NOAA Technical Memorandum NOS CS 43

UPDATE VDATUM FOR THE COASTAL WATERS OF TEXAS AND WESTERN LOUISIANA: MODELED TIDAL DATUMS AND THEIR ASSOCIATED SPATIALLY VARYING UNCERTAINTIES

Silver Spring, Maryland
May 2020

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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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

NOAA NOS has been conducting a continuous development for a seamless nationwide vertical datum transformation system (a software tool "VDatum") for an effective transformation of geospatial data among a variety of three-dimensional ellipsoidal, orthometric, and tidal datum reference systems. The current modeling work was aimed at updating modeled tidal datums in the Texas and western Louisiana coastal regions in support of the development of the NOAA VDatum tool.

An initial development of tide model in this model domain was made in 2013 for tidal datum calculations. The initial work is important for understanding basic characteristics of tidal datums in the coastal regions.

This work was focused on: (1) updating the tide model by using the most currently available shoreline, bathymetry, and tide station data; (2) implementing a Spatially Varying Uncertainty (SVU) statistical interpolation method (Shi and Myers, 2016) for correcting modeled tidal datums and computing associated uncertainties; and (3) using modeled tidal datums to upgrade coastal non-tidal polygons for improving the quality of tidal datum marine grid population.

A two-dimensional depth-integrated barotropic version of the ADvanced CIRCulation (ADCIRC) hydrodynamic model (version 51.52.34, released in January 2016) was used for this work. The model domain was extended to include new tide stations. The model's boundary and bathymetry were updated based on the most currently available shoreline and bathymetry data. The updated tide model includes 542,936 unstructured triangular finite elements with a total of 297,227 nodes.

The ADCIRC-based tide model was used to generate 6-minute water level time series at each model grid point by using the open ocean boundary forcing which equals the sum of the water elevations of the eight tidal harmonic constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2, and K_2) from the EC2015 tidal database (Szpilka et al., 2016). The model ran for a 67-day simulation. Modeled water level time series of the last 60 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 evaluated by comparing to the observed tidal datums at 75 tide stations. Then, several techniques were used to reduce the errors in the modeled tidal datums for improving model performance. After that, the modeled tidal datums were corrected by using the SVU statistical interpolation method. The statistical interpolation method is able to limit the interpolated tidal datums to within a user-defined model error limit (0.01 m in this work) at each tide station and produce a spatially varying uncertainty field for each interpolated tidal datum field. Modeled non-tidal field (MHW minus MLW is less than 9 cm) was then estimated for upgrading existing non-tidal polygons for enhancing the quality of marine grid population. Finally, seven bounding polygons were created, marine grids in the seven VDatum areas were generated, and the SVU-statistically-interpolated modeled tidal datums and their associated spatially varying uncertainties were populated onto the marine grids.

Key Words: Coastal and estuarine modeling, ADCIRC, shoreline, bathymetry, water level time series, VDatum, tidal datums, non-tidal polygons, spatially varying uncertainty, marine grid population, Texas, western Louisiana, Gulf of Mexico.

1. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) has been dedicated to developing a seamless nationwide vertical datum transformation system (a software tool "VDatum"), which enables effective transformation of geospatial data among a variety of three-dimensional ellipsoidal, orthometric, and tidal datum reference systems (e.g., Gill and Schultz, 2001; Hess, 2001; Milbert, 2002; Parker, 2002; Parker et al., 2003; Hess and White, 2004; Hess et al., 2005; Myers et al., 2005; Myers and Hess, 2006; Spargo et al., 2006; Hess et al., 2012; Hess et al., 2016; White et al., 2016). A total of 48 vertical datums are currently included in the NOAA VDatum. The VDatum is crucial to coastal applications that rely on vertical accuracy in bathymetric, topographic, and shoreline datasets (Myers, 2005; Myers et al., 2007).

The purpose of the NOAA VDatum development is to build a seamless nationwide utility that facilitates more effective sharing of vertical data and also complements a vision of linking such data through national elevation and shoreline databases (Myers, 2005; Myers et al., 2007). Currently the NOAA VDatum is 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 to update foundational geodetic and tidal datum data. The NOAA VDatum will eventually cover all of the U.S. coastal waters from the landward navigable reaches of estuaries and charted embayments out to 75-nautical-mile offshore limit, including all tidal datum and sea surface topography transformations over the water and all transformations between the ellipsoidal and orthometric datums over the water and the land. The nationwide NOAA VDatum enables bathymetric, topographic, and shoreline data to be easily transformed and assembled in a manner that complements dissemination through national databases (Myers, 2005).

Tidal datums are key components in the NOAA VDatum. Knowledge of spatial distributions of tidal datums is essential to the accuracy of VDatum applications (Milbert 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), are 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.

In support of the NOAA VDatum development, an initial tide model for the coastal waters of Texas (TX) and western Louisiana (LA) was developed in 2013 for the products of modeled tidal datums and associated uncertainties (Xu and Myers, 2009, Xu et al. 2013). The previous modeling work includes: (1) creating unstructured triangular model grids with bathymetry assigned; (2) running a two-dimensional barotropic version of the ADvanced Circulation (ADCIRC) hydrodynamic model; (3) conducting sensitivity tests for determining optimal model parameters; (4) calculating and analyzing tidal datums using modeled water level time series; (5) analyzing and correcting the model errors by comparing modeled and observed tidal datums; and (6) producing a VDatum marine grid population for the final VDatum products. The initial development of modeling tidal datums in the TX and western LA coastal regions was important for gaining fundamental understanding of tidal datum characteristics in the model regions.

Shoreline and bathymetry change significantly with time due to a variety of reasons such as severe weather impacts. Such changes directly influence the accuracy of modeled tidal datum products. Therefore, it is necessary to update the 2013 tide model by incorporating the most currently available shoreline and bathymetry data to improve the accuracy of modeled tidal datum products. Based on Xu et al. (2013), the previous tide model for the TX and western LA coastal waters used the NOS bathymetry data which were collected through the hydrographic surveys from 1885 to 2005 (available when the 2013 tide model was in development). For the current model update, we used additional NOS bathymetry survey data which were collected through hydrographic surveys from 2005 to 2015. The additional 11 years of the new data represent the most currently available bathymetry information from NOS hydrographic surveys, which enhanced the accuracy of model bathymetry. Detailed information on the bathymetry data used for the model update will be introduced in Section 2.

Figure 1 shows a map of the current updated model domain. The updated tidal datum products were developed for the water areas from the shoreline to the 75-nautical-mile offshore limit.

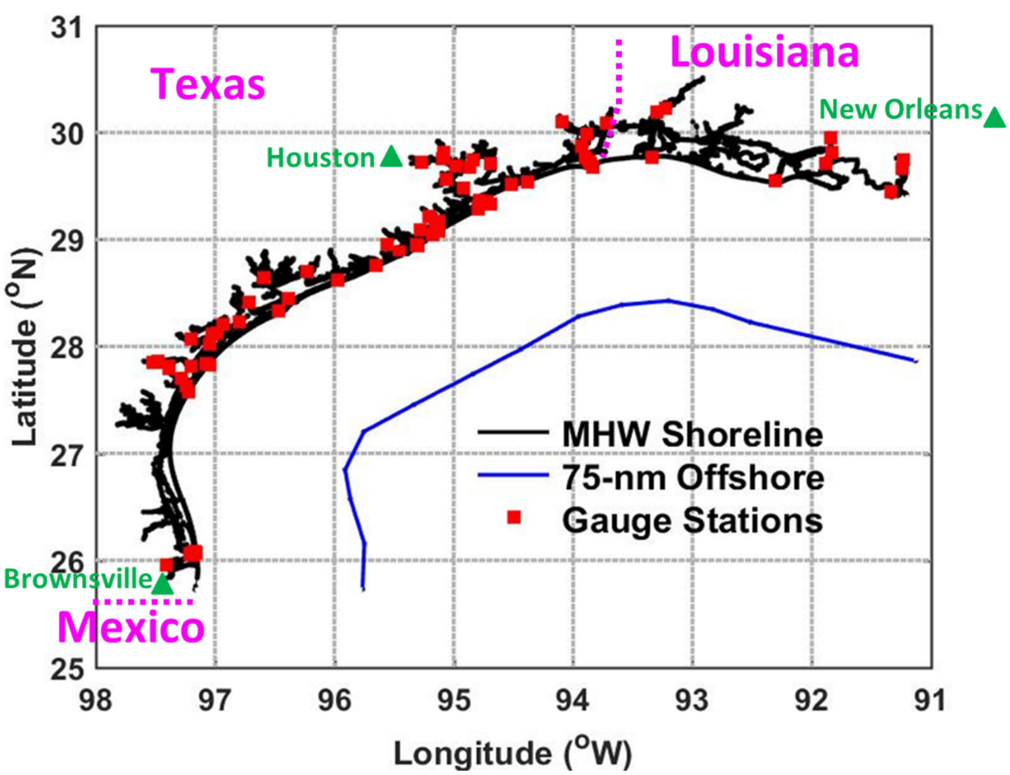

Figure 1. Current updated model domain of TX and western LA coastal waters. The black line represents model shoreline (MHW). The blue line denotes VDatum interested area which runs from the shoreline to the 75-nautical-mile offshore limit. The red squares represent the locations of the available 75 tide stations.

The major goals of the current model update include: (1) updating the 2013 tide model and modeled tidal datums by incorporating the most currently available shoreline, bathymetry, and tide station data; (2) implementing the Spatially Varying Uncertainty (SVU) statistical interpolation method (Shi and Myers, 2016) to correct ADCIRC modeled tidal datums and compute their associated spatially varying uncertainties; and (3) upgrading the existing non-tidal polygons by incorporating modeled non-tidal grid points for enhancing the quality of marine grid population. It is worthwhile to mention that "non-tidal" is defined as MHW minus MLW (the mean tidal range) less than 0.09 m (Gill and Michalski, 2016). Thus, if a model grid point satisfied the condition that the mean tidal range (i.e., the difference between MHW and MLW) was less than 0.09 m, we marked the model grid point as non-tidal. The non-tidal threshold was established by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) for masking areas with negligible tides from the determination of tidal datums since it is difficult to identify and tabulate regular daily high and low tides in those areas (Gill and Michalski, 2016).

For the current model update, we first extended model mesh grids to include new tide stations, and updated model shoreline and bathymetry using the most currently available data. Next, we ran a two-dimensional depth-integrated barotropic version of the ADvanced CIRCulation (ADCIRC) hydrodynamic model (version 51.52.34, released in January 2016) for modeled water level time series at each model grid point. The modeled water level time series were then used to compute modeled tidal datums (i.e., MHHW, MHW, MLW, MLLW, DTL, and MTL). Modeled tidal datums were evaluated by using observed tidal datums at the 75 tide stations available in this model domain. Large (>0.10 m) model biases were reduced by adjusting the tide model. After that, we implemented the SVU statistical interpolation method to correct the modeled tidal datums and compute their associated spatially varying uncertainties. The modeled non-tidal grid points were incorporated to upgrade the existing non-tidal zones. Lastly, we created seven bounding polygons, generated marine grids, and populated the SVU-statistically-interpolated tidal datums and their associated spatially varying uncertainties onto the marine grids as the final VDatum products.

This technical report is organized as follows: After the introduction in Section 1, Section 2 describes the data used in this work and the existing non-tidal polygons before this upgrade. Section 3 introduces the current update of tide model and model configuration for the tidal datum simulation. Section 4 presents the modeled tidal datums before and after model adjustments for reducing model errors, the corrected tidal datums and their associated spatially varying uncertainties after the SVU statistical interpolation, and non-tidal polygon upgrade. Section 5 introduces the creation of seven bounding polygons, the generation of regularly structured marine grids, and the marine grid population with the SVU-statistically-interpolated modeled tidal datums and their associated spatially varying uncertainties. Section 6 gives a brief summary.

It is worthwhile to mention that the results of this work were published in Wu et al. (2019), and thus there are overlapping contexts and figures between this report and Wu et al. (2019).

2. DATA DESCRIPTION

This section briefly describes the most current shoreline, bathymetric, and tide station data available for use at the time of this model update. The existing non-tidal polygons before this upgrade are also introduced in this section.

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

NOAA's Continually Updated Shoreline Product (CUSP) provides the most currently available shoreline representation of the U.S. and its territories, available at https://www.ngs.noaa.gov/CUSP/. The CUSP shoreline dataset was created to deliver a continuous shoreline with frequent updates to support various applications in coastal regions.

CUSP references a MHW shoreline based on vertical modeling or image interpretation using both water level stations and/or shoreline indicators if applicable. CUSP covers the continental U.S., with portions of Hawaii, the Pacific Islands, Alaska, Puerto Rico, and the U.S. Virgin Islands. In the current model update, the CUSP shoreline data were used as a reference to: (1) determine the model boundary when extending the model domain; and (2) update the shoreline data file for producing the VDatum marine grid population.

2.2. Bathymetric Data

We used the most currently available data to assign bathymetry values at the updated model grid points. The bathymetry data used are described below. The more reliable and more recent bathymetry data have a higher priority.

Priority 1. NOAA NOS available hydrographic survey data from 2005 to 2015, processed and provided by the bathymetry data team at NOAA/NOS/OCS (Office of Coast Survey)/CSDL (Coast Survey Development Laboratory)/GADB (Geospatial Applications Development Branch). Note that the hydrographic survey data from 2001, 2002, and 1935 were also used for the extended waterways near Weeks Bay and Atchafalaya River in the western LA coastal region (Figure 2), where no recent-year hydrographic survey data were available.

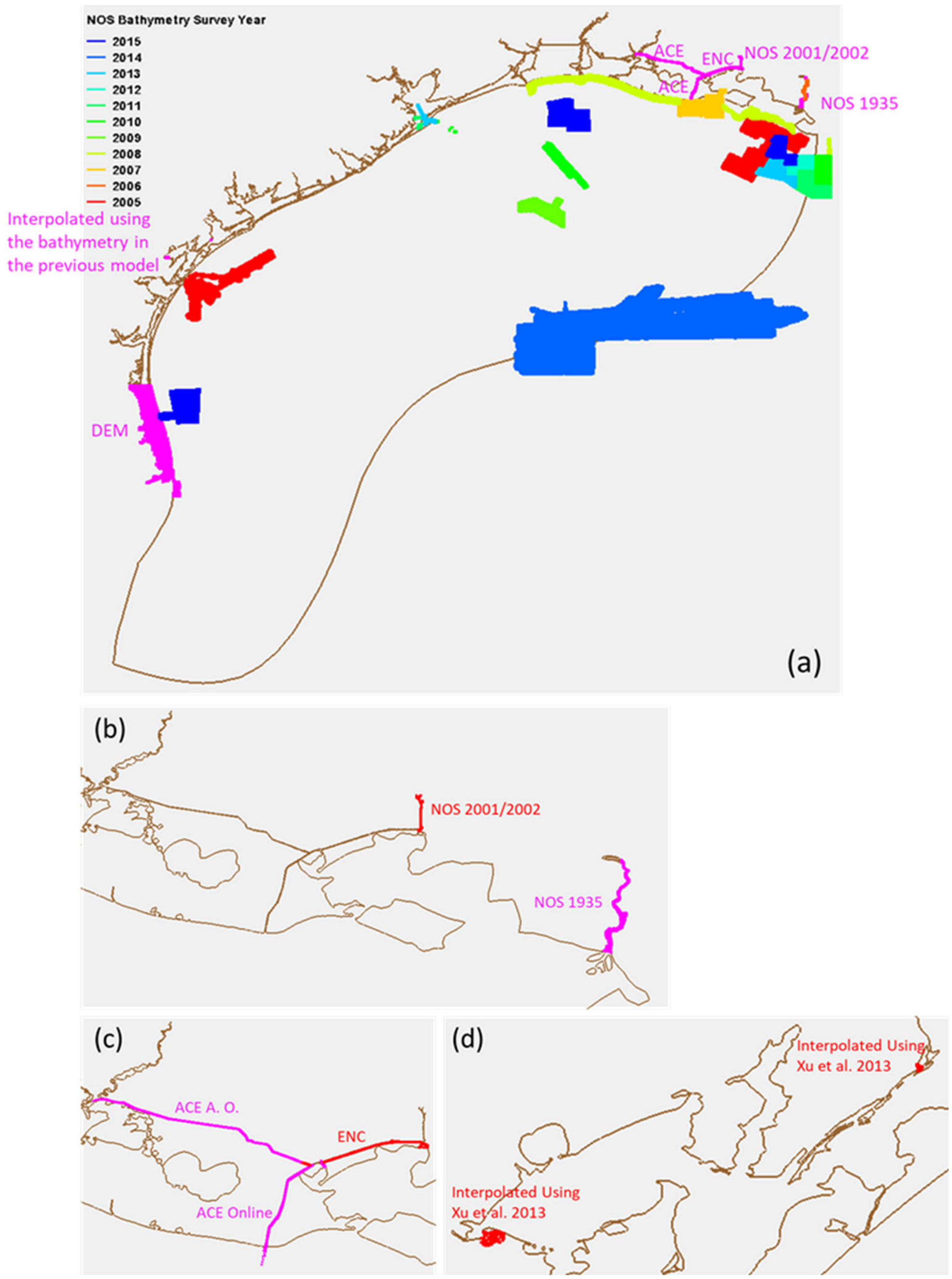

Figure 2. The locations, types, and years of the new bathymetry data used for the model update (a), where the areas in pink represent data other than NOAA NOS hydrographic survey data. The areas with the extended water paths are enlarged in (b) and (c) (the western LA region) and in (d) (TX region). "A. O." represents the 10-year accumulated bathymetry data kindly provided by the U.S. Army Corps of Engineers' (ACE's) Andrew Oakman. "Interpolated Using Xu et al. 2013" means the bathymetry was interpolated based on Xu et al. 2013's fort.14 bathymetry data.

Priority 2. The U.S. Army Corps of Engineers (ACE) hydrographic survey data in the extended southern LA's Freshwater Bayou area (http://www.mvn.usace.army.mil) and in the extended western LA's the Intracoastal Waterway (ICW) between Grand Lake and Vermilion Bay (Figure 2c), where no NOS hydrographic survey data were available.

Priority 3. NOAA NOS Electronic Navigational Chart (ENC, Chart #11345) data (http://www.charts.noaa.gov/OnLineViewer/11345.shtml) for assigning bathymetry in the extended western LA ICW between Vermilion Bay and Weeks Bay, where no hydrographic survey data were available.

Priority 4. NOAA's National Geophysical Data Center (NGDC) High-Resolution Digital Elevation Model (DEM) data in the southwestern TX coastal area, "South_Padre_TX_1/3_arc_second_DEM_MHW.asc" (https://www.ngdc.noaa.gov/), for assigning bathymetry in that area where no bathymetry data were available from the abovementioned three resources. Note that the NGDC was recently merged into the National Centers for Environmental Information (NCEI) (https://www.ngdc.noaa.gov/).

Priority 5. The 2013 tide model's bathymetry (in its input file "fort.14") (Xu et al. 2013), which was created by using NOAA NOS hydrographic survey data from 1885 to 2005, NOAA's ENCs for Sabine Lake and southern Laguna Madre (see Figure 2b in Xu et al., 2013), and ACE bathymetry data (for major shipping channels and ICW).

Detailed locations, types, and years of the new bathymetry data used for the model update are shown in Figure 2. It is worthwhile to mention that some small new areas (such as extended rivers) without any bathymetry were assigned by using an averaged bathymetry in the closest model grid points.

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

We used observed tidal datums (MHHW, MHW, MLW, and MLLW) at a total of 75 tide stations within the model domain [98° W to 91° W, 24° N to 31° N] for the current model update. The observed tidal datums were used for evaluating ADCIRC model performance. Both the observed tidal datums and their associated RMS errors were used for conducting the SVU statistical interpolation of ADCIRC modeled tidal datums. It is worthwhile to mention that 16 out of the 75 tide stations did not have RMS error data, and therefore we used the average of the RMS errors at the remaining 59 tide stations to represent the RMS errors in the 16 tide stations for the statistical interpolation. Appendix A lists their identification numbers, longitude, latitude, and location names. Appendix B lists corresponding observed tidal datum values and their RMS errors.

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

Figure 3 shows the observed MHHW, MHW, MLW, and MLLW at the 75 tide stations. The observed tidal datums are referenced to the LMSL at each station. The maximum value of the observed tidal datums in the model domain is less than 0.40 m. The observed tidal datums show relatively larger values from the Houston area to the east: MHHW and MHW are greater than 0.10 m, and MLW and MLLW are deeper than -0.20 m. The area from Houston to the west shows relatively smaller tidal datums.

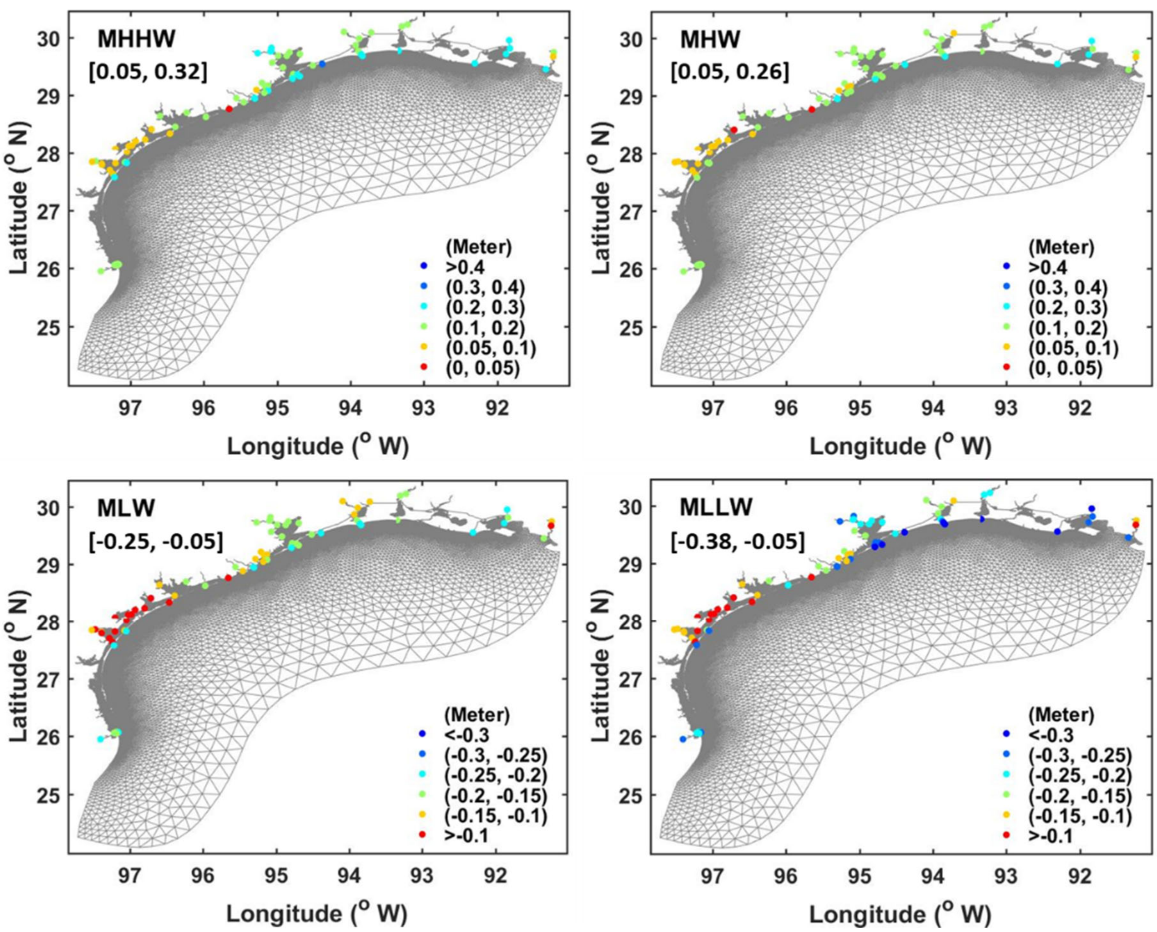

Figure 3. Observed tidal datums with minimum and maximum values listed in the brackets.

Figure 4 shows the observed mean tidal ranges from the 75 tide stations, ranging from 0.10 m to 0.49 m. The mean tidal range from Houston to the east is much larger than that from Houston to the west. The averaged value of the observed mean tidal ranges equals 0.33 m for the region from Houston to the east (blue polygon) and 0.23 m for the region from Houston to the west (red polygon).

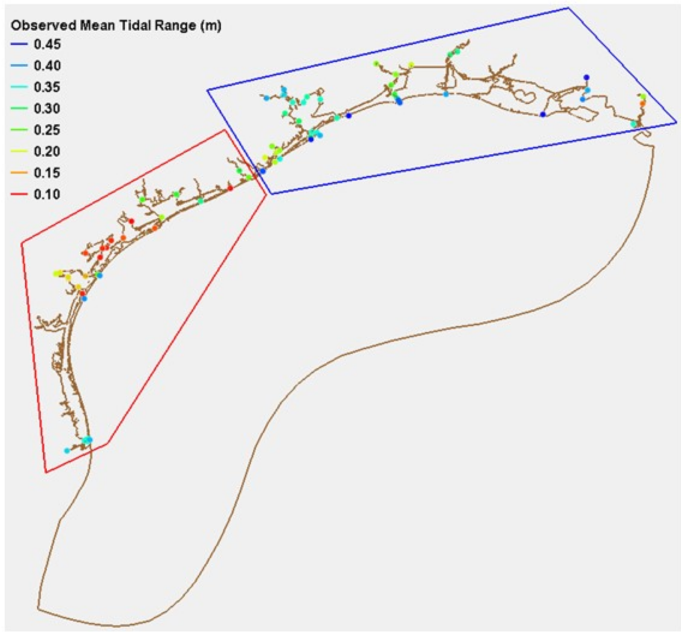

Figure 4. The observed mean tidal ranges from the 75 tide stations. The blue polygon includes 43 tide stations from Houston to the east (with a mean tidal range of 0.33 m), and the red polygon includes 32 tide stations from Houston to the west (with a mean tidal range of 0.23 m).

2.4. Non-Tidal Polygons

The existing non-tidal polygons before the current upgrade were best estimated by CO-OPS, representing areas where a periodic tide is present and consistent but the mean tidal range is negligible (MHW minus MLW is less than 0.09 m) (Gill and Michalski, 2016). However, the best estimated non-tidal polygons may not be accurate in some areas which lack tide observations.

Figure 5 shows the existing best estimated non-tidal polygons (closed thick black lines). It can be seen that there are two large non-tidal areas in this model domain: one in the western LA coastal region, and the other in the southwestern TX coastal region.

Figure 5. The existing non-tidal polygons (closed thick black lines) before the current upgrade.

3. TIDAL DATUM SIMULATION

This section introduces tidal datum simulation including the hydrodynamic model used, the updated model domain, model grids and bathymetry, and model configurations respectively.

3.1. Hydrodynamic Model

ADCIRC is an advanced hydrodynamic model which has been developed since the early 1990s (Luettich et al., 1992; Westerink et al., 1993, 1994). The model has been demonstrated to be effective in modeling ocean, coastal, and estuarine processes and thus has been widely used in the coastal ocean modeling community. The model simulates tides by solving shallow water equations and proves to be effective for modeling tides from open oceans to coastal and estuarine waters (Luettich et al., 1999; Mukai et al., 2002; Myers, 2005). We used a two-dimensional depth-integrated barotropic version of the ADCIRC hydrodynamic model (version 51.52.34, released in January 2016, https://adcirc.org/) for the current model update.

3.2. Model Domain Extension and Model Grid Creation

We first extended the model domain of the 2013 model version (Xu et al., 2013) to include new tide stations, in particular in the western LA coastal region (Figure 6), using the Surface-water Modeling System© (SMS, a commercial software package, https://www.aquaveo.com/software/sms-surface-water-modeling-system-introduction). Figure 6 shows a comparison between the 2013 model domain and the current updated model domain. The enlarged western LA region exhibits a significant extension of model domain coverage. The ADCIRC unstructured triangular model mesh grids were adjusted and increased with the model domain extension. The updated tide model mesh includes a total of 297,227 nodes and 542,936 elements in comparison with the 284,217 nodes and 523,047 elements in the 2013 tide model.

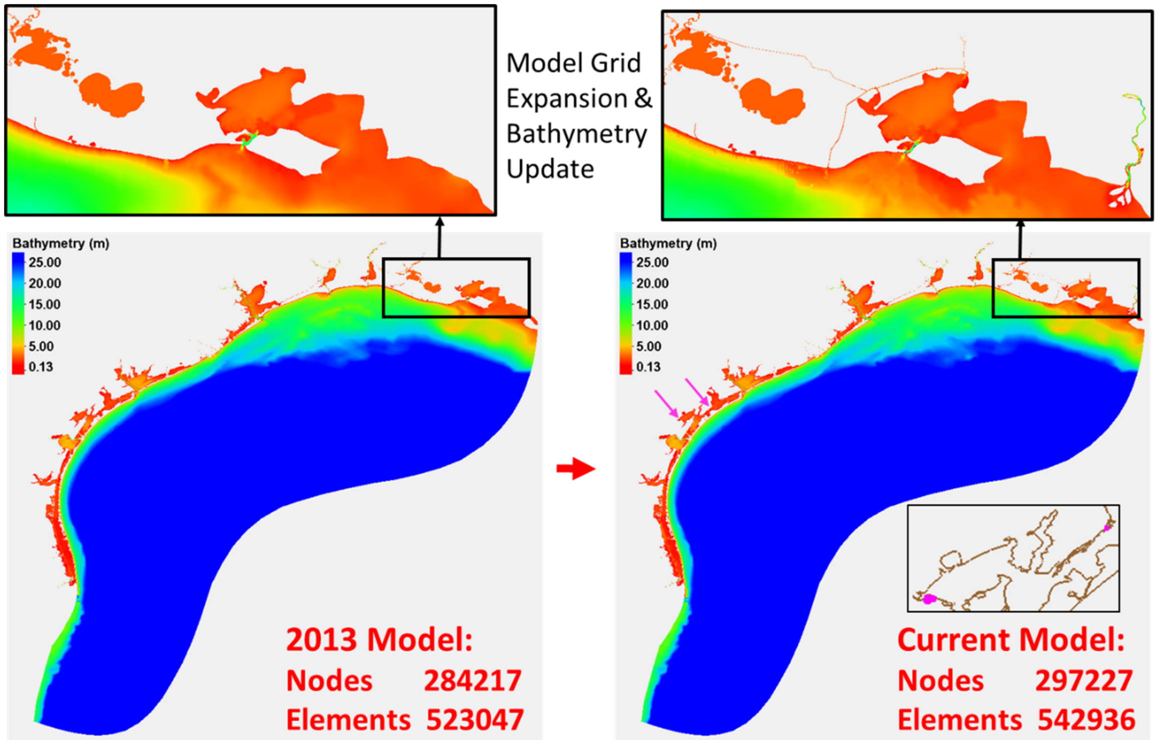

Figure 6. Model grid extension into smaller rivers and the Intracoastal Waterway (ICW) with updated bathymetry: before (left) and after (right) the current update. The two pink arrows in the right panel show the two areas with a minor extension of model grids in the middle of the TX coast. The extended model grid points in the two areas are shown as pink dots in the enlarged plot inserted in the lower right corner of the right panel.

Figure 7 shows the updated triangular model mesh grids and grid spacing in this model domain. The spatial resolution of the updated model grids ranges from 14.38 m in the coastal region to 28.58 km near the open ocean boundary. The grid resolution increases from the open ocean to the coasts and embayments to better represent the complexity in the shorelines and resolve shallow water tidal dynamics.

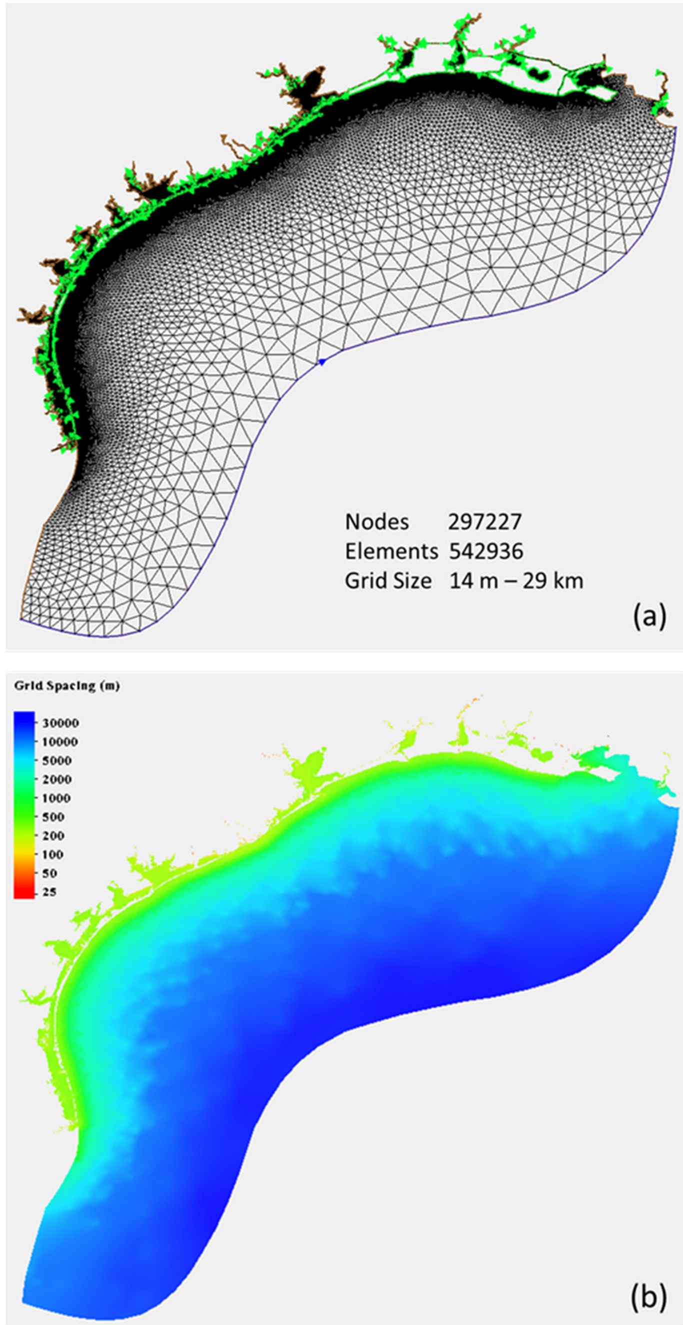

Figure 7. (a) The updated triangular model mesh grids for the TX and western LA coastal waters. Blue line denotes the model's open ocean boundary, brown line denotes land boundary, and green lines denote island boundaries. (b) The grid spacing in the model domain.

3.3. Bathymetry on the Model Grids

The bathymetry on the updated model grid point was assigned using the most currently available bathymetry data by priority as described in Section 2.1. The bathymetry data used include NOAA NOS hydrographic survey data, ACE hydrographic survey data, NOAA NOS ENC data, NOAA NGDC DEM data, and the 2013 tide model's bathymetry data. The more reliable and more recent bathymetry data have a higher priority.

The updated model grid point's bathymetry (in reference to mean sea level: Hess et al., 2012) as shown in Figure 8 ranges from 0.13 m to 2090.40 m. The model bathymetry increases from the coasts toward the open ocean boundary with the shallowest bathymetry (0.13 m) located in the lakes, and the deepest bathymetry (2090.40 m) at the open ocean boundary.

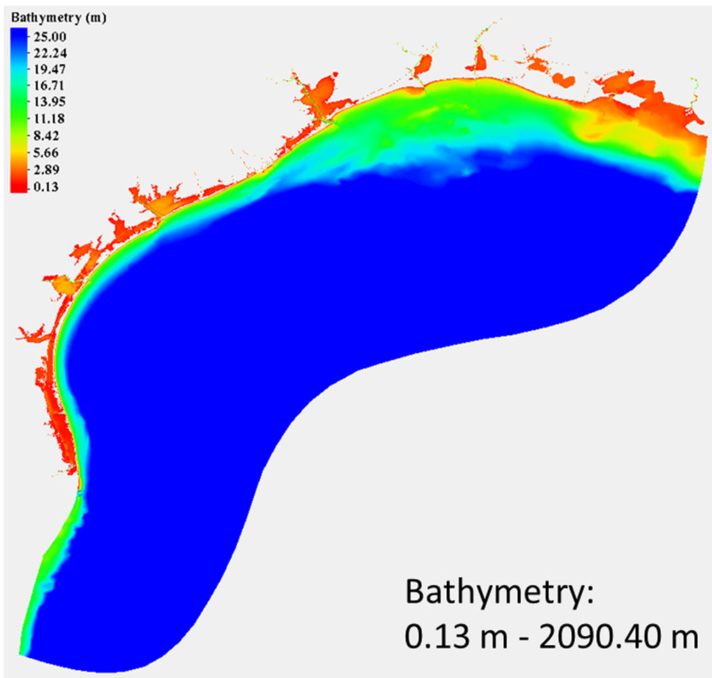

Figure 8. The updated model grid point's bathymetry (in reference to mean sea level).

3.4. Model Configuration

Key model parameter settings are similar to the 2013 tide model, except the open ocean boundary forcing setting. The common model parameter settings include:

(1) nonlinear quadratic bottom friction with a spatially constant bottom friction coefficient of 0.002;
(2) a spatially constant horizontal eddy viscosity of 5.0 m^2/s for the momentum equations;
(3) wetting and drying process enabled with a minimum water depth of 0.05 m as the wet node/element criterion;
(4) a spatially uniform Generalized Wave-Continuity Equation (GWCE) weighting factor of 0.02;
(5) advective terms were included;
(6) neither atmospheric forcing nor river flow was imposed;
(7) a tidal potential body force of the eight principal tidal constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2, and K_2) was included;

(8) a total of 67 days for the ADCIRC model run. A hyperbolic tangent ramp function was specified for the beginning six days. The time step for the ADCIRC model run was 3 seconds. The output from the ADCIRC model run is the 6-min water level time series at each model grid point from the final 60 days of the run, which were used for computing tidal datums at each model grid point.

The current updated tide model used the open ocean boundary forcing which equals the sum of the elevations of the eight tidal harmonic constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2, and K_2) extracted from the EC2015 tidal database (Szpilka et al., 2016) available at http://adcirc.org/products/adcirc-tidal-databases/. However, the 2013 tide model used the open ocean boundary forcing extracted from Oregon State University's (OSU's) regional tide prediction model in the Gulf of Mexico (OSU-GOM) (http://volkov.oce.orst.edu/tides/Mex.html; Xu and Myers 2010; Xu et al. 2013).

4. MODEL RESULTS, VALIDATION, STATISTICAL INTERPOLATION, and NON-TIDAL POLYGON UPGRADE

4.1. Model Results and Validation

ADCIRC modeled water level time series at 6-minute intervals were used to compute the six modeled tidal datums (MHHW, MHW, MLW, MLLW, DTL, and MTL) in reference to LMSL by using the NOAA NOS OCS CSDL's standard FORTRAN program lv8j.f, which was an improved version of the initial code developed in the early 2000s (Hess, 2001). The six modeled tidal datums after subtracting the model derived LMSL were first evaluated by using the observed tidal datums at the 75 tide stations (Figure 9a). Model grid points with large model errors (>0.10 m) were identified and then several techniques were used to adjust the tide model for reducing the large model errors (Figure 9b).

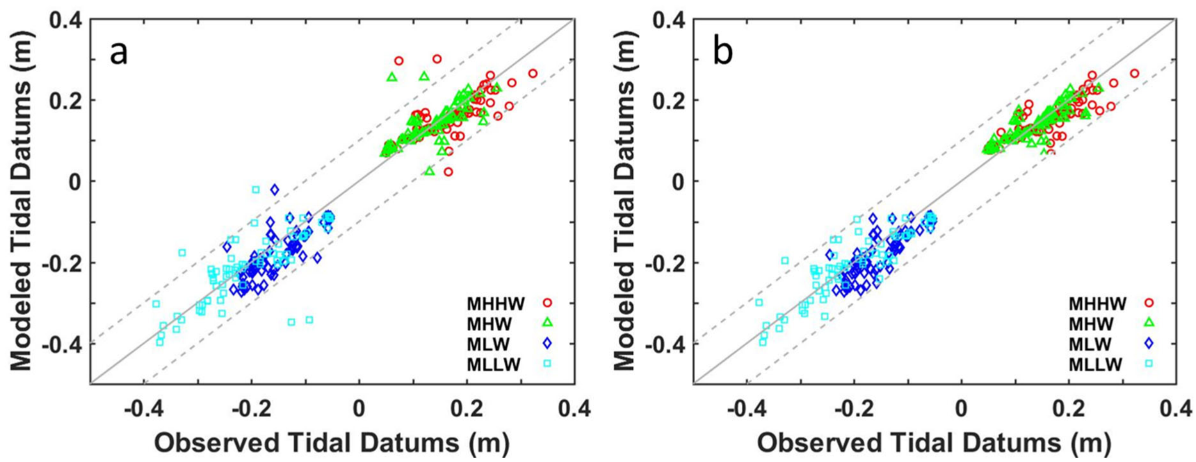

Figure 9. Modeled tidal datums vs observed tidal datums before (a) and after (b) model adjustments. The dashed lines represent 0.10 m model error limits.

The effective techniques used for the model improvement include: (1) extending the river length in the upper streams (for fixing model overestimation); (2) refining the model grids near a river's entrance, for example, enhancing model grid resolution and removing land patches from a model element (for fixing model overestimation); (3) increasing the model grid resolution along rivers (for fixing model underestimation); (4) enhancing the width of a narrow river (for fixing model underestimation); and (5) correcting bathymetry near a river's entrance (for fixing model underestimation).

Figure 10 shows ADCIRC modeled tidal datums (MHHW, MHW, MLW, MLLW, DTL, and MTL). The modeled tidal datums (except for MLW and DTL with relatively uniform distributions) show relatively larger values in the eastern coastal region than in the western coastal region which are consistent with the observed tidal datums. The patterns of the modeled tidal datums are also similar to those of 2013 modeled tidal datums (see Figure 10 in Xu et al., 2013).

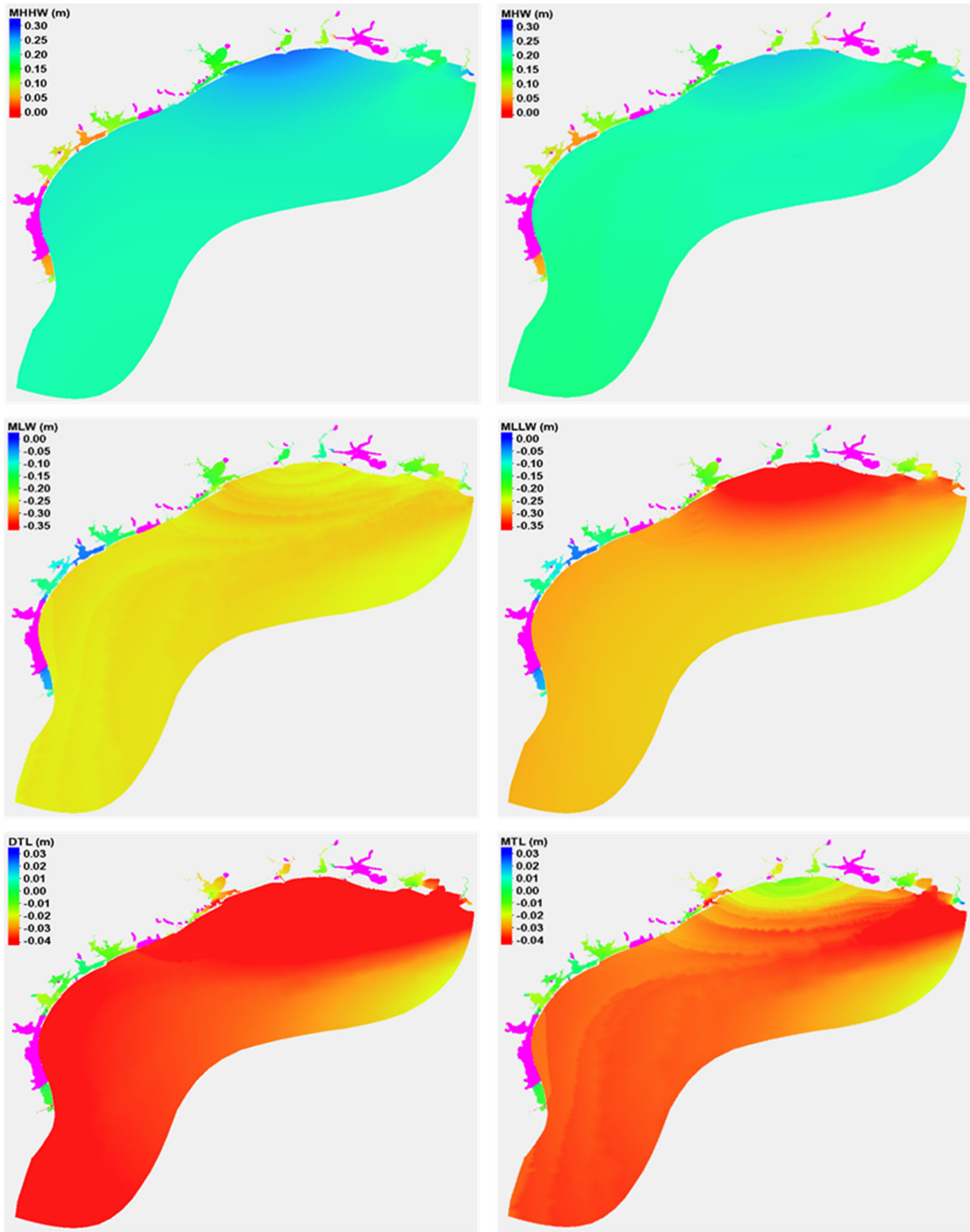

Figure 10. ADCIRC modeled MHHW, MHW, MLW, MLLW, DTL, and MTL. Model grid points in pink represent modeled non-tidal grid points (i.e., modeled MHW-MLW < 0.09 m).

Table 1 lists the statistical values (minimum, maximum, mean, and standard deviation "STD") of observed tidal datums, ADCIRC modeled tidal datums, and ADCIRC model errors. In this model domain, the maximum value of the observed MHHW is 0.32 m and the maximum value of the observed MLLW is -0.38 m. The maximum value of the modeled MHHW is 0.28 m, 0.04 m smaller than the observed MHHW maximum value. The maximum value of the modeled MLLW is -0.43 m, which is 0.05 m deeper than the observed MLLW maximum value.

The largest model error occurred in modeled MLLW (0.132 m), and the second largest model error occurred in modeled MLW (0.072 m). The model errors in the modeled MHHW and MHW are 0.063 m and 0.067 m, slightly smaller than that in modeled MLW. The mean value of model errors is larger for MLLW (0.032 m) and MLW (0.035 m) than for MHHW (0.028 m) and MHW (0.021 m). The difference between the largest standard deviation of model errors (0.042 m for MLLW) and the smallest standard deviation of model errors (0.028 m for MHW) is small, only 0.014 m. The small mean values of absolute model errors and the small standard deviations of model errors indicate overall small model errors in the ADCIRC modeled tidal datums.

Table 1. Statistics of observed tidal datums (“Observation”), ADCIRC modeled tidal datums (“ADCIRC”), and ADCIRC model errors (“Model Error”) (in units of meters). Note: “Model Error” refers to ADCIRC modeled tidal datum minus observed tidal datum; “Min” and “Max” refer to minimum and maximum values. “abs” refers to “absolute value”.

Data Type	MHHW	MHW	MLW	MLLW
[Min, Max] (Observation)	[0.05, 0.32]	[0.05, 0.26]	[−0.25, -0.05]	[−0.38, -0.05]
Mean (Observation)	0.16	0.14	-0.15	-0.20
STD (Observation)	0.066	0.052	0.053	0.090
[Min, Max] (ADCIRC)	[0.03, 0.28]	[0.03, 0.24]	[−0.31, -0.03]	[−0.43, -0.03]
Mean (ADCIRC)	0.16	0.15	-0.18	-0.21
STD (ADCIRC)	0.066	0.056	0.074	0.102
[Min, Max] (Model Error)	[-0.010, 0.063]	[-0.088, 0.067]	[-0.093, 0.072]	[-0.089, 0.132]
Mean [abs (Model Error)]	0.028	0.021	0.035	0.032
STD (Model Error)	0.035	0.028	0.033	0.042

4.2. Statistical Interpolation and Spatially Varying Uncertainty (SVU)

After the ADCIRC modeled tidal datums were validated by reducing model errors to the error limit of 0.10 m, the ADCIRC modeled tidal datums were interpolated by using observed tidal datums and their RMS errors via the SVU statistical interpolation method (Shi and Myers, 2016).

The SVU statistical interpolation method was developed based on the variational principle (Shi and Myers, 2016). First, a cost function was constructed according to the statistical characteristics (error covariance) of the observed and modeled tidal datums. Then, a blended tidal datum field was derived by optimizing the cost function. In the final step, as a by-product, the associated uncertainty was calculated for the blended tidal datum field. According to Shi and Myers (2016), the statistical interpolation has a few advantages over the traditional deterministic correction method: 1) It provides a spatially varying uncertainty; 2) It provides a framework to assimilate future data streams with known uncertainty to improve the quality of the final tidal datum product; 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.

Figures 11 and 12 show the SVU-statistically-interpolated modeled tidal datums (called “tidal datum SVU” in Figure 11) and their associated uncertainties (called “tidal datum SVU Uncertainty” in Figure 12) of MHHW/MHW, MLW/MLLW, and DTL/MTL, respectively.

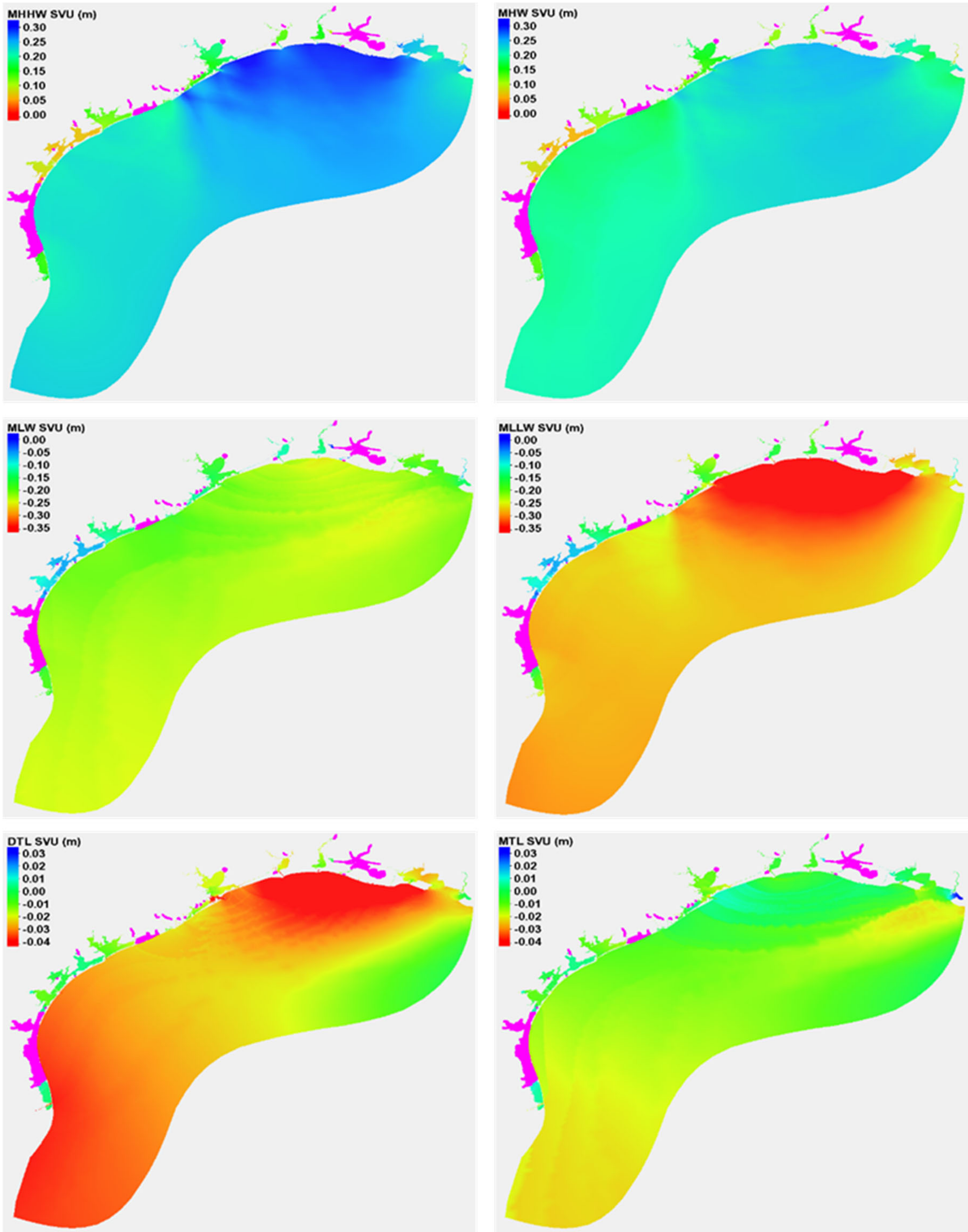

Figure 11. The SVU-statistically-interpolated modeled MHHW, MHW, MLW, MLLW, DTL, and MTL. Model grid points in pink represent the modeled non-tidal grid points (i.e., modeled MHW-MLW < 0.09 m).

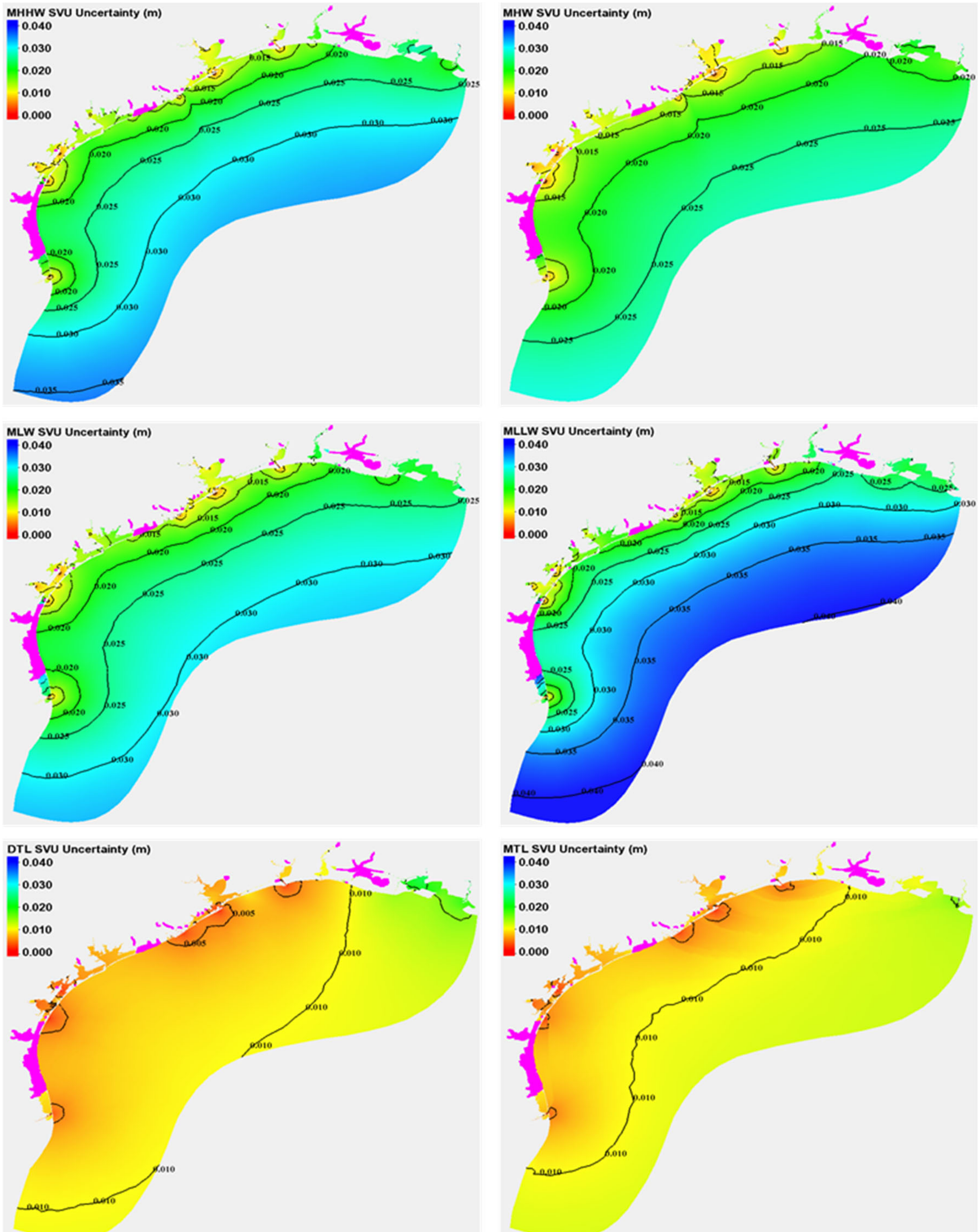

Figure 12. The spatially varying uncertainties of the SVU-statistically-interpolated modeled MHHW, MHW, MLW, MLLW, DTL, and MTL. Model grid points in pink represent the modeled non-tidal grid points (i.e., modeled MHW-MLW < 0.09 m).

As shown in Figure 11, the SVU-statistically-interpolated modeled tidal datums have relatively larger values in the eastern coastal region than in the western coastal region, similar to the ADCIRC modeled tidal datums and the observations.

Based on Figure 12, the spatially varying uncertainty of the four major SVU-statistically-interpolated modeled tidal datums exhibit the largest uncertainty in MLLW, the second largest in MHHW, the third largest in MLW, the fourth largest in MHW, and the smallest and about evenly distributed uncertainties in DTL and MTL. The spatially varying uncertainty was smaller at nodes close to the coastal lines and tide stations, and increased as the distance from tide stations increased. The largest uncertainties were located at the open ocean boundary, where no tide stations existed and the distance from the tide stations was the greatest.

As pointed out in Wu et al. (2019), the difference among tidal datums' spatially varying uncertainties was mainly determined by the difference in the model error covariance, which was 0.0417 m (MLLW), 0.0347 m (MHHW), 0.0327 m (MLW), or 0.0281 m (MHW). Also, the SVU statistical interpolation method was designed to make those nodes with greater distances from tide stations have larger uncertainties at the nodes. This explains the spatially varying uncertainty patterns of the four major tidal datums and why the greatest uncertainty was located at the open ocean boundary.

Table 2 lists the statistical values (minimum, maximum, mean, and standard deviation "STD") of the SVU-statistically-interpolated modeled tidal datums, their associated spatially varying uncertainties, and model errors in the SVU-statistically-interpolated modeled tidal datums. The SVU-statistically-interpolated modeled tidal datums match the observed tidal datums at all the tide stations to an error limit less than 0.010 m as coded in the SVU method. The mean value of the SVU uncertainty is the greatest in the SVU-statistically-interpolated modeled MLLW and the smallest in the SVU-statistically-interpolated modeled MHW. Similarly, the maximum value of the SVU uncertainty is the greatest in the SVU-statistically-interpolated modeled MLLW and the smallest in the SVU-statistically-interpolated modeled MHW. The explanations were provided in the paragraph above.

It is worthwhile to mention that the minimum values of the SVU uncertainty for the four major tidal datums were all less than 0.0005 m and thus were listed as "0.000" in Table 2.

Table 2. Statistics of the SVU-statistically-interpolated modeled tidal datums ("ADCIRC-SVU"), their associated spatially varying uncertainties ("SVU Uncertainty"), and model errors in the SVU-statistically-interpolated modeled tidal datums ("SVU Model Error") (in units of meters). Note: "SVU Model Error" refers to the SVU-statistically-interpolated modeled tidal datums ("ADCIRC-SVU") minus observed tidal datums; "Min" and "Max" refer to minimum and maximum values. "abs" refers to "Absolute Value".

Data Type	MHHW	MHW	MLW	MLLW
[Min, Max] (ADCIRC-SVU)	[0.03, 0.31]	[0.03, 0.25]	[-0.27, 0.00]	[−0.45, -0.03]
Mean (ADCIRC-SVU)	0.17	0.15	-0.16	-0.22
STD (ADCIRC-SVU)	0.069	0.055	0.057	0.095
[Min, Max] (SVU Uncertainty)	[0.000, 0.036]	[0.000, 0.033]	[0.000, 0.034]	[0.000, 0.046]
Mean (SVU Uncertainty)	0.015	0.013	0.015	0.018
STD (SVU Uncertainty)	0.004	0.004	0.005	0.006

Data Type	MHHW	MHW	MLW	MLLW
[Min, Max] (SVU Model Error)	[-0.010, 0.010]	[-0.010, 0.010]	[-0.010, 0.010]	[-0.010, 0.010]
Mean [abs (SVU Model Error)]	0.005	0.005	0.005	0.005
STD (SVU Model Error)	0.006	0.006	0.007	0.006

4.3. Non-Tidal Polygon Upgrade

The accuracy of non-tidal polygons directly influences the quality of the final-step VDatum marine grid population (The reason and explanation will be given in Section 5.2). In order to ensure the accuracy of VDatum marine grid population, it is necessary to upgrade the existing best estimated non-tidal polygons by incorporating modeled non-tidal grids for the areas lacking observations.

As mentioned before, a modeled non-tidal grid refers to a modeled grid if its modeled MHW minus MLW was less than 0.09 m (Gill and Michalski, 2016). The current modeled non-tidal grids were generated by using the modeled tidal datums after applying the SVU statistical interpolation.

Figure 13 shows the non-tidal polygons before (left) and after (right) the current upgrade. As shown in the figure (the left panel), the modeled non-tidal grid points (pink dots) in general agree with the CO-OPS best estimated non-tidal polygons (closed black lines).

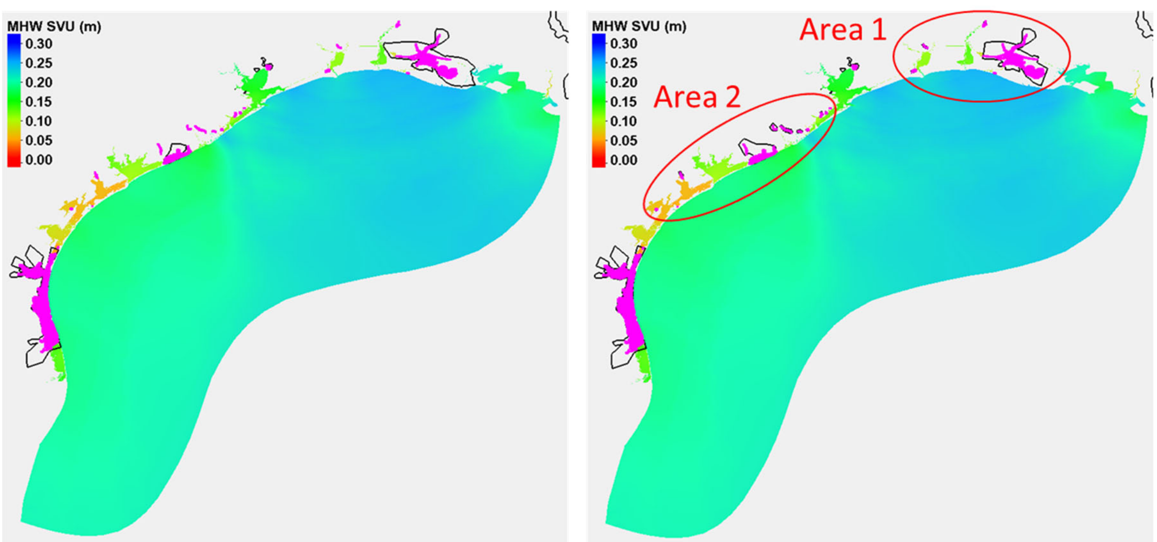

Figure 13. Non-tidal polygons (closed black lines) before (left) and after (right) the current upgrade. Modeled non-tidal grid points are marked as pink dots. Area 1 and Area 2 (within the closed red lines) are the two areas which had major adjustments for the non-tidal polygon upgrade.

The non-tidal polygon upgrade includes two major adjustments: (1) a significant reduction in the non-tidal area and four new small non-tidal areas in the western LA coastal region (Area 1); and (2) a significant extension in the non-tidal area and several new non-tidal areas in the middle TX coastal region (Area 2). The CO-OPS best estimated non-tidal polygons remained the same in areas where CO-OPS has tide observations or references but the model missed predicting non-tidal information, such as part of the Houston coastal region (the non-tidal polygons between Area 1 and Area 2) and part of the southwestern TX coastal region.

5. CREATION AND POPULATION OF VDATUM MARINE GRID

5.1. Creation of VDatum Marine Grid

Tidal datums in the NOAA VDatum are defined on a regularly structured grid called the VDatum marine grid. The standard resolution of each marine grid is high and set to be 0.001 degree in both zonal and meridional directions. Due to the large size of the current model domain and the very high resolution of the VDatum marine grid, seven bounding polygons were created for meeting the requirement of the VDatum marine grid generation (as shown in Figure 14). The bounding polygons are designed to be non-overlapping but sharing common borders. In the NOAA VDatum tool the bounding polygons are used to determine the appropriate marine grid region for datum transformations.

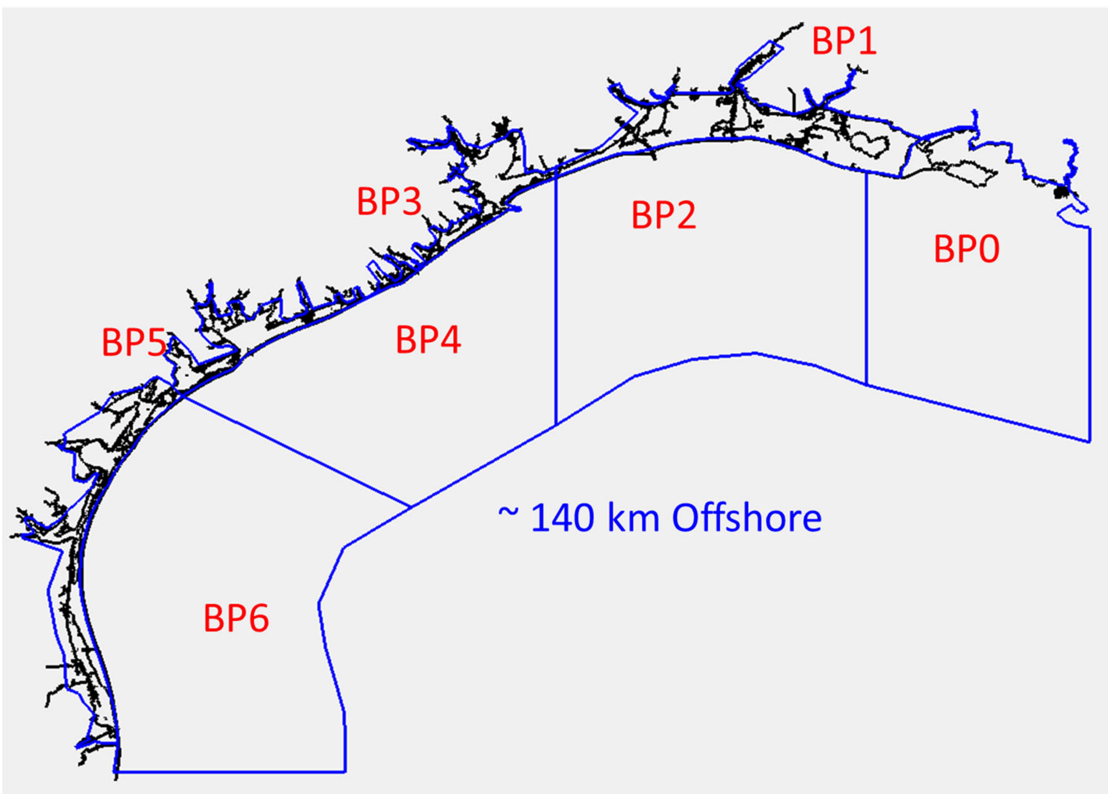

Figure 14. Seven bounding polygons (closed blue lines) created for VDatum marine grid generation. Black lines are shorelines. “BPi” (i = 0, 1, 2, 3, …, 6) denotes the ith bounding polygon.

Figure 15 shows an example of the generated VDatum marine grids which include seven layers. Each node in the marine grid is designated as either a water node or a land node based on the high resolution shoreline (Figure 1) and the seven bounding polygons (Figure 14). Five water layers which were artificially added landward from the shoreline in the marine grid generation, are equivalent to a total distance of about 500 m or greater in this model domain. The five artificially added water layers extend the non-null points over land, which allow datums to extend artificially to land to aid in obtaining datum transformations on the land adjacent to the water. Details of the VDatum marine grids in the seven VDatum regions are listed in Table 3.

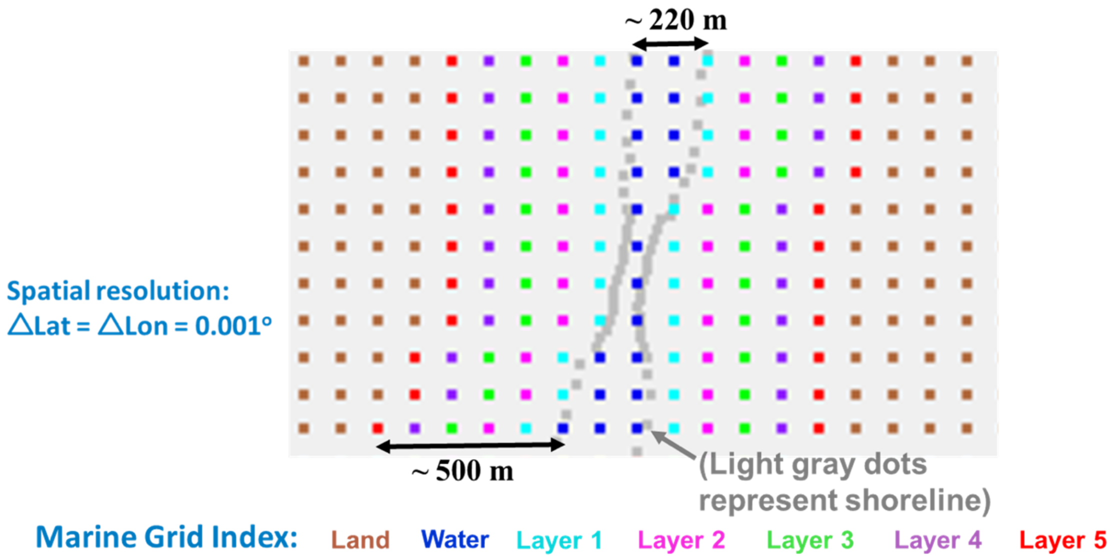

Figure 15. An example of the detailed marine grid field surrounding a narrow water path (light gray dots representing shoreline). The marine grids on land and in water are marked in brown and blue, respectively. The artificially added water layers 1 to 5 are marked in cyan, pink, green, purple, and red, respectively.

Table 3. VDatum marine grid information in the seven VDatum regions. Note: "Horiz" refers to Horizontal.

VDatum Region	Longitude-Latitude Window (deg)	Horiz. Spacing (deg)	Vertical Spacing (deg)	No of Horiz. Nodes	No of Vertical Nodes
R0	[27.8660 29.9529 -92.5160 -91.1294]	0.001	0.001	1388	2088
R1	[29.5380 30.3926 -94.4400 -91.8199]	0.001	0.001	2622	856
R2	[27.9720 29.7896 -94.4400 -92.5160]	0.001	0.001	1925	1819
R3	[28.1569 29.8598 -96.8163 -94.4400]	0.001	0.001	2378	1704
R4	[27.4560 29.5380 -96.7550 -94.4400]	0.001	0.001	2316	2083
R5	[25.9403 28.2768 -97.7499 -96.7550]	0.001	0.001	996	2338
R6	[25.7880 28.1569 -97.3898 -95.3330]	0.001	0.001	2058	2370

The generated VDatum marine grids in the seven VDatum regions are shown in Figure 16.

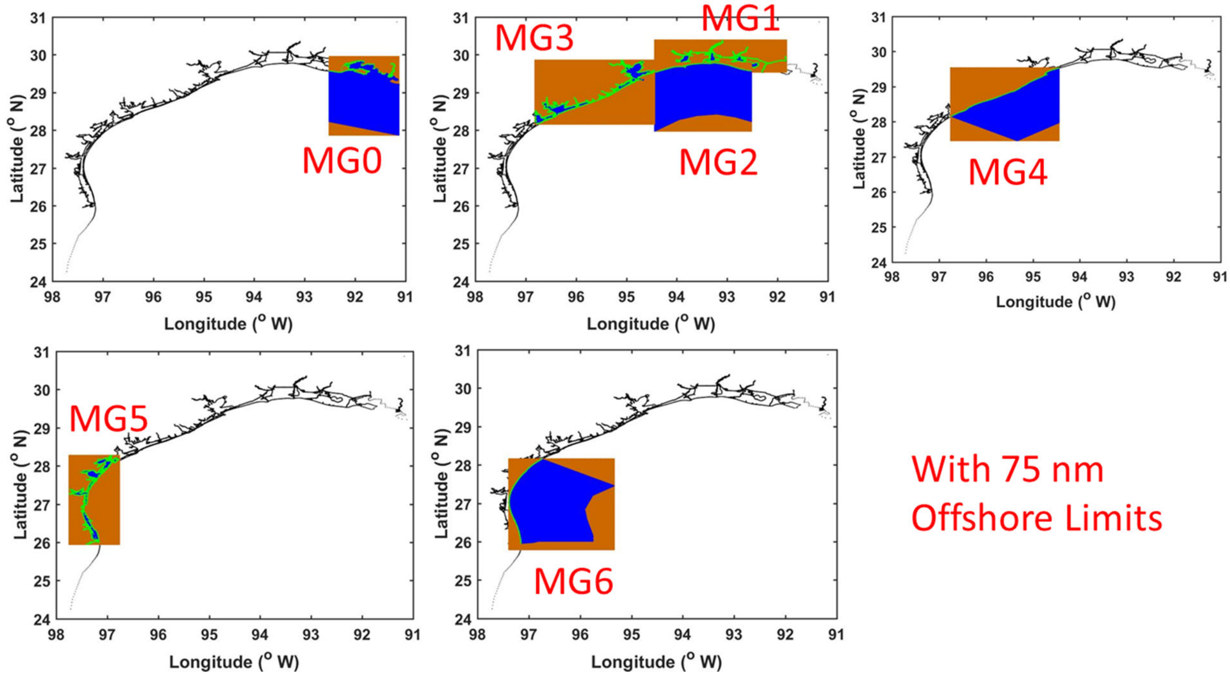

Figure 16. The generated VDatum marine grids in the seven VDatum regions. “MGi” (i = 0, 1, 2, 3, …, 6) refers to the ith marine grid region. Black lines are shorelines. Blue dots represent water nodes and brown dots represent land nodes. “nm” refers to “nautical miles”.

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

The final step is to generate VDatum marine grid population; that is, the SVU-statistically-interpolated modeled tidal datums and their associated spatially varying uncertainties were populated onto the water nodes of the VDatum marine grid points using averaging or linear interpolation. The details of the population methodology can be found in Hess et al. (2012).

Figure 17 shows the SVU-statistically-interpolated modeled tidal datum (MHHW for an example) before and after the VDatum marine grid population.

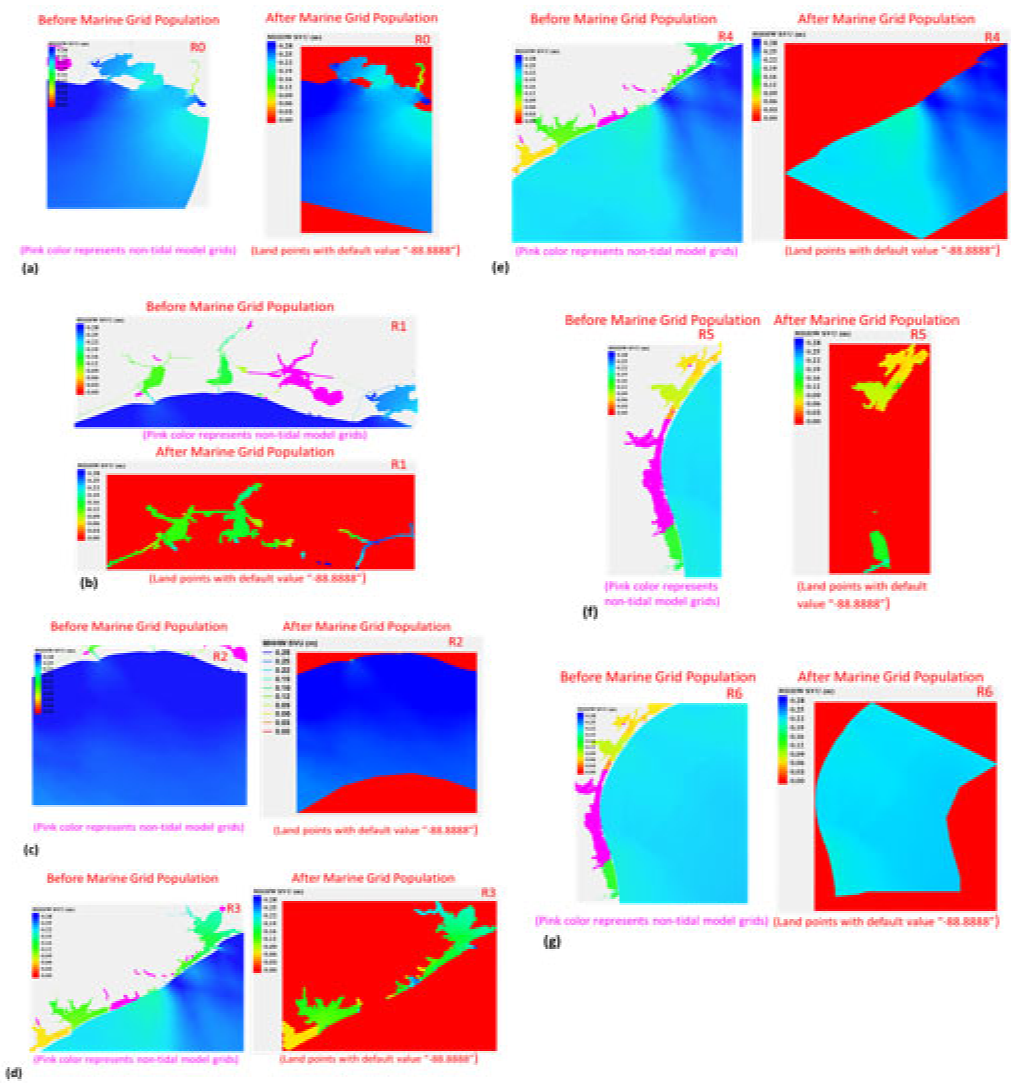

Figure 17. The SVU-statistically-interpolated modeled tidal datum (MHHW-SVU as an example) before and after the VDatum marine grid population in the seven VDatum marine grid regions.

As shown in Figure 17, the populated MHHW-SVU does not have any values inside the non-tidal polygons.

Figure 18 shows an example of the improvement of the marine grid population made by the non-tidal polygon upgrade. As can be seen in the figure, using the existing non-tidal polygons led to several areas with valid tidal datum values being excluded from the final valid VDatum marine grid product. This was because the existing non-tidal polygons covered part of the region with valid tidal datums that prohibited the generation of a complete picture of the VDatum marine grid population. However, the upgraded polygons enabled the VDatum marine grid population to reveal a complete picture of the valid tidal datum values. Thus, the upgrade of the non-tidal polygons improved the quality of the VDatum marine grid population.

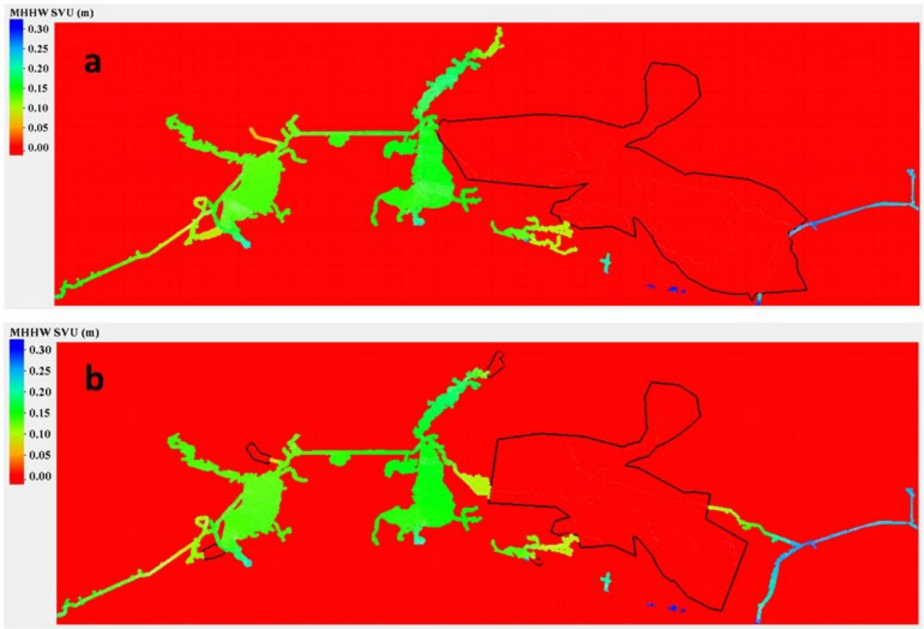

Figure 18. An example of the improvement in marine grid population achieved by the non-tidal polygon upgrade. It shows the marine grid populated SVU-statistically-interpolated modeled MHHW in the western LA coastal region by using the non-tidal polygons before (a) and after (b) the current non-tidal polygon upgrade.

The statistical values (minimum, maximum, mean, and standard deviation) of the marine grid populated SVU-statistically-interpolated modeled tidal datums and their associated spatially varying uncertainties are listed in Tables 4 and 5.

Table 4. Statistics of the marine grid populated SVU-statistically-interpolated modeled tidal datums (in units of meters) in each VDatum marine grid region. All are relative to LMSL.

Region	Tidal Datum	Minimum	Maximum	Mean	Standard Deviation
R0	MHHW	0.082	0.296	0.244	0.020
R0	MHW	0.070	0.246	0.216	0.017
R0	MLW	-0.271	-0.063	-0.225	0.019
R0	MLLW	-0.404	-0.090	-0.286	0.043
R0	DTL	-0.051	0.002	-0.019	0.012
R0	MTL	-0.030	0.038	-0.010	0.008
R1	MHHW	0.000	0.297	0.091	0.074
R1	MHW	0.000	0.245	0.077	0.063
R1	MLW	-0.239	0.000	-0.077	0.066
R1	MLLW	-0.407	0.000	-0.114	0.093
R1	DTL	-0.058	0.002	-0.011	0.010
R1	MTL	-0.028	0.018	-0.003	0.005

Region	Tidal Datum	Minimum	Maximum	Mean	Standard Deviation
R2	MHHW	0.000	0.315	0.270	0.024
R2	MHW	0.000	0.248	0.229	0.018
R2	MLW	-0.265	0.000	-0.233	0.020
R2	MLLW	-0.431	0.000	-0.349	0.042
R2	DTL	-0.085	0.000	-0.036	0.009
R2	MTL	-0.020	0.007	-0.006	0.007
R3	MHHW	0.000	0.265	0.127	0.054
R3	MHW	0.000	0.222	0.112	0.047
R3	MLW	-0.242	0.000	-0.127	0.051
R3	MLLW	-0.403	0.000	-0.151	0.067
R3	DTL	-0.063	0.026	-0.013	0.010
R3	MTL	-0.030	0.015	-0.007	0.007
R4	MHHW	0.000	0.307	0.232	0.022
R4	MHW	0.000	0.243	0.199	0.015
R4	MLW	-0.264	0.000	-0.213	0.010
R4	MLLW	-0.375	0.000	-0.281	0.025
R4	DTL	-0.052	0.002	-0.026	0.002
R4	MTL	-0.038	0.013	-0.009	0.005
R5	MHHW	0.000	0.198	0.055	0.051
R5	MHW	0.000	0.180	0.052	0.047
R5	MLW	-0.228	0.000	-0.063	0.064
R5	MLLW	-0.277	0.000	-0.067	0.070
R5	DTL	-0.051	0.009	-0.003	0.007
R5	MTL	-0.036	0.016	-0.002	0.005
R6	MHHW	0.000	0.225	0.219	0.007
R6	MHW	0.000	0.204	0.193	0.008
R6	MLW	-0.244	0.000	-0.227	0.011
R6	MLLW	-0.295	0.000	-0.280	0.009
R6	DTL	-0.056	0.004	-0.032	0.003
R6	MTL	-0.040	0.007	-0.017	0.002

Table 5. Statistics of the marine grid populated spatially varying uncertainties of the SVU-statistically-interpolated modeled tidal datums (in units of meters) in each VDatum marine grid region. Note: “Unc” refers to “Uncertainty”.

Region	Tidal Datum-Unc	Minimum	Maximum	Mean	Standard Deviation
R0	MHHW-Unc	0.018	0.033	0.027	0.004
R0	MHW-Unc	0.017	0.029	0.023	0.003
R0	MLW-Unc	0.018	0.031	0.026	0.003
R0	MLLW-Unc	0.021	0.039	0.031	0.005

Region	Tidal Datum-Unc	Minimum	Maximum	Mean	Standard Deviation
R0	DTL-Unc	0.011	0.025	0.013	0.002
R0	MTL-Unc	0.010	0.016	0.012	0.001
R1	MHHW-Unc	0.000	0.032	0.011	0.009
R1	MHW-Unc	0.000	0.030	0.010	0.008
R1	MLW-Unc	0.000	0.032	0.012	0.010
R1	MLLW-Unc	0.000	0.043	0.014	0.011
R1	DTL-Unc	0.000	0.026	0.006	0.006
R1	MTL-Unc	0.000	0.011	0.006	0.005
R2	MHHW-Unc	0.000	0.031	0.024	0.005
R2	MHW-Unc	0.000	0.025	0.020	0.004
R2	MLW-Unc	0.000	0.030	0.023	0.004
R2	MLLW-Unc	0.000	0.037	0.028	0.006
R2	DTL-Unc	0.000	0.013	0.009	0.002
R2	MTL-Unc	0.000	0.012	0.009	0.002
R3	MHHW-Unc	0.000	0.020	0.012	0.004
R3	MHW-Unc	0.000	0.031	0.010	0.003
R3	MLW-Unc	0.000	0.025	0.012	0.004
R3	MLLW-Unc	0.000	0.033	0.014	0.005
R3	DTL-Unc	0.000	0.012	0.006	0.002
R3	MTL-Unc	0.000	0.010	0.006	0.002
R4	MHHW-Unc	0.000	0.030	0.022	0.005
R4	MHW-Unc	0.000	0.025	0.019	0.004
R4	MLW-Unc	0.000	0.028	0.021	0.005
R4	MLLW-Unc	0.000	0.035	0.026	0.006
R4	DTL-Unc	0.000	0.009	0.007	0.001
R4	MTL-Unc	0.000	0.011	0.008	0.002
R5	MHHW-Unc	0.000	0.023	0.007	0.006
R5	MHW-Unc	0.000	0.020	0.006	0.006
R5	MLW-Unc	0.000	0.032	0.008	0.008
R5	MLLW-Unc	0.000	0.038	0.010	0.010
R5	DTL-Unc	0.000	0.010	0.003	0.003
R5	MTL-Unc	0.000	0.011	0.003	0.003
R6	MHHW-Unc	0.000	0.031	0.024	0.004
R6	MHW-Unc	0.000	0.025	0.019	0.003
R6	MLW-Unc	0.000	0.030	0.022	0.004
R6	MLLW-Unc	0.000	0.037	0.028	0.005
R6	DTL-Unc	0.000	0.010	0.007	0.001
R6	MTL-Unc	0.000	0.011	0.008	0.001

6. 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 Texas and western Louisiana coastal regions. This work updates and extends the previously modeled tidal datums in this VDatum region (Xu et al., 2013).

We first extended the previous model domain to include new tide stations and to incorporate the most currently available shoreline data. Model mesh grids were then generated in the updated model domain. The updated model mesh contains 542,936 unstructured triangular finite elements and 297,227 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 the time series of 6-minute tidal elevation at each model grid point for 67 days. The key model parameter settings used include nonlinear quadratic bottom friction, spatially constant horizontal eddy viscosity, wetting and drying process, a spatially uniform Generalized Wave-Continuity Equation weighting factor, advective terms, the tidal potential body force of the eight principal tidal constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2, and K_2), and the open ocean boundary forcing that equals the sum of the elevations of the eight tidal harmonic constituents which were extracted from the EC2015 tidal database (Szpilka et al., 2016). Neither atmospheric forcing nor river flow was imposed.

The ADCIRC modeled tidal datums were derived from the final 60-day 6-minute modeled water level time series at each model grid point. Modeled tidal datums were first evaluated by using observed tidal datums at 75 tide stations. The model grid points with large (>0.10 m) model errors were identified and several techniques (Section 4.1) were used to adjust the tide model for reducing model errors and improving model performance.

After the model improvement, the modeled tidal datums were blended with observed tidal datums using the 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 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 error limit (0.01 m in this work) at each tide station. The produced spatially varying uncertainty field for each interpolated tidal datum field was an improvement over the previous interpolation method that only provided a single-value model uncertainty over an entire VDatum region according to Shi and Myers (2016). Next, modeled non-tidal grid points (where the SVU-statistically-interpolated modeled MHW minus the SVU-statistically-interpolated modeled MLW was less than 0.09 m) were identified. These were used to upgrade the existing best estimated non-tidal polygons for the improved quality in the VDatum marine grid population (Sections 4.3 and 5.2).

Finally, seven 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 then interpolated onto those regularly distributed VDatum marine grids as the current VDatum modeling final data products.

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APPENDIX A. INFORMATION OF TIDE STATIONS

Below lists the information of a total of 75 tide stations used in the current tidal datum modeling work in Texas and the western Louisiana regions. Longitude and latitude are in units of degrees.

No.	Station ID	Longitude	Latitude	Station Location Name
1	8764025	-91.230000	29.743300	STOUTS PASS AT SIX MILE LAKE
2	8764044	-91.237611	29.667500	BERWICK, ATCHAFALAYA RIVER, LA LOUISIANA
3	8764227	-91.338111	29.449583	LAWMA, AMERADA PASS LOUISIANA
4	8765148	-91.826700	29.811700	WEEKS BAY LOUISIANA
5	8765171	-91.838300	29.948300	NEW IBERIA DRAINAGE CANAL LOUISIANA
6	8765251	-91.880000	29.713361	CYPREMORT POINT LOUISIANA
7	8766072	-92.305262	29.551755	FRESHWATER CANAL LOCKS LOUISIANA
8	8767816	-93.221667	30.223639	LAKE CHARLES, CALCASIEU RIVER LOUISIANA
9	8767961	-93.300694	30.190306	BULK TERMINAL #1 LOUISIANA
10	8768094	-93.342889	29.768167	CALCASIEU PASS, EAST JETTY LOUISIANA
11	8770475	-93.930000	29.866700	PORT ARTHUR, SABINE NACHES CANAL
12	8770501	-95.078333	29.818333	ANNIE'S LANDING, SAN JACINTO RIVER TEXAS
13	8770520	-93.881700	29.980000	RAINBOW BRIDGE, NECHES RIVER
14	8770539	-93.895000	29.766700	MESQUITE POINT
15	8770557	-94.831830	29.740500	Point Barrow
16	8770559	-94.690000	29.713300	ROUND POINT, TRINITY BAY
17	8770570	-93.870100	29.728400	SABINE PASS NORTH TEXAS
18	8770590	-93.853300	29.705000	SABINE PASS TEXAS
19	8770595	-94.090000	30.095000	Beaumont
20	8770597	-93.717200	30.084800	Orange
21	8770613	-94.985000	29.681700	MORGANS POINT, BARBOURS CUT TEXAS
22	8770625	-94.868333	29.680000	UMBRELLA POINT, TRINITY BAY TEXAS
23	8770733	-95.078300	29.765000	LYNCHBURG LANDING, SAN JACINTO RIVER TEXAS
24	8770743	-95.090000	29.756700	BATTLESHIP TEXAS S.P, HOUSTON SHIP CHANN
25	8770777	-95.265806	29.726278	MANCHESTER, HOUSTON SHIP CHANNEL TEXAS
26	8770822	-93.837220	29.678330	Texas Point
27	8770923	-94.385000	29.538300	High Island
28	8770933	-95.066700	29.563300	CLEAR LAKE TEXAS
29	8770971	-94.513300	29.515000	ROLLOVER PASS
30	8771013	-94.918300	29.480000	EAGLE POINT, GALVESTON BAY TEXAS
31	8771328	-94.780000	29.365000	PORT BOLIVAR, BOLIVAR ROADS TEXAS
32	8771341	-94.724833	29.357333	GALVESTON BAY ENTRANCE, NORTH JETTY TEXAS
33	8771416	-94.691700	29.326700	Galveston Entrance Channel, South Jetty
34	8771450	-94.793300	29.310000	GALVESTON PIER 21, GALVESTON CHANNEL TEXAS
35	8771510	-94.789400	29.285300	GALVESTON PLEASURE PIER, GULF OF MEXICO TEXAS
36	8771708	-95.206700	29.211700	Chocolate Bayou
37	8771801	-95.125000	29.166700	Alligator Point
38	8771854	-95.159600	29.144300	West Bay
39	8771972	-95.122570	29.075700	San Luis Pass
40	8771984	-95.281700	29.090000	Bastrop Bayou

No.	Station ID	Longitude	Latitude	Station Location Name
41	8772132	-95.175000	29.041700	CHRISTMAS BAY TEXAS
42	8772440	-95.308300	28.948300	FREEPORT, DOW BARGE CANAL TEXAS
43	8772447	-95.302500	28.943306	USCG FREEPORT, FREEPORT ENTR CHANNEL TEXAS
44	8772689	-95.454600	28.877800	San Bernard Rivers End
45	8773001	-95.653300	28.761700	East Matagorda Bay
46	8773037	-96.711700	28.408300	SEADRIFT, SAN ANTONIO BAY
47	8773156	-96.231700	28.696700	Palacios
48	8773259	-96.595000	28.640000	PORT LAVACA, LAVACA CAUSEWAY
49	8773304	-95.970000	28.623300	Rawlings
50	8773701	-96.388300	28.451700	PORT O'CONNOR, MATAGORDA BAY
51	8773963	-96.461700	28.333300	NORTH MATAGORDA TEXAS
52	8774513	-97.021700	28.118300	COPANO BAY STATE FISHING PIER
53	8774522	-96.978300	28.126700	Goose Island
54	8774652	-97.203300	28.066700	Bayside
55	8774770	-97.046700	28.021700	ROCKPORT, ARANSAS BAY TEXAS
56	8775188	-97.475000	27.858300	WHITE POINT BAY
57	8775222	-97.520900	27.846230	Viola Turning Basin
58	8775237	-97.073300	27.838300	PORT ARANSAS
59	8775270	-97.050000	27.826700	PORT ARANSAS, H. CALDWELL PIER TEXAS
60	8775283	-97.203300	27.821700	PORT INGLESIDE, CORPUS CHRISTI BAY
61	8775296	-97.390000	27.811700	TEXAS STATE AQUARIUM, CORPUS CHRISTI
62	8775351	-97.387600	27.794700	Lawrence St. T-Head
63	8775421	-97.280000	27.705000	CORPUS CHRISTI NAVAL AIR STATION
64	8775792	-97.236700	27.633300	PACKERY CHANNEL
65	8775870	-97.216700	27.580000	CORPUS CHRISTI, GULF OF MEXICO TEXAS
66	8779724	-97.170000	26.078300	QUEEN ISABELLA CAUSEWAY, PADRE ISLAND TEXAS
67	8779739	-97.191700	26.071700	W QUEEN ISABELLA CAUSEWAY, PORT ISABEL TEXAS
68	8779748	-97.176700	26.076700	SOUTH PADRE ISLAND C.G. STATION
69	8779750	-97.156700	26.068300	PADRE ISLAND, BRAZOS SANTIAGO PASS TEXAS
70	8779768	-97.181700	26.051700	SOUTH BAY TEXAS
71	8779770	-97.215000	26.060000	PORT ISABEL, LAGUNA MADRE TEXAS
72	8779977	-97.401700	25.951700	PORT OF BROWNSVILLE TEXAS
73	8780037	-96.928000	28.202300	Indian Head Point
74	8780038	-96.799000	28.231500	False Live Oak
75	8780050	-95.555300	28.949800	Churchill - San Bernard

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

Below list the observed tidal datums and RMS errors at the 75 tide stations used in the current tidal datum modeling work in Texas and the western Louisiana regions. Longitude and latitude are in units of degrees. MHHW, MHW, MLW, MLLW, and RMS Errors are in units of meters.

No.	Station ID	Longitude	Latitude	MHHW	MHW	MLW	MLLW	RMS Errors
1	8764025	-91.230000	29.743300	0.145	0.121	-0.105	-0.126	0.034
2	8764044	-91.237611	29.667500	0.074	0.061	-0.078	-0.092	0.031
3	8764227	-91.338111	29.449583	0.232	0.186	-0.158	-0.255	0.023
4	8765148	-91.826700	29.811700	0.219	0.192	-0.195	-0.271	0.030
5	8765171	-91.838300	29.948300	0.258	0.231	-0.245	-0.329	0.035
6	8765251	-91.880000	29.713361	0.244	0.202	-0.202	-0.274	0.045
7	8766072	-92.305262	29.551755	0.279	0.232	-0.219	-0.377	0.024
8	8767816	-93.221667	30.223639	0.188	0.158	-0.165	-0.239	0.024
9	8767961	-93.300694	30.190306	0.178	0.149	-0.164	-0.229	0.044
10	8768094	-93.342889	29.768167	0.226	0.192	-0.198	-0.363	0.018
11	8770475	-93.930000	29.866700	0.134	0.117	-0.135	-0.184	0.019
12	8770501	-95.078333	29.818333	0.218	0.193	-0.191	-0.266	0.028
13	8770520	-93.881700	29.980000	0.124	0.109	-0.122	-0.160	0.021
14	8770539	-93.895000	29.766700	0.153	0.129	-0.151	-0.229	0.006
15	8770557	-94.831830	29.740500	0.182	0.153	-0.177	-0.217	-9.999
16	8770559	-94.690000	29.713300	0.195	0.167	-0.176	-0.231	0.026
17	8770570	-93.870100	29.728400	0.195	0.164	-0.169	-0.293	0.001
18	8770590	-93.853300	29.705000	0.227	0.195	-0.223	-0.339	0.000
19	8770595	-94.090000	30.095000	0.129	0.107	-0.125	-0.171	0.023
20	8770597	-93.717200	30.084800	0.107	0.091	-0.116	-0.148	0.024
21	8770613	-94.985000	29.681700	0.182	0.160	-0.182	-0.217	0.020
22	8770625	-94.868333	29.680000	0.176	0.164	-0.183	-0.212	0.021
23	8770733	-95.078300	29.765000	0.203	0.176	-0.194	-0.247	0.022
24	8770743	-95.090000	29.756700	0.204	0.175	-0.188	-0.241	0.008
25	8770777	-95.265806	29.726278	0.226	0.188	-0.199	-0.275	0.024
26	8770822	-93.837220	29.678330	0.244	0.203	-0.216	-0.371	0.011
27	8770923	-94.385000	29.538300	0.323	0.256	-0.234	-0.368	0.016
28	8770933	-95.066700	29.563300	0.162	0.144	-0.175	-0.192	0.027
29	8770971	-94.513300	29.515000	0.183	0.157	-0.178	-0.227	0.020
30	8771013	-94.918300	29.480000	0.156	0.143	-0.166	-0.182	0.018
31	8771328	-94.780000	29.365000	0.168	0.144	-0.199	-0.258	0.015
32	8771341	-94.724833	29.357333	0.214	0.177	-0.177	-0.296	0.013
33	8771416	-94.691700	29.326700	0.237	0.194	-0.188	-0.330	0.012
34	8771450	-94.793300	29.310000	0.177	0.151	-0.160	-0.252	0.000
35	8771510	-94.789400	29.285300	0.284	0.225	-0.219	-0.338	0.000
36	8771708	-95.206700	29.211700	0.123	0.109	-0.123	-0.152	-9.999
37	8771801	-95.125000	29.166700	0.109	0.098	-0.126	-0.140	-9.999

No.	Station ID	Longitude	Latitude	MHHW	MHW	MLW	MLLW	RMS Errors
38	8771854	-95.159600	29.144300	0.105	0.098	-0.115	-0.126	-9.999
39	8771972	-95.122570	29.075700	0.205	0.172	-0.181	-0.253	0.015
40	8771984	-95.281700	29.090000	0.071	0.072	-0.128	-0.131	-9.999
41	8772132	-95.175000	29.041700	0.115	0.102	-0.114	-0.134	0.021
42	8772440	-95.308300	28.948300	0.245	0.203	-0.208	-0.291	0.000
43	8772447	-95.302500	28.943306	0.253	0.206	-0.217	-0.296	0.017
44	8772689	-95.454600	28.877800	0.126	0.107	-0.134	-0.153	-9.999
45	8773001	-95.653300	28.761700	0.050	0.048	-0.053	-0.058	-9.999
46	8773037	-96.711700	28.408300	0.057	0.050	-0.054	-0.060	0.022
47	8773156	-96.231700	28.696700	0.140	0.119	-0.156	-0.173	0.024
48	8773259	-96.595000	28.640000	0.133	0.123	-0.133	-0.150	0.010
49	8773304	-95.970000	28.623300	0.189	0.161	-0.164	-0.216	-9.999
50	8773701	-96.388300	28.451700	0.112	0.106	-0.116	-0.127	0.025
51	8773963	-96.461700	28.333300	0.059	0.058	-0.070	-0.072	0.018
52	8774513	-97.021700	28.118300	0.056	0.055	-0.061	-0.061	0.014
53	8774522	-96.978300	28.126700	0.058	0.055	-0.055	-0.055	-9.999
54	8774652	-97.203300	28.066700	0.060	0.059	-0.065	-0.069	-9.999
55	8774770	-97.046700	28.021700	0.053	0.052	-0.057	-0.058	0.000
56	8775188	-97.475000	27.858300	0.101	0.096	-0.094	-0.104	0.025
57	8775222	-97.520900	27.846230	0.095	0.091	-0.115	-0.122	-9.999
58	8775237	-97.073300	27.838300	0.118	0.106	-0.136	-0.183	0.017
59	8775270	-97.050000	27.826700	0.217	0.182	-0.213	-0.282	0.014
60	8775283	-97.203300	27.821700	0.080	0.078	-0.093	-0.096	0.019
61	8775296	-97.390000	27.811700	0.085	0.081	-0.103	-0.106	0.004
62	8775351	-97.387600	27.794700	0.083	0.080	-0.100	-0.103	-9.999
63	8775421	-97.280000	27.705000	0.086	0.082	-0.098	-0.102	0.022
64	8775792	-97.236700	27.633300	0.055	0.054	-0.058	-0.059	0.019
65	8775870	-97.216700	27.580000	0.215	0.186	-0.214	-0.282	0.000
66	8779724	-97.170000	26.078300	0.160	0.144	-0.193	-0.231	-9.999
67	8779739	-97.191700	26.071700	0.167	0.154	-0.165	-0.195	0.011
68	8779748	-97.176700	26.076700	0.163	0.148	-0.194	-0.237	0.006
69	8779750	-97.156700	26.068300	0.183	0.166	-0.216	-0.266	0.013
70	8779768	-97.181700	26.051700	0.169	0.151	-0.195	-0.241	0.011
71	8779770	-97.215000	26.060000	0.171	0.153	-0.198	-0.247	0.000
72	8779977	-97.401700	25.951700	0.187	0.166	-0.204	-0.271	0.014
73	8780037	-96.928000	28.202300	0.063	0.062	-0.053	-0.054	-9.999
74	8780038	-96.799000	28.231500	0.072	0.063	-0.068	-0.070	-9.999
75	8780050	-95.555300	28.949800	0.166	0.131	-0.157	-0.192	-9.999