial interpolation techniques were used to create a correction field to be applied to the model results to derive a corrected field of tidal datums that are consistent with the observations.

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

2.1. Digital Coastline

The mean high water shoreline is used as the coastline to delineate the land-water boundaries (Parker, 2002). The shoreline data (Figure 1) used in the present study represent a combination of three MHW shoreline data sets: (1) the Extracted Vector Shoreline (EVS) from the NOS Office of Coast Survey (OCS), (2) NOAA raster nautical chart (RNC) shoreline, and (3) the World Vector Shoreline (WVS).

The combination was achieved in the following way. First, the EVS shoreline was used to form a baseline shoreline dataset. However, compared to NOAA RNC shoreline, this dataset demonstrated evident errors in certain nearshore marshland areas. The erroneous MHW depictions were corrected using computer-aided techniques to match the MHW coastline represented on the RNC. This was implemented via a commercial software package called Surface-water Modeling System© (SMS). Using SMS, geo-referenced RNCs and the EVS data were overlaid and contrasted visually. Wherever the two did not match, the EVS was judged to be incorrect and replaced by the chart coastline. Figure 1 shows the combined EVS and RNC shorelines.

However, the combined shoreline coverage ceases near the U.S.-Canadian border around Calais, Maine (Figure 1). Hence, the relatively low resolution WVS coastline was used to supply the omitted coverage over the Canadian coastline.

2.2. Bathymetric Data

Bathymetric data used in this study were from four sources: NOS soundings, the NOAA Electronic Navigational Charts (ENCs) bathymetry, bathymetry archived by Bedford Institute of Oceanography (BIO), Dartmouth, Nova Scotia, Canada; and ETOPO2v2 archived by the NOAA National Geophysical Data Center (NGDC).

The NOS sounding data include surveys conducted between 1930 and 2010. The data were referenced to either MLW or MLLW, depending on the years of data collection. The ENC data were treated as referenced to MLLW. The data from the remaining two sources are both referenced to mean sea level (MSL). Figures 2-5 illustrate the spatial coverage of distribution of the NOS soundings, ENC, BIO, ETOPO2v2 used in the present study. The horizontal and vertical accuracy standards for NOAA surveys are listed in Table A.1 of Appendix A.

The NOS soundings possess a higher spatial distribution density than the ENC data. In some areas, the two are commonly available. However, neither of them provides complete coverage for the whole study area. Hence, they were blended for a better regional coverage. It is noted that even the merged data set omits the Bay of Fundy (BF) and the areas beyond the continental shelf. The BIO and ETOPO2v2 bathymetry data were then adopted for the BF and off-shelf break areas, respectively.

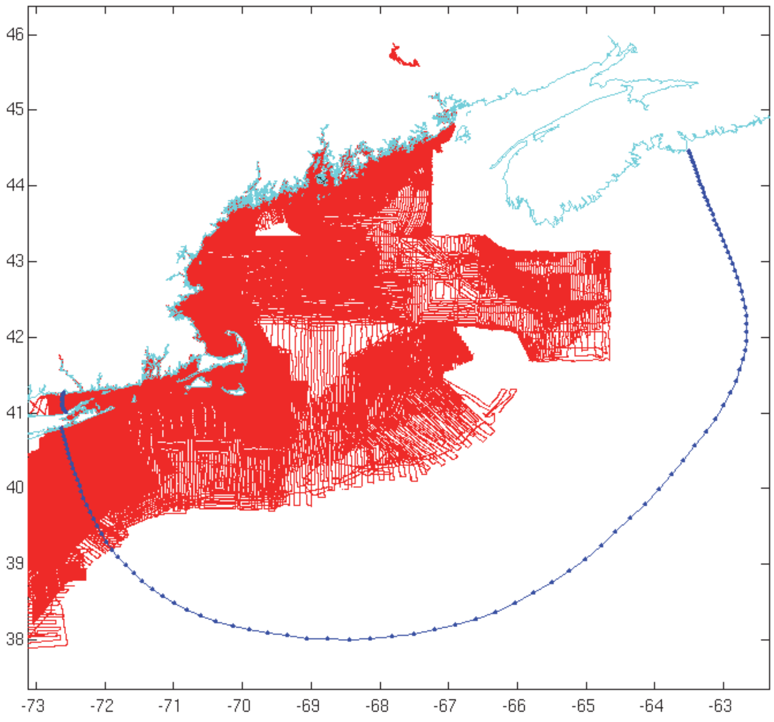

Figure 2. Locations of NOS soundings (red points). Two dotted blue lines represent the open ocean boundary of the hydrodynamic model grid.

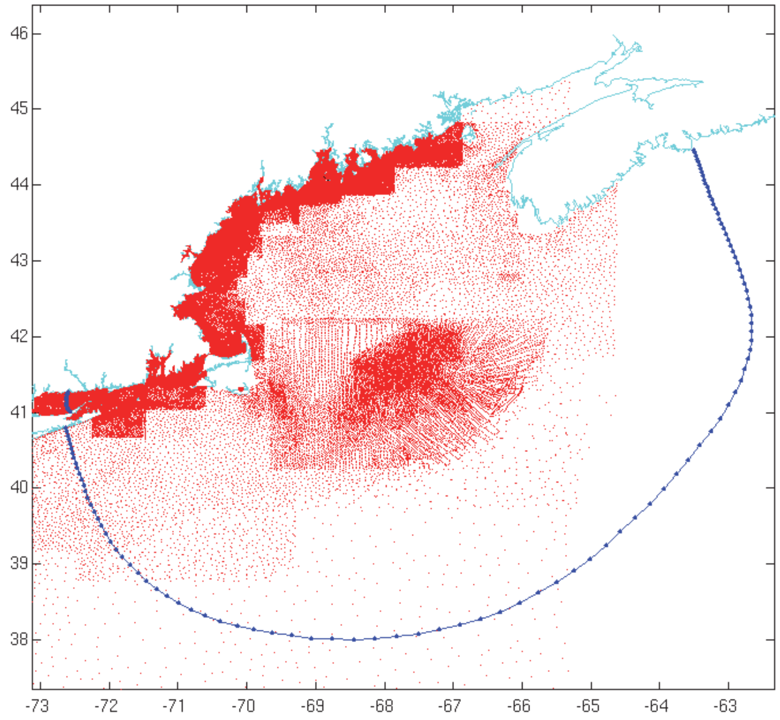

Figure 3. Locations of ENC bathymetric data (red points). Two dotted blue lines represent the open ocean boundary of the hydrodynamic model grid.

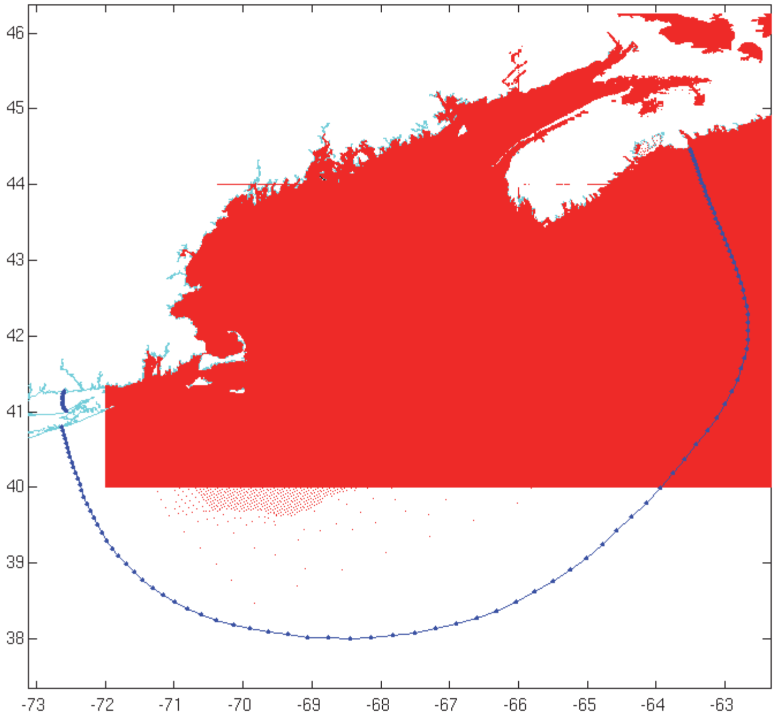

Figure 4. Locations of bathymetric data obtained from Bedford Institute of Oceanography, Canada (red points). Two dotted blue lines represent the open ocean boundary of the hydrodynamic model grid.

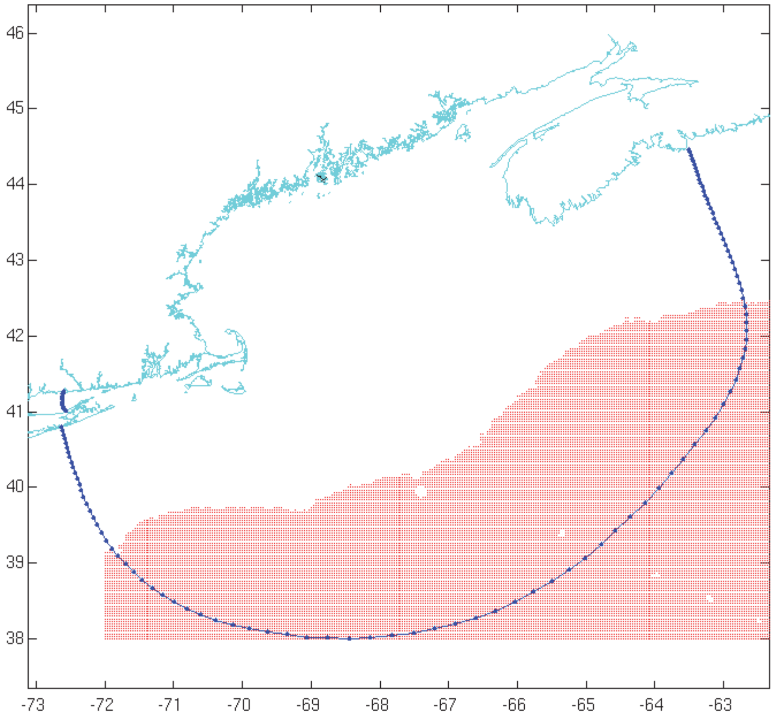

Figure 5. Locations of the subset of ETOPO2v2 data used in the present study (red points). Two dotted blue lines represent the open ocean boundary of the hydrodynamic model grid.

2.3. Tidal Datum Data

Tidal datums from CO-OPS water level stations were used for verifying model results. Observational data were from CO-OPS and are available online. They are computed to correspond to the 1983-2001 National Tidal Datum Epoch (NTDE). Many stations are located within either embayments or near obstructions not mapped by the present model grid (Section 3.2), or at upper-reaches of riverine areas where datums exhibit strong seasonal variability. Data from these stations were judged to be unsuitable for validating model results and hence discarded.

Data from 113 stations were selected for the model validation. Tables B.1 and B.2 in Appendix B list their names, identification numbers, locations, and corresponding tidal datum values.

3. TIDAL DATUM SIMULATION

3.1. Hydrodynamic Model

The ADvanced CIRCulation (ADCIRC) model (Luettich et al., 1992; Westerink et al., 1993) was employed to simulate water level time histories and derive tidal harmonic constant fields. The ADCIRC model is a prognostic, unstructured grid, hydrodynamic circulation model. It simulates tides by solving shallow water equations and proves to be valid for modeling tides from open oceans to coastal and estuarine waters (Luettich et al., 1999; Mukai et al., 2002; Myers, 2005). The ADCIRC model provides a variety of options for users to specify various aspects of tidal dynamics and execution modes. For instance, the model run could be in either two- or three-dimensonal modes, serial or parallel execution dependent on machine infrastructures, linear or quadratic bottom friction formulations with constant or variable friction coefficients, etc. More details on the model setup such as model grid generation, population of the model grid bathymetry, and parameter specifications are addressed in following sections.

3.2. Model Grid

The present model domain encompasses the GOM and adjacent coastal waters, covering eastern LIS, Georges Bank, the entire GOM, the Bay of Fundy, and Nova Scotia (Figure 1). The domain extends from the shoreline to deep ocean areas beyond the continental shelf (Figure 6). A high-resolution, unstructured grid of 167,923 nodes and 311,121 triangular elements was created to map the domain up to the MHW shoreline. Figures 7(a-c) show close-up views of the grid (from southwest to northeast) for (a) Buzzards Bay, Nantucket Sound, and Cape Cod Bay, (b) Massachusetts Bay and the southern Maine Coast, and (c) the northern Maine Coast. The spacing between grid nodes ranges from around 15 m to 25 km. In general, finer elements were used to map nearshore areas compared to those in deep waters, so as to accurately resolve fine coastline features and reflect bathymetry variability.

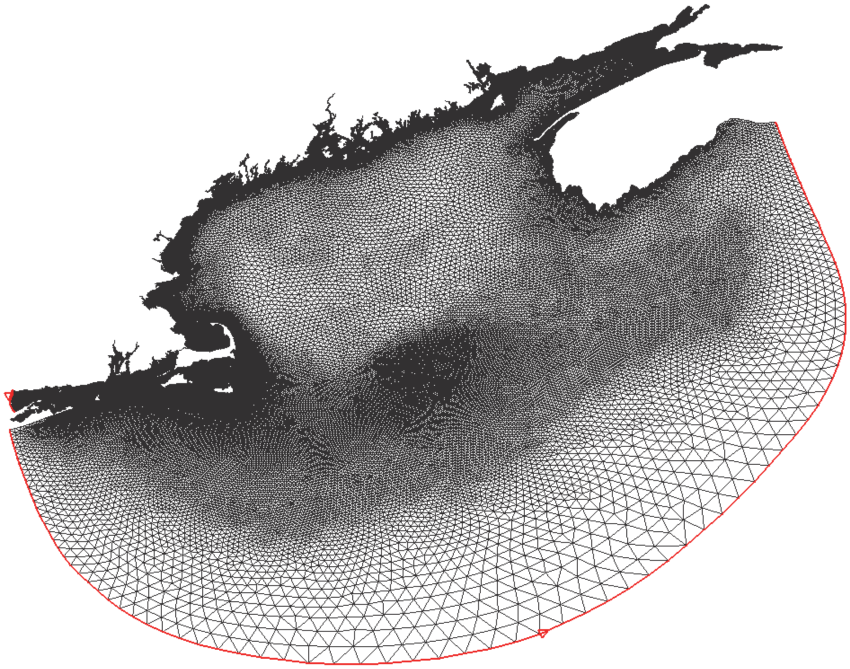

Figure 6. Finite element grid for the entire model domain. Two red lines denote the model's ocean boundaries in eastern LIS and the open ocean.

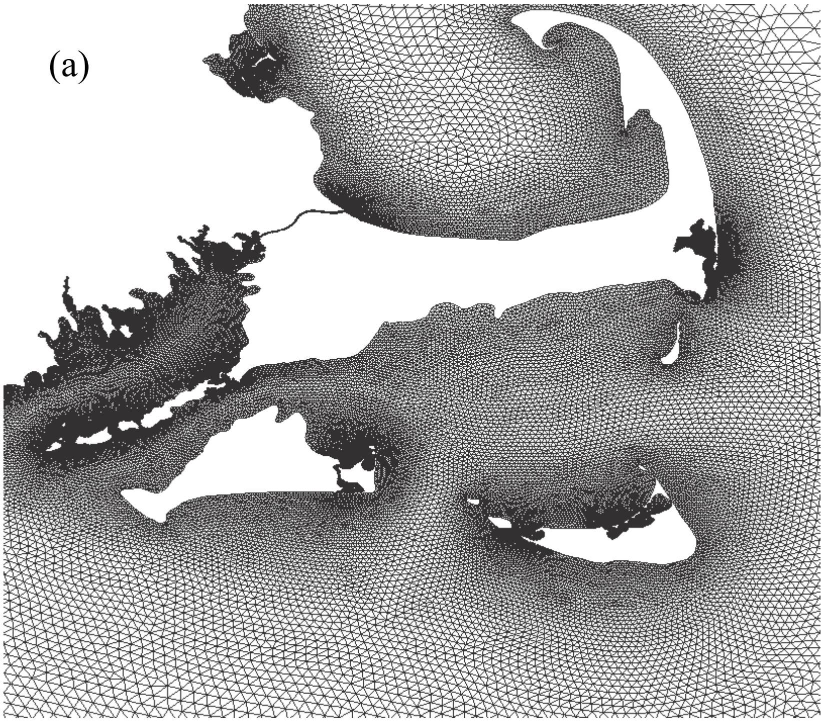

Figure 7. Close-up views of the model grid in (a) Buzzards Bay, Nantucket Sound, and Cape Cod Bay area, (b) Massachusetts Bay and the southern Maine Coast, and (c) the northern Maine Coast.

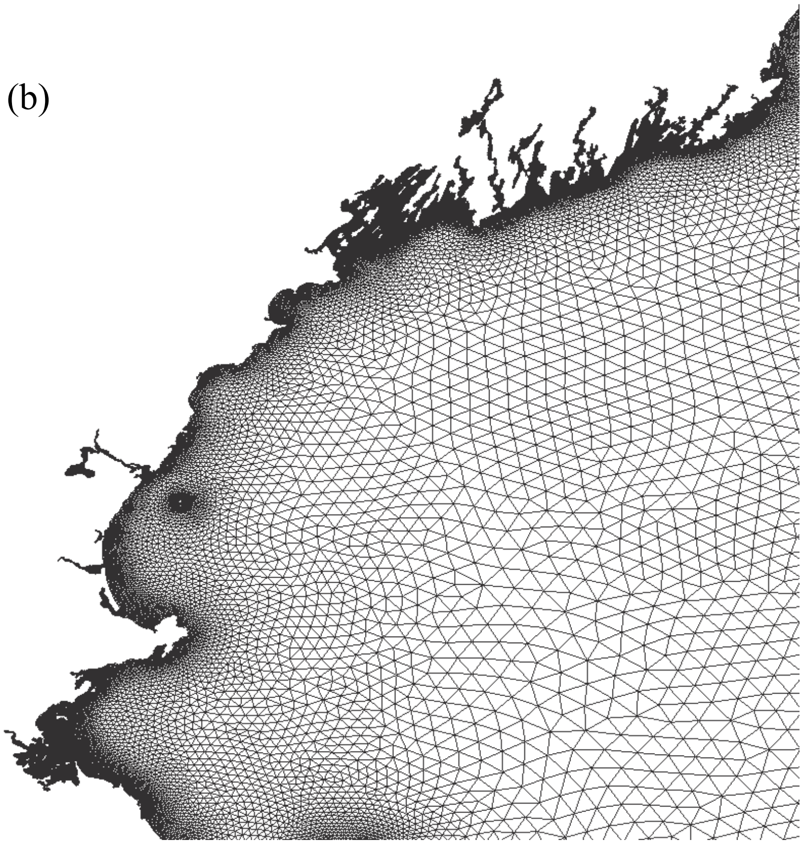

Figure 7. (Continued)

(c)

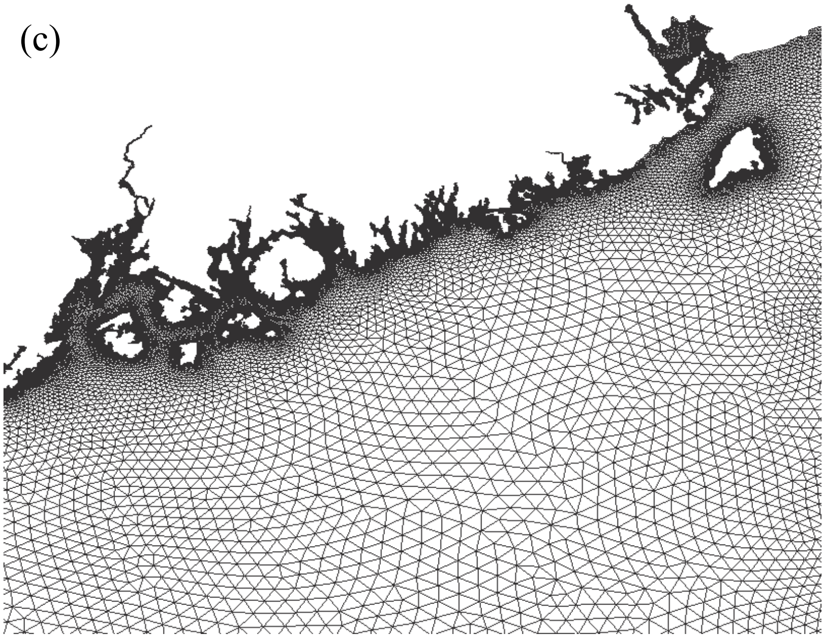

Figure 7. (Continued)

3.3. Bathymetry on Model Grid

The model grid was populated separately with the four bathymetric datasets (Section 2.2) using a cluster averaging approach (Yang et al., 2005) to form four bathymetry grids, referenced to (1) ENC, (2) NOS soundings, (3) BIO, and (4) ETOPO2v2. Due to the limited spatial coverage of each data set, each of the four grids left numerous unpopulated nodes. Meanwhile, the nodes with valid bathymetry vary from grid to grid.

The four grids were then merged to form an improved coverage. First, the ENC grid was treated as a baseline grid. Next, the NOS grid was used to assign values to the baseline grid nodes with null bathymetry. The BIO grid was then added to the remaining null-value nodes. Finally, the ETOPO2v2 grid was employed. After the merging, there were still some unpopulated nodes (less than 2% over the entire domain). They were then filled in by interpolating or extrapolating from surrounding nodes with valid bathymetry values.

The merged grid was referenced to MLLW. The hydrodynamic model requires bathymetry referenced to a model zero (MZ), which represents a geopotential surface. Prior to any initial model runs, the difference between MZ and MLLW is unknown. For the initial guess, the bathymetry was adjusted to MSL, which was considered to be equal to MZ for the first run, by adding 0.5 meters to every node.

After each model run, a new set of model tidal datum fields was derived and the model bathymetry was adjusted accordingly. This process was repeated iteratively until the modeled tidal datums converged. Figure 8 displays bathymetry used for the final model run.

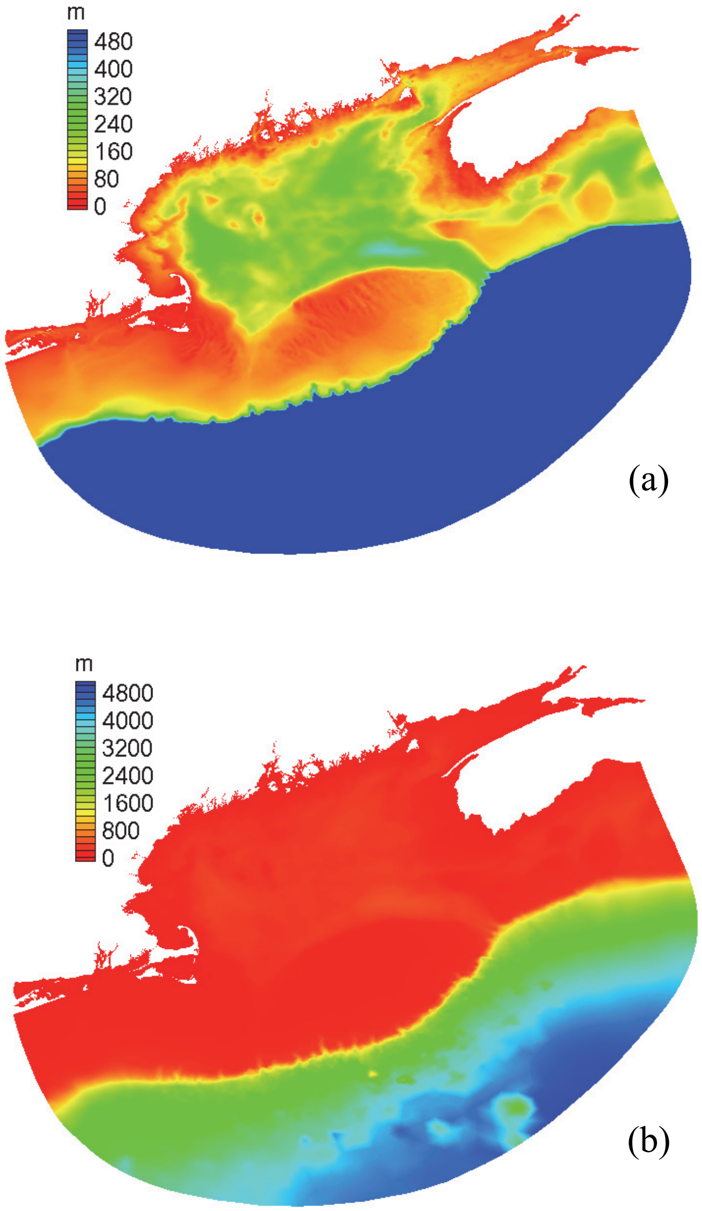

Figure 8. Model grid bathymetry relative to MSL, (a) bathymetries between [0, 500] m; those beyond 500 m are denoted in the same scale as the 500-m bathymetry; (b) bathymetries between [500, 4800] m; those less than 500 m are denoted in the same scale as the 500-m bathymetry. Color bar units are meters.

3.4. Model Parameter Selection

In the present study, model parameters were selected to solve the shallow water equations in Two-Dimensional Depth-Integrated (2DDI) mode with activated finite amplitude and convection terms. Lateral viscosity was set as a constant, 5.0 m s^{-2}, throughout the model domain. A quadratic friction scheme with spatially-varying coefficients (C_f) was specified to calculate bottom friction. Multiple runs were conducted to test various C_f values in an attempt to mitigate model-data discrepancy in terms of tidal datums. Figure 9 shows the C_f values for the final tidal simulations. Note that bottom friction coefficients of $C_f \sim 9\times10^{-3}$ were specified in the northeastern Muscongus Bay, Maine, area. This introduced a strong bottom friction dissipation mechanism in the hydrodynamic model and helped facilitate a favorable model-data agreement in the area.

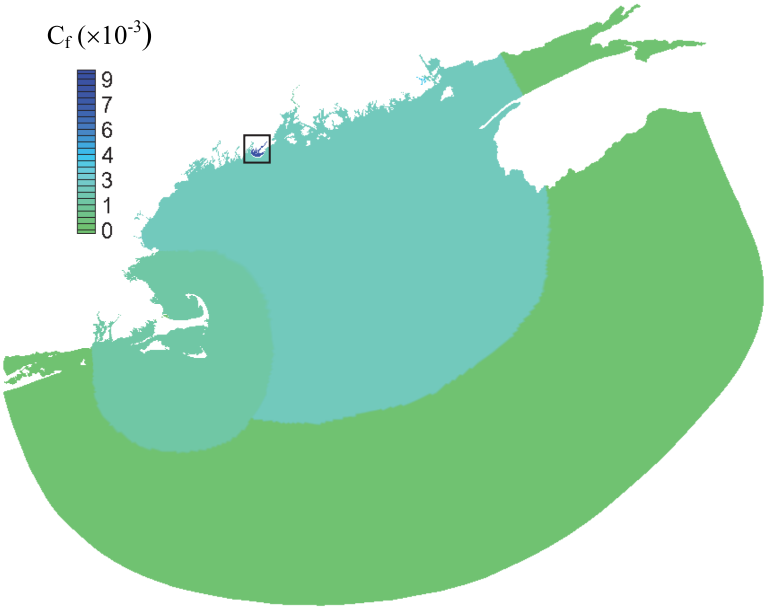

Figure 9. Spatially varying bottom friction coefficients (C_f) used for model simulations. Relatively large values of $C_f \sim 9\times10^{-3}$ were specified in the northeastern Muscongus Bay, Maine (black square) area.

The nine most significant astronomical tidal constituents (M_2, S_2, N_2, K_2, K_1, P_1, O_1, Q_1, and M_4) were chosen to drive the model on its open boundary. Corresponding harmonic constants were interpolated based on a tidal database derived from the Western North Atlantic Ocean tidal model (WNATM) (Myers, unpublished manuscript). A time step at 1.0 second was used to ensure computational stability. The simulation was time-integrated for 55 days. First, the model was ramped up for 5 days with a hyperbolic tangent function. It was then integrated for another 5 days to allow for the tidal field reaching an equilibrium state. Afterwards, 6-minute interval water level time series were recorded for 45 days for the computation of the tidal datums. It is noted that water level records of various lengths were tested to gain insight into the sensitivity of record lengths to the stability of the resultant tidal datum values. The test proved that a 45-day period is an appropriate choice to obtain statistically stable results.

The parallel version of ADCIRC was adopted and the model run was conducted on 50 processors of the JET high performance computing system at NOAA' Earth System Research Laboratory. It took approximately eight hours to complete the 55-day simulation.

3.5. Tidal Datum Computation and Results

From the modeled water time series, tidal datums including MSL, MHHW, MHW, MLW, and MLLW at each model node were derived relative to the MZ. The latter four were then adjusted to be referenced to MSL. Note that MTL is defined as the algebraic average of MHW and MLW, and DTL is the algebraic average of MHHW and MLLW. The two fields were not computed until error-corrected MHHW, MHW, MLW, and MLLW fields were derived (Section 4.2).

Figures 10(a-d) display the model derived tidal datum fields for MHHW, MHW, MLW, and MLLW, respectively. As expected, the four fields exhibit a similar spatial pattern. They demonstrate good agreement with previously published results in both spatial patterns and magnitudes. The tidal range over the NS and GB appear to be as low as 0.4 m. They are amplified as propagating along the eastern GOM coast. In BF, the MHHW increases from 2 m at the Bay mouth to nearly 7 m in the upper Bay. In the western Gulf, it increases from 1 to 2 m from south to north.

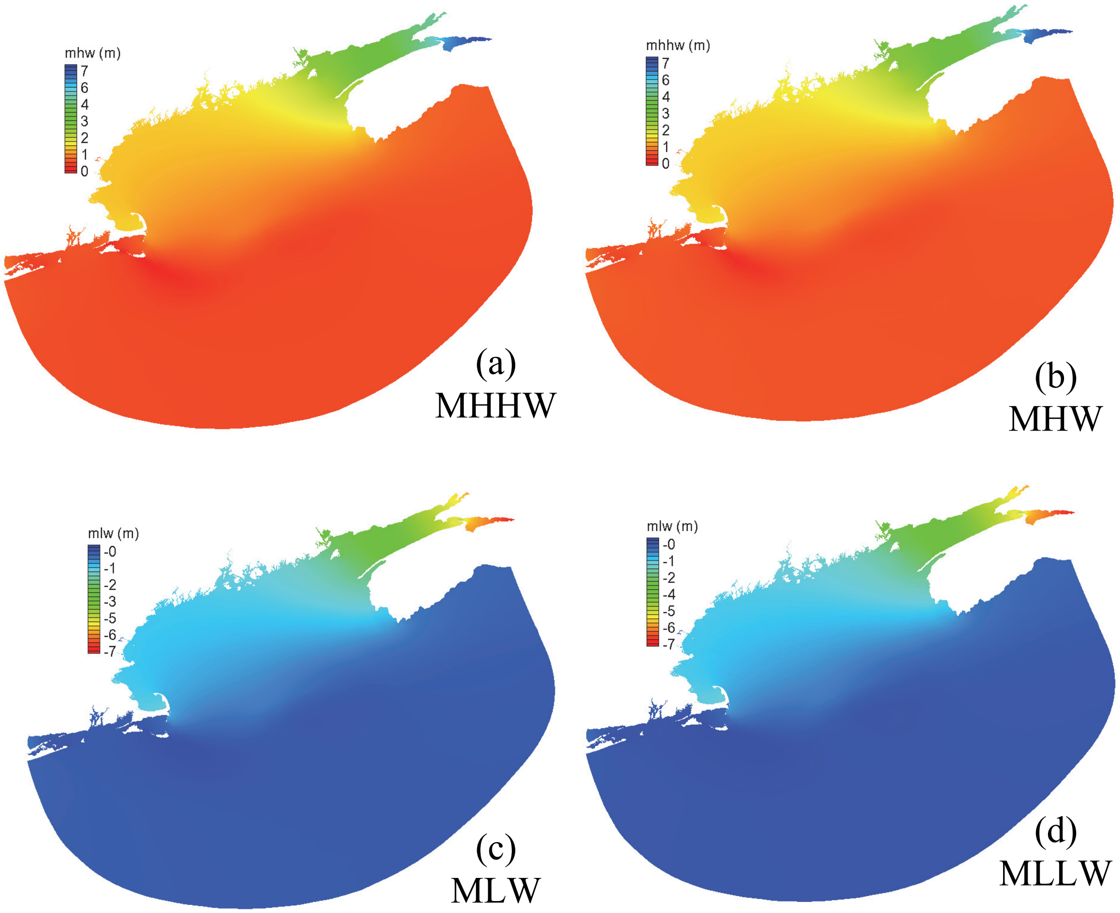

Figure 10. Model-derived tidal datum fields, (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW over the whole model domain.

3.6. Verification and Error Correction

3.6.1. Comparison with Observations

To validate model results, modeled tidal datums were compared with those from 113 CO-OPS water level gauges in the region (Appendix B). Figures 11(a)-(d) display model-data contrasts for MHHW, MHW, MLW, and MLLW, respectively. In general, the plots illustrate good model-data agreement. Table 1 list mean magnitudes (averaged over the 113 stations) and standard deviations of model errors for each of the four datums.

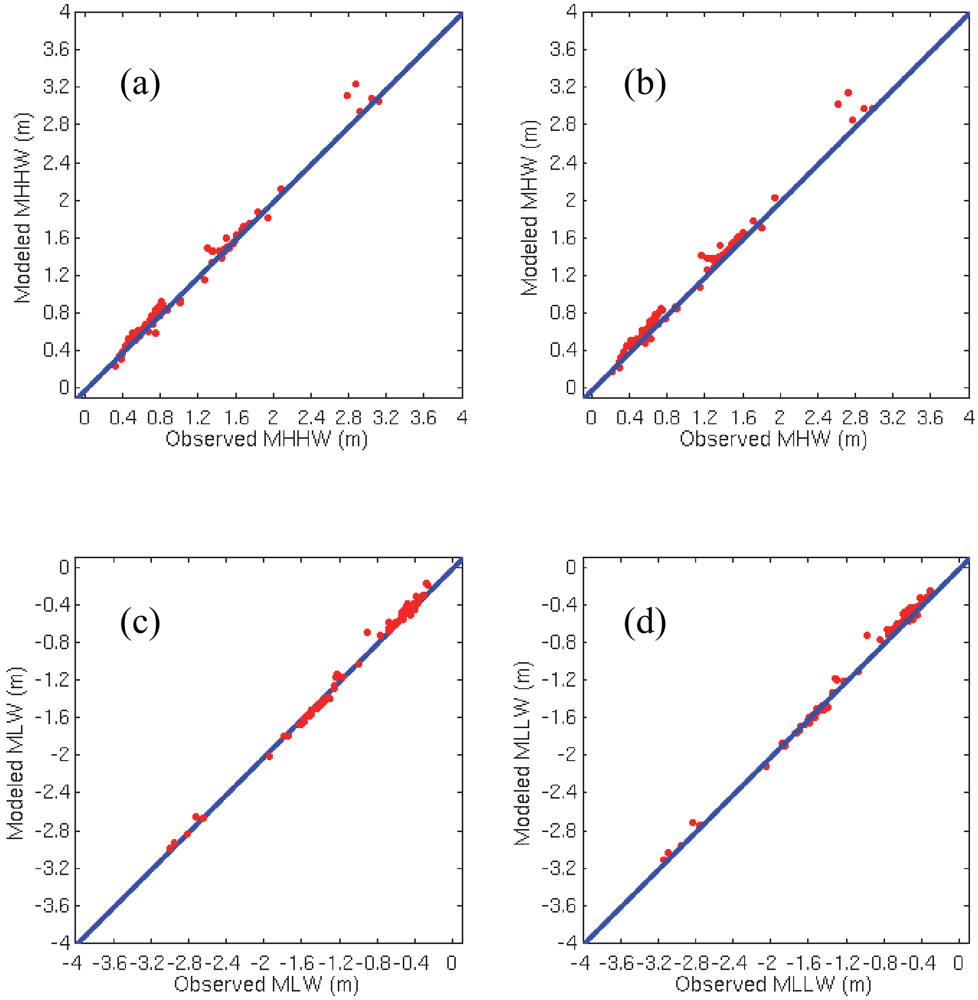

Figure 11. Comparisons of the modeled (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW against observations.

Table 1. Statistics of model errors for MHHW, MHW, MLW, and MLLW

	MHHW (cm)	*MHW (cm)*	*MLW (cm)*	*MLLW (cm)*
Average model errors	1.1	4.5	-1.3	0.9
Mean magnitudes of model errors	4.1	5.6	4.2	4.3
Standard deviations of model errors	6.7	6.9	5.0	5.4

Figure 12 displays the mean magnitude (averaged over MHHW, MHW, MLW and MLLW) of model errors at each station. Figures 13a-c show close-up views of Figure 12 in three areas, (a) eastern LIS and Narragansett Bay, (b) Cape Cod Bay and Boston Harbor, and (c) the Maine coast.

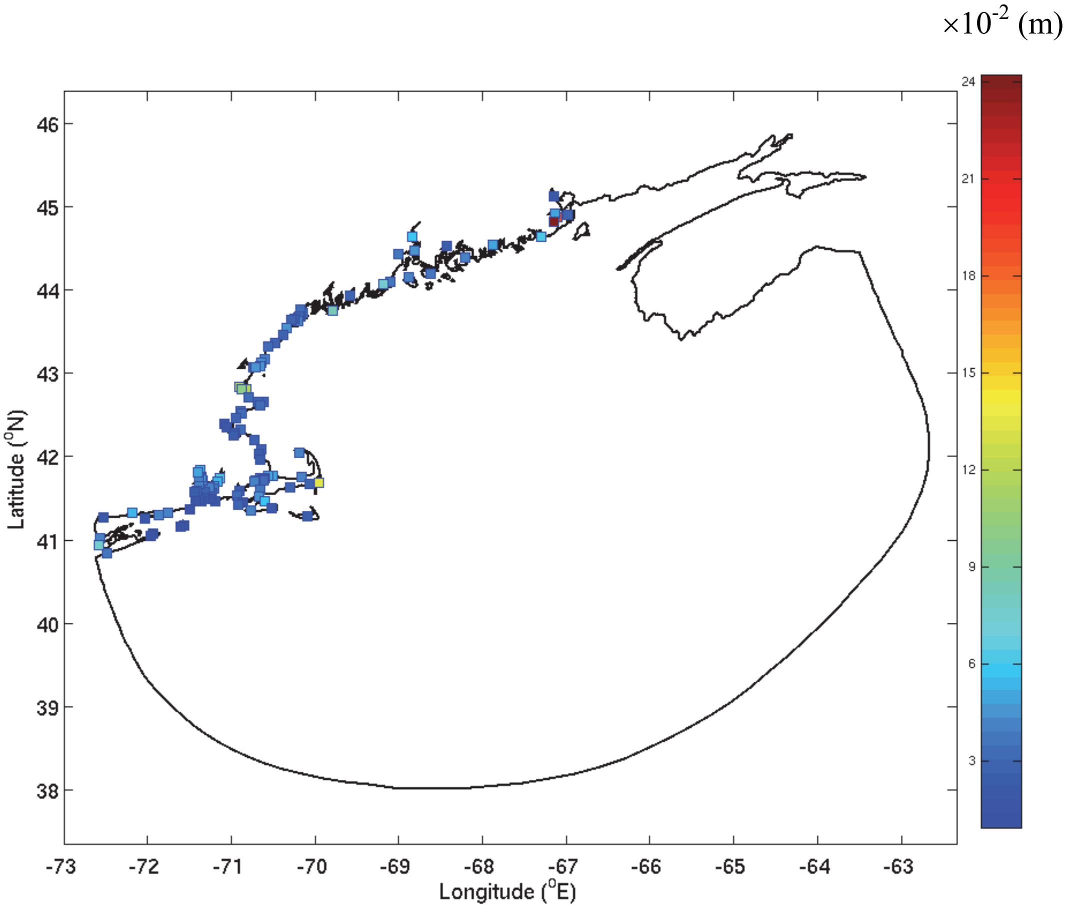

Figure 12. Mean magnitude of model-data differences averaged over MHHW, MHW, MLW and MLLW.

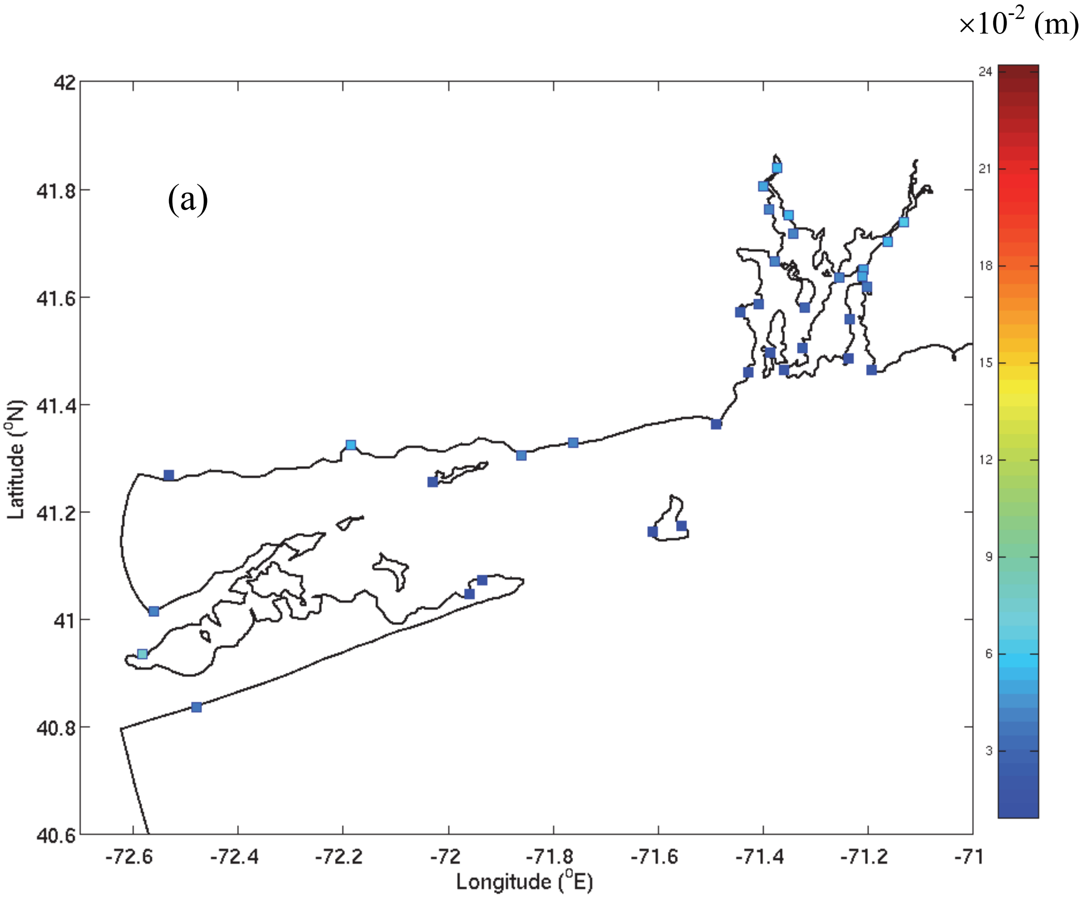

Figure 13. Close-up views of model-data differences (Figure 12) in three areas, (a) eastern LIS and Narragansett Bay, (b) Cape Cod Bay and Boston Harbor, and (c) the Maine coast.

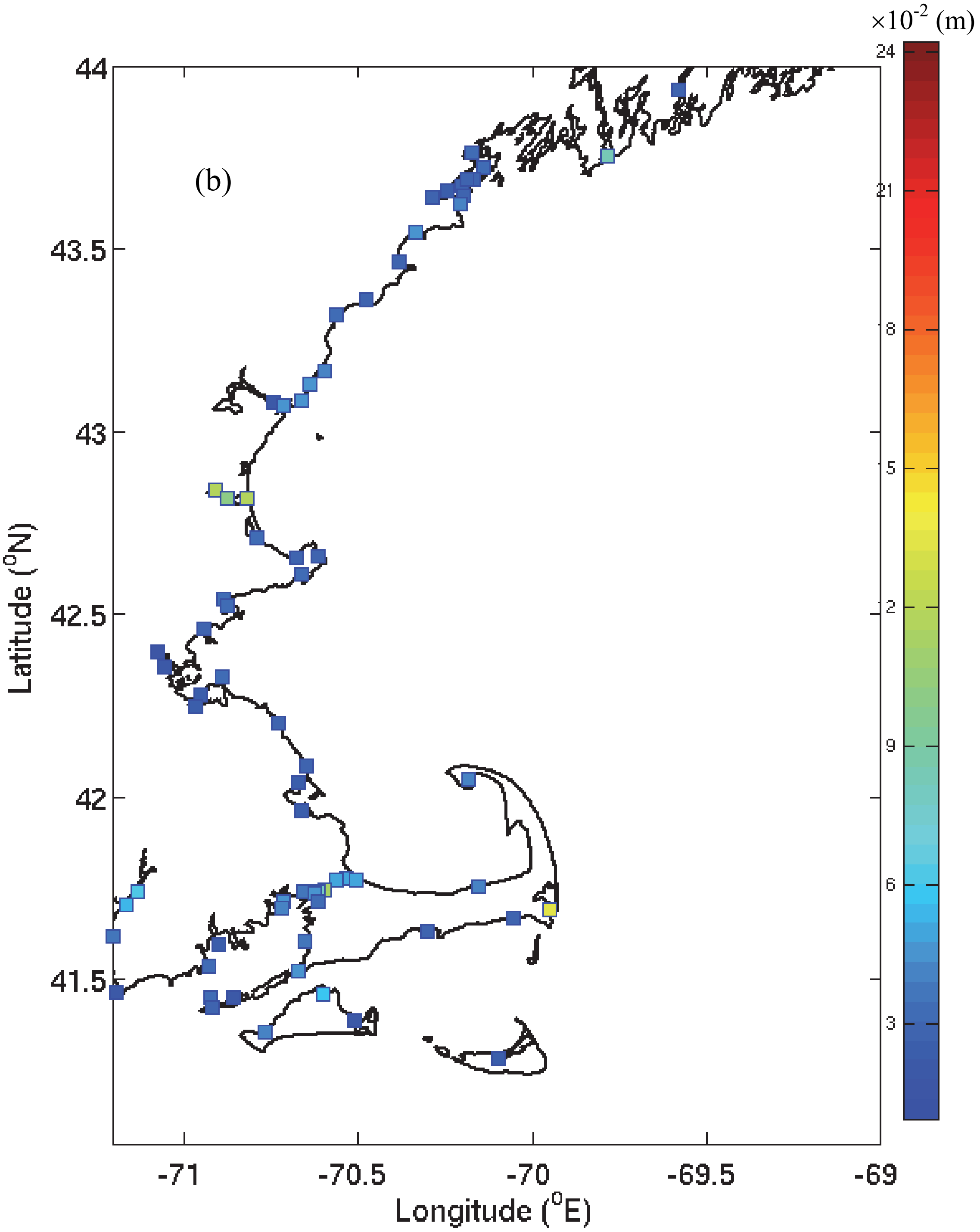

Figure 13. (Continued)

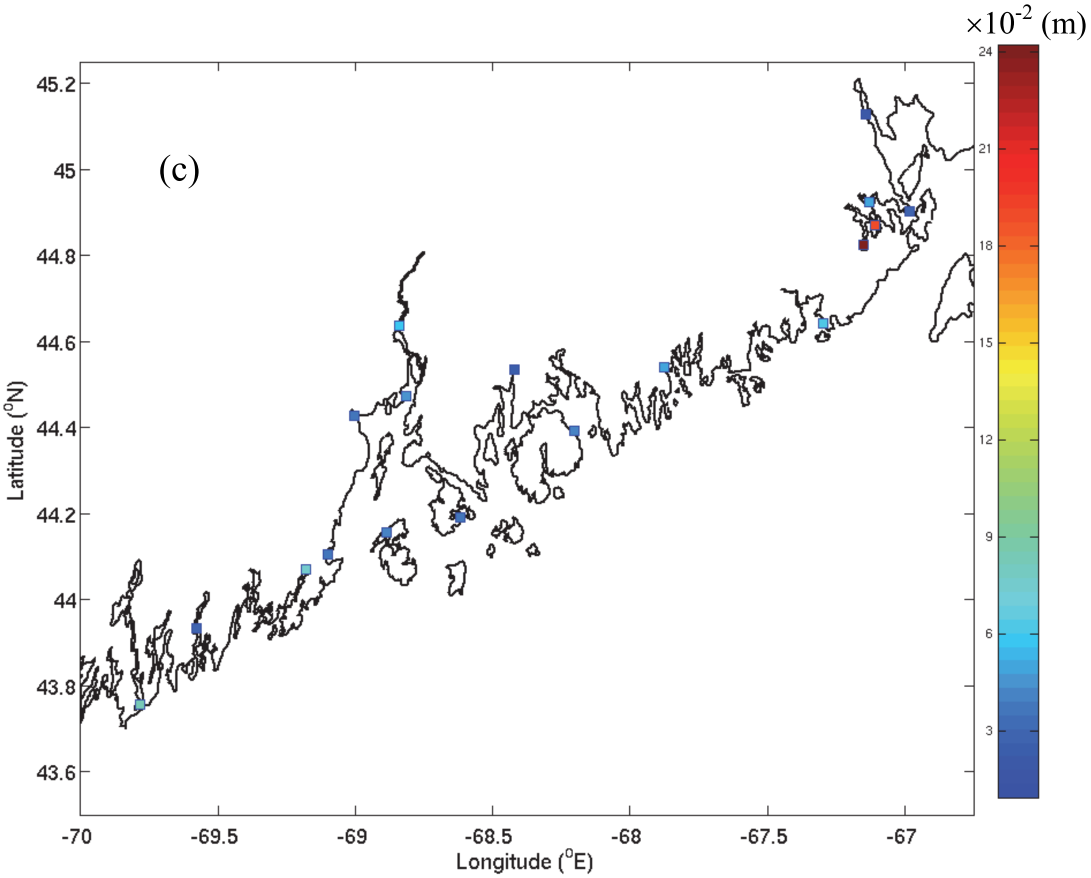

Figure 13. (Continued)

3.6.2. Comparison with Tidal Datums in Adjacent Areas

The present GOM model domain overlaps with the LIS-NYB VDatum domain (Yang et. al, 2010b). The two domains overlap in the eastern New York Bight area. Transect AB (the blue line in Figure 14) marks the boundary of the LIS-NYB VDatum domain and the present GOM VDatum domain (Section 4).

In reality, tidal datum fields should be matched seamlessly across domain boundaries. However, this is not necessarily guaranteed, since the two sets of datum fields were developed separately with different model setups in terms of tidal boundary forcing, magnitudes of the bottom friction coefficients, etc. For instance, the open boundary tidal forcing harmonic constants were derived from different tidal databases. The LI-NY model was based on the EastCoast 2001 (Mukai et al., 2002)-database while the present GOM model was from WNATM database (Myers, unpublished manuscript). It is therefore worthwhile to examine discrepancies and work out ways to achieve seamless matches if needed.

Comparisons between the present model results and those of the LIS-NY domain were made along transect AB (Figure 14). Table 2 lists statistics of the datum difference along the transect for MHHW, MHW, MLW, and MLLW, respectively.

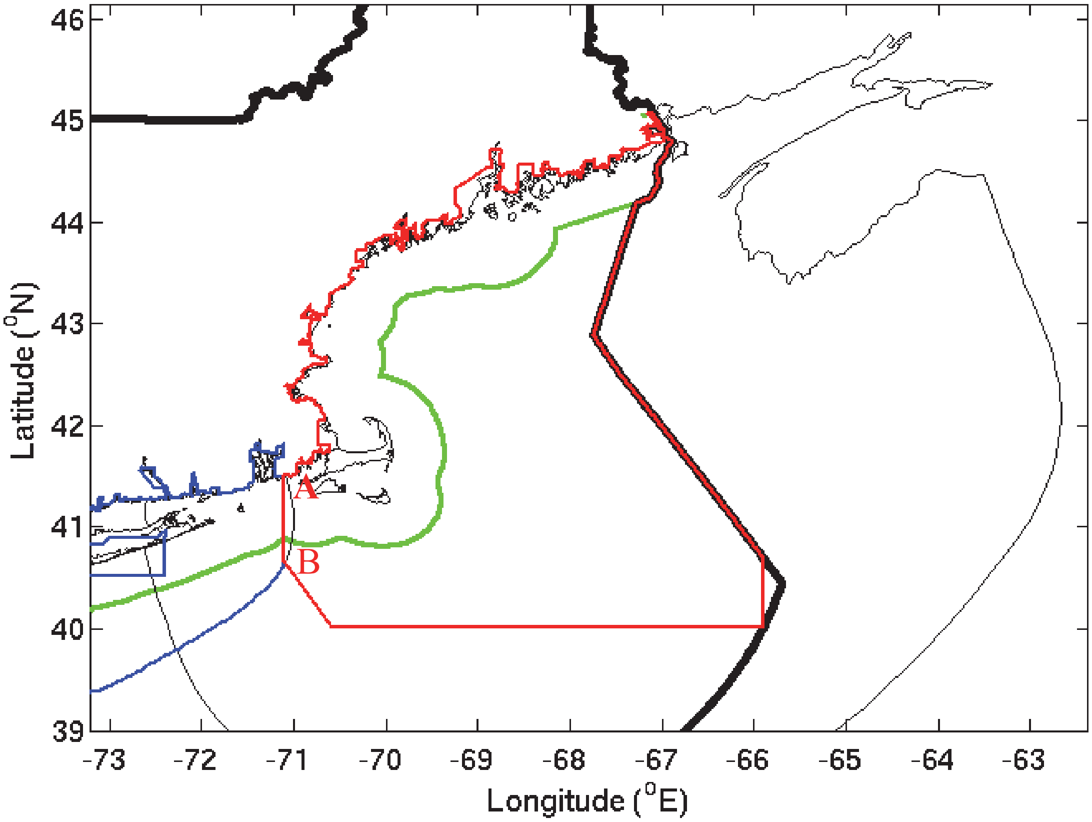

Figure 14. Bounding polygons for two VDatum domains: (1) LIS-NYB (blue line) and (2) GOM (red line). Transect AB denote locations where tidal datum agreement is being examined (Section 3.6.2). The green line illustrates locations 25-nautical miles offshore. The thick and thin dark lines represent, respectively, the U.S. border and the ADCIRC tidal model domain boundaries (Section 3.2).

Table 2. Statistics of tidal datum differences (Δ) across the boundary (transect AB in Figure 14) between the LIS-NY and GOM domains.

	MHHW (cm)	*MHW (cm)*	*MLW (cm)*	*MLLW (cm)*
min(|Δ|)	0.2	1.9	0.6	2.3
max(|Δ|)	2.6	3.4	3.5	6.4
mean(|Δ|)	0.8	2.6	2.4	5.3
std(Δ)	0.4	0.4	0.5	0.6

As illustrated in the table, the magnitude of the average differences for MHHW and MLLW ranges from 0.8 cm to 5.3 cm, respectively, whereas the standard deviation of the differences ranges from 0.4 cm to 0.6 cm. It was therefore necessary to make adjustments to the present model results so as to reach a seamless match of tidal datums between different adjacent regions. The method of adjustment is described in the next section.

3.6.3. Corrections

Tidal datum corrections aim at eliminating model-data differences at observational stations (Section 3.6.1) as well as diminishing datum discrepancies across boundaries of different VDatum domains (Section 3.6.2). This was achieved using the TCARI (Tidal Constituent And Residual Interpolation) interpolation software (Hess, 2001; Hess, 2002; Hess, 2003). TCARI spatially interpolates the error values defined at a number of individual control stations onto the whole domain by solving Laplace's equation. TCARI has been implemented for both structured and unstructured model grids in CSDL, and a version of the latter was employed in this study.

To use the TCARI interpolation, both the observational stations and the domain boundary stations are treated as control stations. For each tidal datum, both model-data differences at NOS water level stations and across-boundary discrepancies were computed and merged into one dataset as the input to TCARI. Figures 15(a-d) display the TCARI interpolated error fields for MHHW, MHW, MLW, and MLLW, respectively.

After applying TCARI, error fields for MHHW, MHW, MLW, and MLLW were derived which matched the tidal datum differences at the control stations. The initial model results (Section 3.5) were then corrected by subtracting the error fields over the entire model grid. Figures 16(a-d) display the four error corrected datum fields.

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

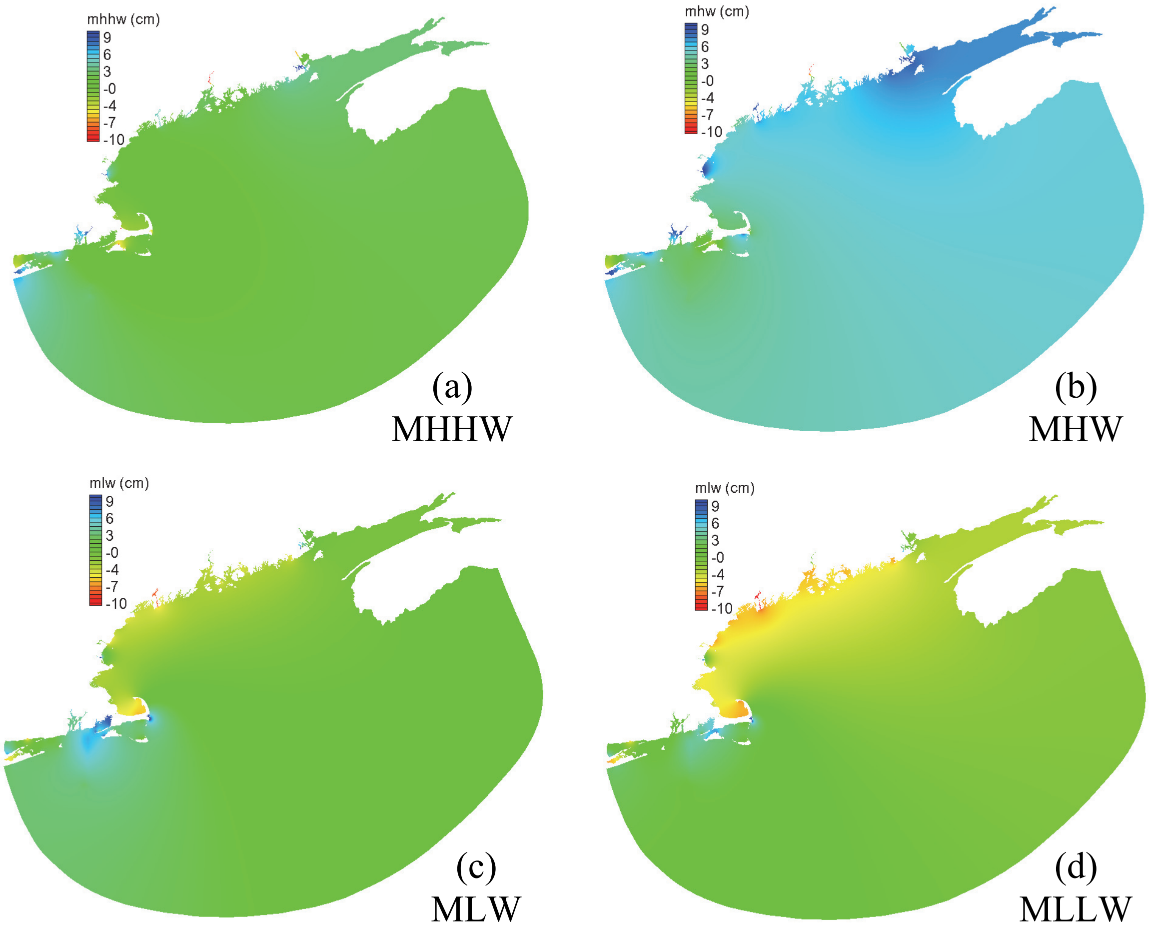

Figure 15. TCARI interpolated error fields for (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW.

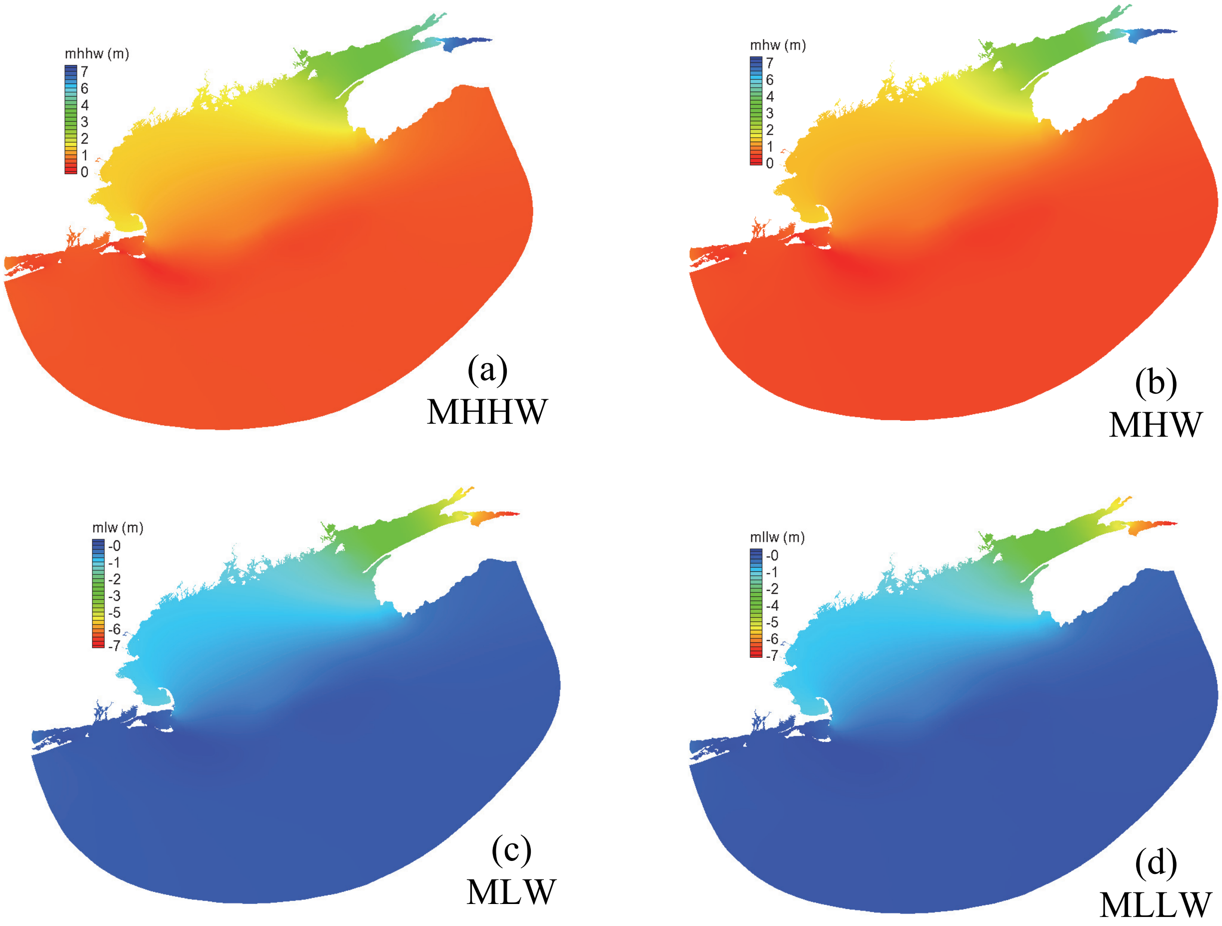

Figure 16. Error-corrected tidal datum fields over the entire model domain, (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW.

4. CREATION AND POPULATION OF THE MARINE GRID

4.1. Creation of VDatum Marine Grid

The VDatum software works on datums defined on regular, structured grids (Hess and White, 2004). Hence, it is necessary to convert the tidal datum fields from the unstructured grid onto an equally-spaced VDatum marine grid.

Nodes on the marine grid are specified as either water points or land points. The water nodes are populated with valid tidal datum values and the land nodes are assigned null values. To create and populate the marine grid, a high-resolution coastline and a bounding polygon (Figure 14) were used. The bounding polygon was set up to guide the delineation of water/land nodes. Only nodes within the bounding polygons or within up to one half of a cell size outside the coastline are delineated as water nodes; those outside of the bounding polygons or those more than one half of a cell size away from the coastline are marked as land nodes.

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

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

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

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

where *(longitude$_1$, latitude$_1$)* are the coordinate at the raster region's northeast corner. Table 3 lists parameters defining the marine grid.

Table 3. Marine grid parameters

Name	*Longitude$_0$ (degree)*	*Latitude$_0$ (degree)*	*del_lon (degree)*	*del_lat (degree)*	*N_lon*	*N_lat*
Gulf of Maine	-71.2000	39.8900	0.0017	0.0017	3307	3341

The second step is to further manually refine the water/land node specification using the imagery coastline definition acquired by NGS. Compared with the aforementioned MHW coastline (Section 2.1), the imagery coastline is more recently updated and gives a more realistic coastline representation. By comparing with the NGS coastline, the nearshore water-land node specifications in the original marine grid were adjusted, while the definition of the marine grid parameters (Table 3) was retained. This NGS marine grid was then used for populating the tidal datums.

4.2. Population of VDatum Grid with Tidal Datums

Tidal datums on the VDatum marine grid were populated by interpolating the TCARI-corrected tidal datums (Section 3.6) following the algorithm of Hess and White (2004). Datums on each grid point were computed by averaging or linearly interpolating within a user-specified search radius or the closest user-specified number of points. Marine points were populated in different ways depending on whether a point lies inside or outside of the ADCIRC model grid. If a marine point was inside an element, datums were computed using an interpolation of the three nodes of the element; otherwise, datums were computed using the inverse distance weighting of the closest two node values. Figures17(a-e) display the populated tidal datums on the marine grid (MHHW, MHW, MLW, MLLW, MTL, DTL).

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

Datum fields across the LIS-NYB and the GOM boundary also demonstrate good consistency. For MHHW, MHW, MLW, and MLLW, average difference and rms difference are less than 0.1 cm and 0.1 cm, respectively.

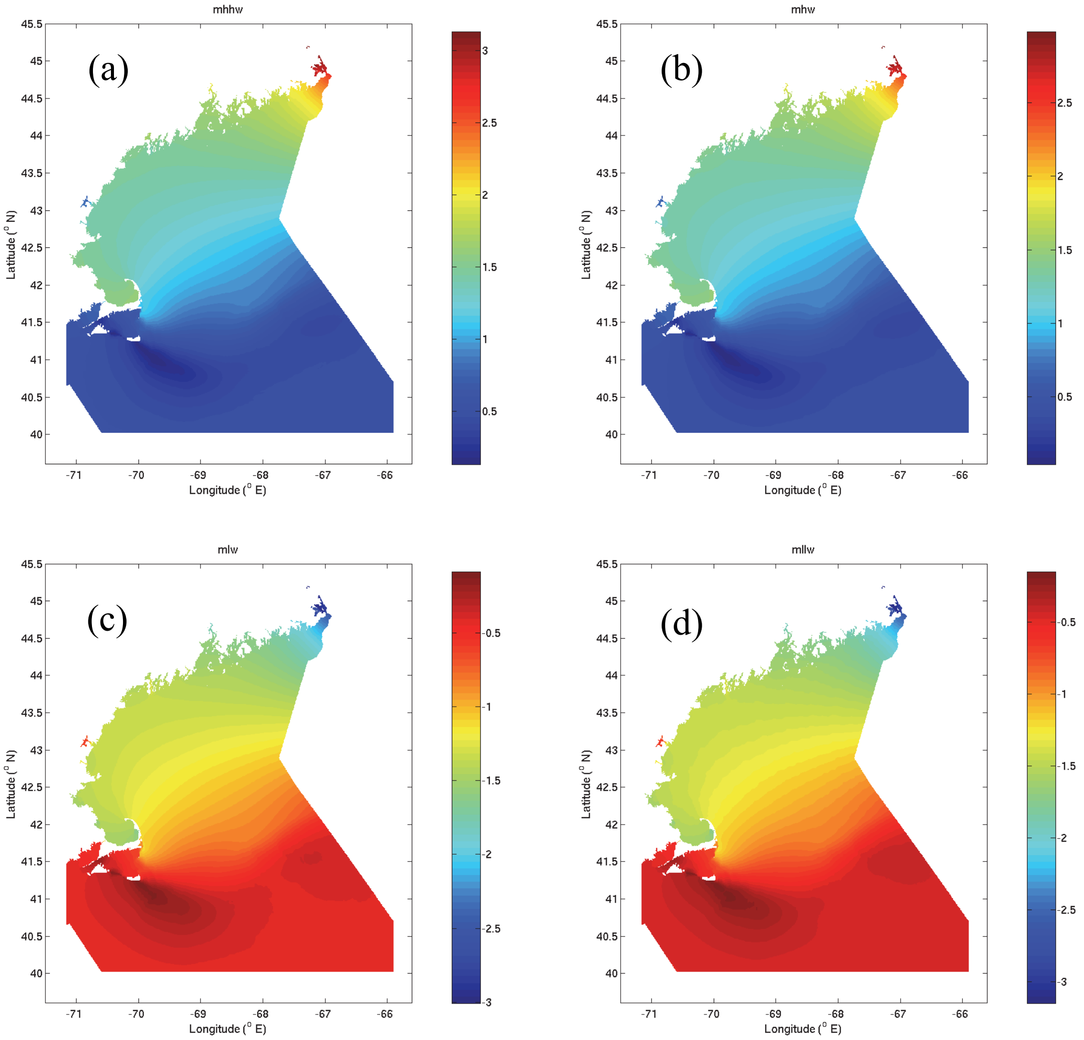

Figure 17**.** Tidal datums on the GOM VDatum grid, (a) MHHW, (b) MHW, (c) MLW, (d) MLLW, (e) MTL, and (f) DTL. Color bar units are meters.

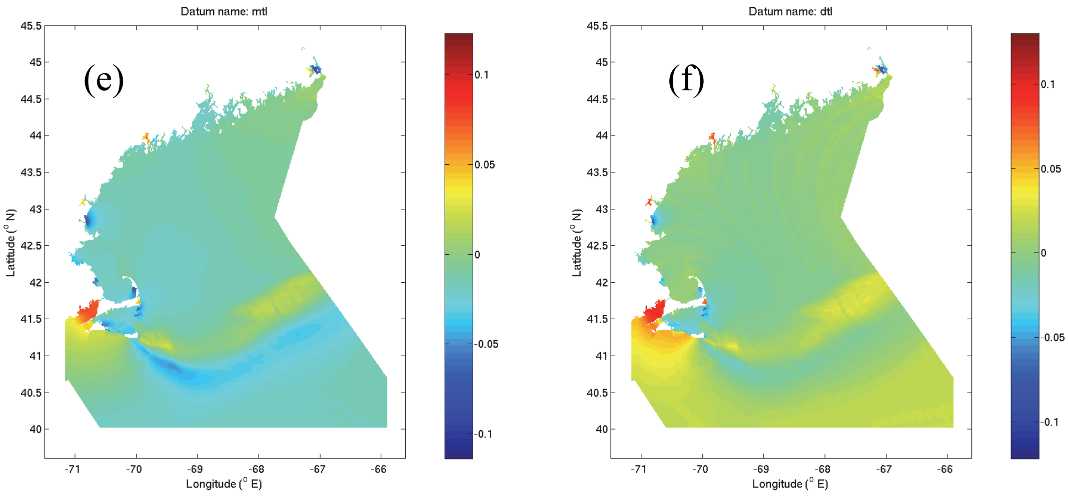

Figure 17. (Continued)

5. TOPOGRAPHY OF THE SEA SURFACE

The Topography of the Sea Surface (TSS) is defined as the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to local mean sea level (MSL). This grid provides compensation for the local variations between a mean sea level surface and the NAVD88 geopotential surface over the GOM VDatum region. A positive value specifies that the NAVD88 reference value is further from the center of the Earth than the local mean sea level surface. All data are based on the most recent National Tidal Datum Epoch (1983-2001). The locations of 48 tide gauges used are illustrated in Figure 18.

The direct method of obtaining NAVD88-to-MSL values includes calculating orthometric-to-tidal datum relationships at NOAA tide gauges where elevation information has been compiled. Data for the direct method were supplied by CO-OPS and NGS.

Next, a continuous surface for each VDatum region was generated representing an inverse sea-surface topography (Figure 19). A mesh covering the entire area of bench marks and water level stations with a spatial resolution similar to that of the tidal marine grids was created. Faultlines were inserted to represent the influence of land. A sea surface topography field was 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 of 0.3 was utilized. Once the gridded topography field has been generated, null values are obtained from the marine tidal grids and are inserted to denote the presence of land.

The data used to compile the TSS grid was compared against the TSS grid product, to generalize internal consistency. The mean delta between NAVD88 and MSL for each tide station utilized for creation of the TSS is depicted for the GOM VDatum region in Table C.1 in Appendix C. The maximum model-data discrepancy is less than 4 mm. The mean and standard deviation for these delta values between NAVD88 to MSL relationships for the GOM VDatum region are $3.5\text{x}10^{-5}$ m and $8.75\text{x}10^{-4}$ m; see Table C.2 in Appendix C.

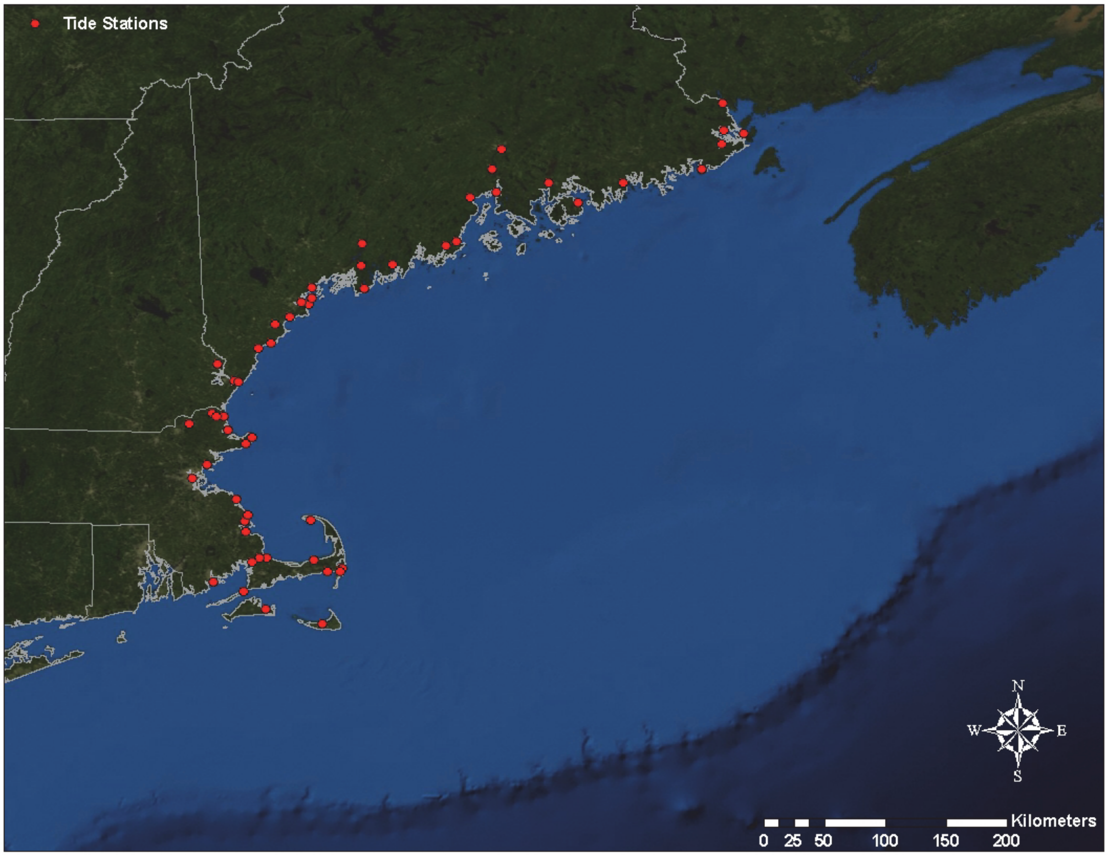

Figure 18. Location of tide stations used to compute the Gulf of Maine VDatum TSS grid.

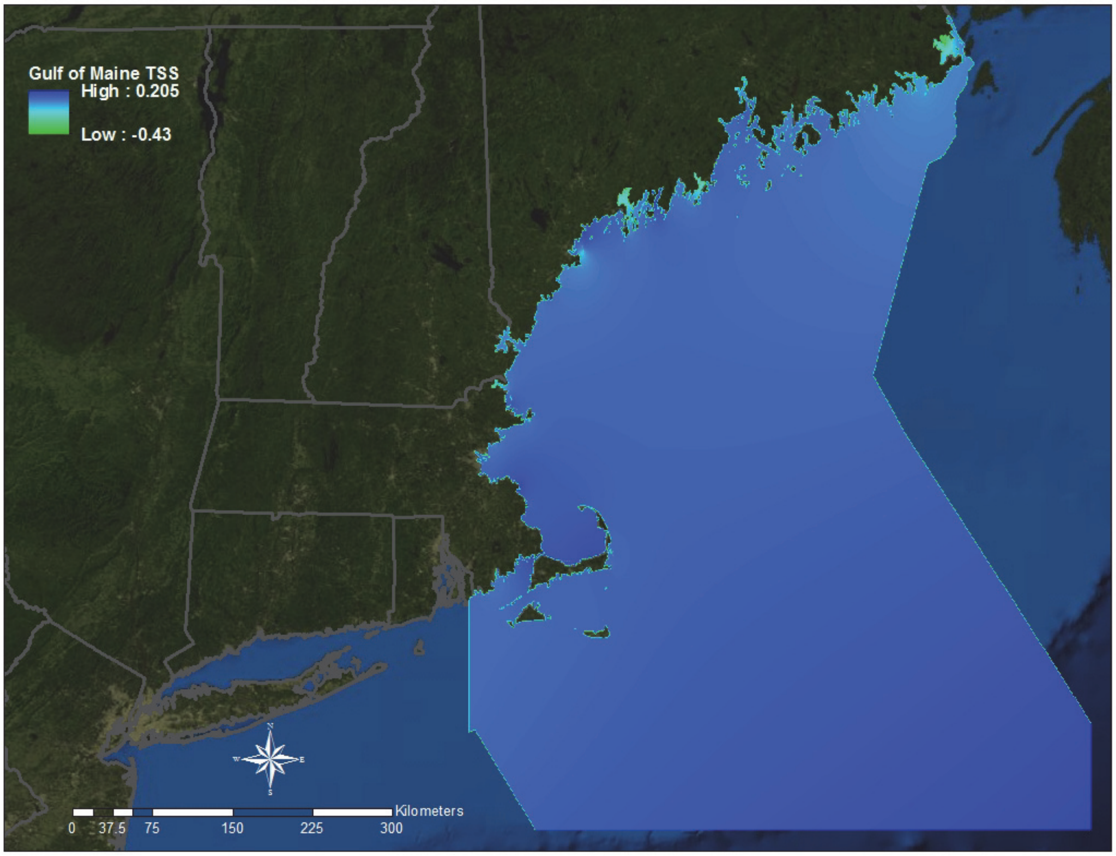

Figure 19. Topography of the Sea Surface for the Gulf of Maine region. Color bar unit is meter.

6. SUMMARY

VDatum tidal datum and TSS fields for the coastal waters of the Gulf of Maine area were developed in this study. Creation of VDatum begins with computing tidal datums using numerical tidal simulations with the ADCIRC model. A triangular finite-element grid consisting of 167,923 nodes and 311,121 cells was created. The model was forced with nine tidal constituents (M_2, S_2, N_2, K_2, K_1, P_1, O_1, Q_1, and M_4) and run for 55 days. Various tidal datum fields, including mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and mean higher high water (MHHW) were derived using the modeled water level time series from the final 45 days of the simulation.

Model results were validated through comparisons with observations at 113 water level stations maintained by NOAA's CO-OPS. Discrepancies between model results and observational datums were attributed to model errors and interpolated over the whole model domain using the TCARI software. The error fields were applied to the direct model results to achieve error-corrected tidal datums on the model grid. Finally, tidal datum fields were interpolated onto a regular VDatum marine grid. The TSS fields were derived by calculating orthometric-to-tidal datum relationships at NOAA tidal gauges.

The TSS field was derived through fitting tidal model results to tidal bench marks leveled in NAVD88 at NOAA tide gauges. The final gridded TSS data were incorporated into the VDatum tool.

The modeled tidal datums and TSS fields are verified through comparisons with observations at 113 water level stations. Of the 113 stations, the average model-data error over four datums (MHHW, MHW, MLW, and MLLW) is about 0.3 cm and the corresponding standard deviation is about 0.3 cm. Of the 48 stations for the TSS validation, the mean and standard deviation for these delta values are 3.5×10^{-5} m and 8.75×10^{-4} m, respectively.

ACKNOWLEDEGEMENTS

The authors would like to acknowledge the support from the chief of CSDL's Marine Modeling and Analysis Programs, Dr. Frank Aikman III. The Authors respectfully thank colleagues from CSDL's Cartographic and Geospatial Technology Program for their help on retrieving bathymetric and digital coastline data sets. Dr. David Greenberg of the Bedford Institute of Oceanography, Canada, kindly provided us high-resolution bathymetric data in the Northern Gulf of Maine and Bay of Fundy areas. We are deeply grateful to his help. The authors would like to express thanks to Drs. Kurt Hess, Jiangtao Xu, and Jindong Wang for their time and effort on reviewing this manuscript and making valuable comments.

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APPENDIX A. HORIZONTAL AND VERTICAL ACCURACY STANDARDS FOR NOAA BATHYMETRIC SURVEYS

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

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

* end of field collection

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

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

[3] International Hydrographic Conference, 1957.

APPENDIX B. WATER LEVEL STATION DATA

Table B.1. NOS water level station numbers, locations, and names

No.	Station ID	Longitude (°E)	Latitude (°N)	Station Name
1	8410140	-66.9829	44.9046	EASTPORT, PASSAMAQUODDY B
2	8410715	-67.13	44.9233	GARNET POINT, HERSEY NECK
3	8410834	-67.144667	45.128444	PETTEGROVE POINT, DOCHET
4	8410864	-67.151667	44.823333	GRAVELLY PT., WHITING B 19
5	8411250	-67.2967	44.6417	CUTLER NAVAL BASE, MACHIA
6	8412581	-67.875	44.54	MILBRIDGE, NARRAGUAGUS RI
7	8413320	-68.205	44.3917	BAR HARBOR, FRENCHMAN BAY
8	8413801	-68.4217	44.535	ELLSWORTH, UNION RIVER
9	8414249	-68.620944	44.192306	OCEANVILLE, DEER ISLAND
10	8414721	-68.8133	44.4717	FORT POINT, PENOBSCOT RIV
11	8414781	-68.8417	44.6367	WINTERPORT, PENOBSCOT RIV
12	8414888	-68.8867	44.1567	PULPIT HARBOR, PENOBSCOT
13	8415191	-69.005	44.4267	BELFAST, PENOBSCOT BAY
14	8415490	-69.1017	44.105	ROCKLAND
15	8415709	-69.1817	44.0717	THOMASTON, ST GEORGE RIVE
16	8416731	-69.58	43.9333	WALPOLE, DAMARISCOTTA RIV
17	8417177	-69.785	43.755	HUNNIWELL POINT, KENNEBEC
18	8417881	-70.1417	43.7217	GREAT CHEBEAGUE ISLAND
19	8417941	-70.17	43.69	LONG ISLAND, CASCO BAY
20	8417948	-70.1733	43.7617	PRINCE POINT, YARMOUTH
21	8417988	-70.2	43.67	GREAT DIAMOND IS., CASCO
22	8417997	-70.1983	43.645	CUSHING ISLAND, CASCO BAY
23	8418009	-70.19	43.69	COW ISLAND, CASCO BAY
24	8418031	-70.2067	43.6233	PORTLAND HEAD LIGHT STATI
25	8418150	-70.2467	43.6567	PORTLAND, CASCO BAY
26	8418268	-70.285	43.6417	FORE RIVER, PORTLAND
27	8418445	-70.3333	43.545	PINE POINT, SCARBOROUGH R
28	8418606	-70.3817	43.4617	CAMP ELLIS, SACO RIVER
29	8418911	-70.4767	43.3583	KENNEBUNKPORT, KENNEBUNK
30	8419317	-70.563306	43.32	WELLS, WEBHANNET RIVER
31	8419399	-70.5933	43.1667	CAPE NEDDICK
32	8419528	-70.6383	43.13	FORT POINT, YORK HARBOR
33	8419590	-70.6617	43.085	SEAPOINT, CUTTS ISLAND
34	8419870	-70.7417	43.08	SEAVEY ISLAND, PORTSMOUTH
35	8423898	-70.7117	43.0717	FORT POINT, NEWCASTLE ISL
36	8440273	-70.9083	42.8383	SALISBURY POINT, MERRIMAC
37	8440452	-70.82	42.8167	PLUM ISLAND, MERRIMACK R
38	8440466	-70.8733	42.815	NEWBURYPORT, MERRIMACK RI
39	8441241	-70.788611	42.710139	PLUM IS. SOUTH END 19
40	8441551	-70.615	42.6583	ROCKPORT HARBOR
41	8441571	-70.6767	42.655	LOBSTER COVE, ANNISQUAM
42	8441841	-70.66	42.61	GLOUCESTER HARBOR
43	8442417	-70.8867	42.54	BEVERLY, BEVERLY HARBOR
44	8442645	-70.8767	42.5233	SALEM, SALEM HARBOR
45	8443187	-70.9433	42.4583	LYNN, LYNN HARBOR
46	8443662	-71.0767	42.395	AMELIA EARHART DAM, MYSTI
47	8443970	-71.0534	42.3548	BOSTON, BOSTON HARBOR
48	8444162	-70.8917	42.3283	BOSTON LIGHT, BOSTON HARB
49	8444525	-70.9533	42.28	NUT ISLAND, QUINCY BAY
50	8444788	-70.9667	42.2483	SHIPYARD POINT, WEYMOUTH
51	8445138	-70.7267	42.2017	SCITUATE, SCITUATE HARBOR
52	8446009	-70.6467	42.0833	BRANT ROCK, GREEN HARBOR
53	8446121	-70.182167	42.049583	PROVINCETOWN, CAPE COD 19
54	8446166	-70.67	42.0383	DUXBURY, DUXBURY HARBOR
55	8446493	-70.6617	41.96	PLYMOUTH, PLYMOUTH HARBOR

56	8447173	-70.535	41.775	SAGAMORE, CAPE COD CANAL
57	8447180	-70.5067	41.7717	SANDWICH MARINA, CAPE COD
58	8447191	-70.5617	41.77	BOURNEDALE, CAPE COD CANA
59	8447241	-70.155	41.7517	SESUIT HARBOR, EAST DENNI
60	8447259	-70.5933	41.745	BOURNE BRIDGE, CAPE COD C
61	8447270	-70.6167	41.7417	BUZZARDS BAY (RR BRIDGE),
62	8447277	-70.6583	41.7417	ONSET BEACH T-12
63	8447281	-71.1317	41.74	STEEPBROOK
64	8447295	-70.6233	41.735	GRAY GABLES, BUZZARDS BAY
65	8447355	-70.6167	41.715	MONUMENT BEACH T-8
66	8447368	-70.715	41.7117	GREAT HILL
67	8447386	-71.1641	41.7043	FALL RIVER, HOPE BAY
68	8447416	-70.72	41.695	PINEY POINT, WINGS COVE
69	8447435	-69.951083	41.688472	CHATHAM, LYDIA COVE
70	8447495	-70.0567	41.6683	SAQUATUCKET HARBOR
71	8447685	-70.6517	41.605	CHAPPAQUOIT POINT, BUZZAR
72	8447712	-70.9	41.5933	NEW BEDFORD, CLARKS POINT
73	8447842	-70.9283	41.5383	ROUND HILL POINT
74	8447930	-70.6717	41.5233	WOODS HOLE, BUZZARDS BAY
75	8448157	-70.6	41.4583	VINEYARD HAVEN, VINEYARD
76	8448251	-70.8567	41.4483	QUICK'S HOLE
77	8448376	-70.9167	41.425	CUTTYHUNK
78	8448558	-70.5117	41.3883	EDGARTOWN, MARTHA'S VINEY
79	8448725	-70.767833	41.354444	MENEMSHA HARBOR
80	8449130	-70.0967	41.285	NANTUCKET ISLAND, NANTUCK
81	8450768	-71.193333	41.465	SAKONNET, RI
82	8450898	-71.21	41.651667	SAKONNET RIVER, NORTH END
83	8450948	-71.211667	41.638333	ANTHONY POINT, RI
84	8450954	-71.203333	41.618333	NANNAQUAKET, RI
85	8451301	-71.236667	41.558333	THE GLEN,SAKONNET RIVER,
86	8451351	-71.238333	41.486667	SACHUEST, FLINT POINT, RI
87	8451552	-71.255	41.636667	BRISTOL FERRY, RI
88	8452555	-71.321667	41.58	NAVY PIER, PRUDENCE ISLAN
89	8452660	-71.326667	41.505	NEWPORT, NARRAGANSETT BAY
90	8452944	-71.343333	41.716667	CONIMICUT LIGHT, NARRAGAN
91	8453033	-71.351667	41.751667	BAY SPRING, BULLOCK COVE,
92	8453201	-71.361667	41.463333	CASTLE HILL, RI
93	8453433	-71.373333	41.84	RUMFORD, SEEKONK RIVER, R
94	8453572	-71.378333	41.666667	WARWICK POINT, RI
95	8453742	-71.386667	41.496667	WEST JAMESTOWN, RI
96	8453767	-71.388333	41.761667	PAWTUXET COVE, PROVIDENCE
97	8454000	-71.4	41.806667	PROVIDENCE, PROVIDENCE RI
98	8454049	-71.41	41.586667	QUONSET POINT, RI
99	8454341	-71.428333	41.46	BOSTON NECK, RI
100	8454538	-71.445	41.571667	WICKFORD, NARRAGANSETT BA
101	8455083	-71.49	41.363333	POINT JUDITH, HARBOR OF R
102	8458022	-71.761667	41.328333	WEEKAPAUG POINT, BLOCK IS
103	8458694	-71.86	41.305	WATCH HILL POINT, RI
104	8459338	-71.556667	41.173333	BLOCK ISLAND HARBOR, OLD
105	8459681	-71.61	41.163333	BLOCK ISLAND, SW END, BLO
106	8461925	-72.186667	41.325	NIANTIC, NIANTIC RIVER, C
107	8463701	-72.531667	41.268333	CLINTON, CLINTON HARBOR,
108	8510448	-71.935	41.073333	U.S. COAST GUARD STATION,
109	8510560	-71.96	41.048333	MONTAUK, FORT POND BAY, N
110	8510719	-72.03	41.256667	SILVER EEL POND, FISHERS
111	8512354	-72.48	40.836667	SHINNECOCK INLET, NY
112	8512668	-72.561667	41.015	MATTITUCK INLET, LONG ISL
113	8512735	-72.581667	40.935	SOUTH JAMESPORT, GREAT PE

Table B.2. Tidal datums (meters) relative to mean sea level and National Tidal Datum Epoch for the stations in Table 1. The ‘N/A’s in the table denote missing values.

No.	Station ID	MHHW (m)	MHW (m)	MLW (m)	MLLW (m)	Epoch
1	8410140	2.916	2.772	-2.822	-2.958	1983-2001
2	8410715	3.048	2.886	-2.957	-3.094	1983-2001
3	8410834	3.119	2.973	-2.989	-3.126	1983-2001
4	8410864	2.876	2.727	-2.731	-2.824	1983-2001
5	8411250	2.075	1.947	-1.942	-2.057	1983-2001
6	8412581	1.842	1.71	-1.738	-1.852	1983-2001
7	8413320	1.738	1.608	-1.612	-1.728	1983-2001
8	8413801	1.733	1.605	-1.624	-1.738	1983-2001
9	8414249	1.628	1.5	-1.505	-1.614	1983-2001
10	8414721	1.687	1.566	-1.6	-1.71	1983-2001
11	8414781	1.94	1.801	-1.783	-1.888	1983-2001
12	8414888	1.609	1.478	-1.523	-1.636	1983-2001
13	8415191	1.667	1.543	-1.575	-1.695	1983-2001
14	8415490	1.599	1.476	-1.505	-1.624	1983-2001
15	8415709	1.492	1.367	-1.388	-1.508	1983-2001
16	8416731	1.554	1.42	-1.43	-1.54	1983-2001
17	8417177	1.418	1.289	-1.295	-1.399	1983-2001
18	8417881	1.517	1.381	-1.397	-1.503	1983-2001
19	8417941	1.504	1.372	-1.398	-1.502	1983-2001
20	8417948	1.524	1.387	-1.412	-1.507	1983-2001
21	8417988	1.504	1.373	-1.395	-1.502	1983-2001
22	8417997	1.495	1.365	-1.385	-1.493	1983-2001
23	8418009	1.514	1.382	-1.395	-1.498	1983-2001
24	8418031	1.477	1.344	-1.363	-1.466	1983-2001
25	8418150	1.514	1.381	-1.4	-1.505	1983-2001
26	8418268	1.524	1.389	-1.404	-1.51	1983-2001
27	8418445	1.451	1.325	-1.35	-1.449	1983-2001
28	8418606	1.481	1.35	-1.368	-1.47	1983-2001
29	8418911	1.462	1.332	-1.361	-1.465	1983-2001
30	8419317	1.457	1.326	-1.348	-1.451	1983-2001
31	8419399	1.447	1.315	-1.335	-1.437	1983-2001
32	8419528	1.433	1.306	-1.342	-1.439	1983-2001
33	8419590	1.433	1.303	-1.338	-1.435	1983-2001
34	8419870	1.343	1.218	-1.253	-1.351	1983-2001
35	8423898	1.434	1.304	-1.326	-1.428	1983-2001
36	8440273	1.298	1.16	-1.169	-1.227	1983-2001
37	8440452	1.346	1.221	-1.217	-1.308	1983-2001
38	8440466	1.367	1.234	-1.232	-1.304	1983-2001
39	8441241	1.463	1.34	-1.334	-1.429	1983-2001
40	8441551	1.447	1.316	-1.337	-1.436	1983-2001
41	8441571	1.468	1.336	-1.35	-1.451	1983-2001
42	8441841	1.464	1.328	-1.352	-1.453	1983-2001
43	8442417	1.487	1.35	-1.373	-1.476	1983-2001
44	8442645	1.479	1.345	-1.377	-1.477	1983-2001
45	8443187	1.508	1.373	-1.419	-1.522	1983-2001
46	8443662	1.552	1.418	-1.496	-1.598	1983-2001
47	8443970	1.545	1.411	-1.482	-1.585	1983-2001
48	8444162	1.494	1.36	-1.398	-1.498	1983-2001
49	8444525	1.539	1.402	-1.47	-1.574	1983-2001
50	8444788	1.553	1.415	-1.5	-1.601	1983-2001
51	8445138	1.479	1.343	-1.383	-1.491	1983-2001
52	8446009	1.501	1.365	-1.402	-1.508	1983-2001
53	8446121	1.539	1.4	-1.433	-1.533	1983-2001
54	8446166	1.58	1.446	-1.569	-1.675	1983-2001
55	8446493	1.571	1.437	-1.537	-1.64	1983-2001
56	8447173	1.273	1.154	-1.253	-1.345	1983-2001
57	8447180	1.446	1.298	-1.365	-1.434	1983-2001

58	8447191	1.009	0.898	-0.987	-1.07	1983-2001
59	8447241	1.597	1.458	-1.509	-1.593	1983-2001
60	8447259	0.751	0.631	-0.678	-0.761	1983-2001
61	8447270	0.669	0.563	-0.481	-0.548	1983-2001
62	8447277	0.707	0.598	-0.47	-0.537	1983-2001
63	8447281	0.814	0.738	-0.634	-0.69	1983-2001
64	8447295	0.713	0.618	-0.485	-0.537	1983-2001
65	8447355	0.77	0.683	-0.527	-0.582	1983-2001
66	8447368	0.755	0.674	-0.535	-0.59	1983-2001
67	8447386	0.785	0.711	-0.618	-0.671	1983-2001
68	8447416	0.75	0.666	-0.526	-0.579	1983-2001
69	8447435	1.009	0.888	-0.905	-0.972	1983-2001
70	8447495	0.643	0.538	-0.597	-0.682	1983-2001
71	8447685	0.732	0.652	-0.514	-0.563	1983-2001
72	8447712	0.696	0.62	-0.466	-0.51	1983-2001
73	8447842	0.659	0.577	-0.469	-0.51	1983-2001
74	8447930	0.372	0.288	-0.257	-0.3	1983-2001
75	8448157	0.325	0.211	-0.275	-0.323	1983-2001
76	8448251	0.569	0.498	-0.42	-0.443	1983-2001
77	8448376	0.627	0.555	-0.471	-0.509	1983-2001
78	8448558	0.381	0.284	-0.366	-0.435	1983-2001
79	8448725	0.539	0.461	-0.377	-0.413	1983-2001
80	8449130	0.55	0.446	-0.478	-0.539	1983-2001
81	8450768	0.593	0.514	-0.453	-0.489	1983-2001
82	8450898	0.755	0.677	-0.593	-0.639	1983-2001
83	8450948	0.699	0.617	-0.527	-0.581	1983-2001
84	8450954	0.661	0.576	-0.492	-0.539	1983-2001
85	8451301	0.645	0.557	-0.479	-0.523	1983-2001
86	8451351	0.589	0.518	-0.434	-0.474	1983-2001
87	8451552	0.752	0.676	-0.566	-0.616	1983-2001
88	8452555	0.69	0.617	-0.522	-0.569	1983-2001
89	8452660	0.645	0.57	-0.487	-0.529	1983-2001
90	8452944	0.756	0.68	-0.59	-0.639	1983-2001
91	8453033	0.759	0.684	-0.61	-0.663	1983-2001
92	8453201	0.611	0.537	-0.453	-0.497	1983-2001
93	8453433	0.828	0.754	-0.666	-0.722	1983-2001
94	8453572	0.72	0.64	-0.556	-0.602	1983-2001
95	8453742	0.639	0.567	-0.485	-0.529	1983-2001
96	8453767	0.786	0.71	-0.616	-0.67	1983-2001
97	8454000	0.79	0.715	-0.63	-0.685	1983-2001
98	8454049	0.683	0.609	-0.52	-0.567	1983-2001
99	8454341	0.625	0.548	-0.464	-0.502	1983-2001
100	8454538	0.692	0.613	-0.518	-0.563	1983-2001
101	8455083	0.562	0.485	-0.43	-0.468	1983-2001
102	8458022	0.458	0.392	-0.378	-0.418	1983-2001
103	8458694	0.457	0.374	-0.412	-0.457	1983-2001
104	8459338	0.535	0.459	-0.411	-0.446	1983-2001
105	8459681	0.482	0.408	-0.383	-0.418	1983-2001
106	8461925	0.472	0.386	-0.398	-0.446	1983-2001
107	8463701	0.801	0.709	-0.679	-0.751	1983-2001
108	8510448	0.393	0.306	-0.305	-0.357	1983-2001
109	8510560	0.393	0.306	-0.325	-0.377	1983-2001
110	8510719	0.428	0.339	-0.374	-0.432	1983-2001
111	8512354	0.559	0.475	-0.535	-0.58	1983-2001
112	8512668	0.876	0.784	-0.77	-0.836	1983-2001
113	8512735	0.501	0.411	-0.438	-0.492	1983-2001

APPENDIX C. Creation and Validation of the TSS field

Table C.1: Tide station data utilized for TSS creation and the deltas computed against the TSS grid. NA denotes a station where a NAVD88 to MSL value cannot be computed with the TSS grid.

ID	Latitude (deg)	Longitude (deg)	NAVD 88 to MSL (m)	TSS Derived Value (m)	Delta (m)
8410140	44.90330	-66.98500	0.071	0.0707	0.000
8412581	44.54000	-67.87500	0.054	0.054	0.000
8413320	44.39170	-68.20500	0.093	0.0929	0.000
8415191	44.42670	-69.00500	0.079	0.0791	0.000
8415709	44.07170	-69.18170	-0.154	-0.1536	0.000
8417997	43.64500	-70.19830	-0.090	-0.0878	-0.002
8418150	43.65670	-70.24670	0.095	0.0946	0.000
8418445	43.54500	-70.33330	0.050	0.05	0.000
8419317	43.32000	-70.56330	0.062	0.0624	0.000
8419870	43.08000	-70.74170	0.058	0.0583	0.000
8443970	42.35500	-71.05170	0.092	0.0919	0.000
8446166	42.03830	-70.67000	0.132	0.1318	0.000
8446493	41.96000	-70.66170	0.118	0.1181	0.000
8447435	41.69330	-69.95000	0.078	0.0786	-0.001
8447495	41.66830	-70.05670	0.106	0.1059	0.000
8447505	41.66670	-69.96670	0.106	0.1058	0.000
8447930	41.52330	-70.67170	0.116	0.1158	0.000
8440273	42.83830	-70.90830	-0.030	-0.0313	0.001
8440452	42.81670	-70.82000	0.057	0.0575	-0.001
8440466	42.81500	-70.87330	-0.023	-0.0222	-0.001
8441241	42.71014	-70.78861	0.136	0.1359	0.000
8441551	42.65830	-70.61500	0.100	0.0999	0.000
8441841	42.61000	-70.66000	0.051	0.0516	-0.001
8443187	42.45830	-70.94330	0.047	0.0472	0.000
8445138	42.20170	-70.72670	0.191	0.1902	0.001
8446009	42.08330	-70.64670	0.105	0.1055	-0.001
8446121	42.04958	-70.18217	0.132	0.1321	0.000
8447180	41.77170	-70.56170	0.197	0.1932	0.004
8447191	41.77000	-70.56170	0.179	0.18	-0.001
8447241	41.75170	-70.15500	0.181	0.1809	0.000
8447270	41.74170	-70.61670	0.185	0.1849	0.000
8447712	41.59330	-70.90000	0.062	0.0623	0.000
8448558	41.38830	-70.51170	0.091	0.0911	0.000
8449130	41.28500	-70.09670	0.098	0.0981	0.000
8423898	43.07170	-70.71170	0.085	0.0846	0.000
8410715	44.92330	-67.13000	-0.328	-0.3255	-0.003
8410834	45.12844	-67.14467	0.100	0.0996	0.000

8410864	44.82333	-67.15167	-0.051	-0.0518	0.001
8411250	44.64170	-67.29670	-0.003	-0.0029	0.000
8413801	44.53500	-68.42170	0.029	0.029	0.000
8414721	44.47170	-68.81330	0.126	0.1258	0.000
8415490	44.10500	-69.10170	0.124	0.1236	0.000
8416731	43.93330	-69.58000	0.193	0.1929	0.000
8417177	43.75500	-69.78500	0.047	0.0473	0.000
8417227	43.92500	-69.81500	-0.066	-0.0674	0.001
8417941	43.69000	-70.17000	0.132	0.132	0.000
8417948	43.76170	-70.17330	0.205	0.204	0.001
8418911	43.35830	-70.47670	0.088	0.0877	0.000

Table C.2: Mean and standard deviations of delta values (meters) for the Gulf of Maine region.

	Mean Delta Value (m)	**Standard Deviation (m)**
Gulf of Maine	0.000035	0.000875