NOAA Technical Memorandum NOS CS 29

VDATUM FOR THE COASTAL WATERS OF TEXAS AND WESTERN LOUISIANA: TIDAL DATUMS AND TOPOGRAPHY OF THE SEA SURFACE

Silver Spring, Maryland
March 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
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VDATUM FOR THE COASTAL WATERS OF TEXAS AND WESTERN LOUISIANA: TIDAL DATUMS AND TOPOGRAPHY OF THE SEA SURFACE

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ABSTRACT

VDatum, NOAA's vertical datum transformation software tool, allows users to transform vertical elevation/depth data between various tidal, orthometric, and ellipsoid-based 3D reference systems. An application of VDatum has been developed for the coastal waters of Texas and west Louisiana, which extends the VDatum coverage to all U.S. coastal waters in the Gulf of Mexico region.

The tidal datums fields for this VDatum application were derived from tidal simulations using the 2D barotropic version of the finite element model ADCIRC. An unstructured triangular grid consisting of 284,217 nodes and 523,047 cells was created for these simulations. The model was forced with eight tidal constituents (M_2, S_2, N_2, K_2, K_1, P_1, O_1 and Q_1) and run for 67 days. Water level time series of the last 60 days were saved. Various tidal datum fields, including mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and mean higher high water (MHHW), were derived from these time series. Water level harmonic analysis was conducted on the model results for the NOAA National Ocean Service's (NOS's) standard 37 tidal constituents. Model results were validated by comparing with observations from 50 water level stations maintained by the NOS's Center for Operational Oceanographic Products and Services (CO-OPS) and 21 additional stations from the Texas Costal Ocean Observation Network (TCOON). Discrepancies between model results and observational datums were attributed to model errors and interpolated over the whole model domain using TCARI (Tidal Constituent And Residual Interpolation), a spatial interpolation tool based on solution of Laplace's equation. These spatially varying error fields were added to the original model results to derive corrected tidal datum fields on the unstructured grid. These corrected tidal datum fields were then interpolated onto a regularly structured marine grid for use as input to the VDatum software. Non-tidal areas, where the astronomical tide is practically absent, were incorporated into the VDatum tool for the first time. The tide-averaged elevation of the water in these non-tidal areas was defined as the Mean Water Level (MWL), and the differences between the other tidal datums and MWL were set to zero.

The Topography of Sea Surface (TSS), defined as the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to local mean sea level (LMSL), was developed based on interpolation of bench mark data maintained by CO-OPS and NOS's National Geodetic Survey (NGS). The NAVD88-to-LMSL values were derived by calculating orthometric-to-tidal datum relationships at NOAA tide stations and spatially interpolating these values onto the marine grid.

Key Words: tides, tidal datums, VDatum, Texas, Louisiana, Gulf of Mexico, ADCIRC, bathymetry, coastline, marine grid, North American Vertical Datum

1. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) has developed a software tool called VDatum to transform elevation data among approximately 30 vertical datums (Milbert, 2002; Parker, 2002; Parker et al., 2003; Myers, 2005; Myers and Hess, 2006). Once VDatum has been established for a region, data sets referenced to different vertical datums can be integrated through transformations to a common vertical datum (Parker, 2002; Parker et al., 2003). VDatum allows bathymetric and topographic data to be integrated in this manner through its inherent geoidal, ellipsoidal, and tidal relationships.

Knowledge of the spatial distribution of tidal datums is necessary for developing accurate VDatum applications (Milbert and Hess, 2001). Tidal datum fields for VDatum, including MHHW, MHW, MLW, MLLW, mean tide level (MTL), diurnal tide level (DTL), and local mean sea level (LMSL) are derived from water level observations and from numerical simulations by hydrodynamic models. The observations provide accurate tidal datums at the station locations, and the hydrodynamic models are an effective way to capture the spatially varying nature of the tidal datums between and away from stations. Differences between the model and the data are spatially interpolated to create a correction field used to produce a final set of tidal datum fields that match the observations.

This report describes the development of VDatum for an area extending from Vermillion Bay, Louisiana, to just south of the U.S.-Mexico border, which, along with the previously-developed VDatums for central Louisiana, the northeast Gulf, and the west Florida shelf, extends VDatum coverage to all U.S. coastal waters in the Gulf of Mexico region.

The Gulf of Mexico is a semi-enclosed marginal sea that connects in the east to the Atlantic Ocean through the Straits of Florida and in the south to the Caribbean Sea through the Yucatan Channel. Barotropic tides in the deep Gulf are predominantly diurnal because it is a quasi-resonant basin (Grace, 1932; Reid and Whitaker, 1981). Along the surrounding coasts, they are either principally diurnal or mixed diurnal-semidiurnal, except on the West Florida shelf, where semi-diurnal tides prevail (Reid and Whitaker, 1981; He and Weisberg, 2008). Figure 1 displays a map of the study area. The figure shows tide stations maintained by the Center for Operational Oceanographic Products and Services (CO-OPS) of the National Ocean Service (NOS) and by the Texas Coastal Ocean Observation Network (TCOON). In the figure, the black line represents the MHW coastline and the green line denotes the 25-nm offshore demarcation. Tidal datums for VDatum are generally developed for water areas between the coastline and the 25-nautical mile offshore limit.

Creation of VDatum begins with tidal simulations using a hydrodynamic model. Tidal datums and harmonic constants of selected tidal constituents were computed from simulated water level time series. Adjustments to model parameters were made based on comparisons between the modeled harmonic constituents and tidal datums with observational data. Final error corrections to the tidal datums were made using the Tidal Constituent And Residual Interpolation (TCARI) software to spatially interpolate model-data differences. Regularly structured marine grids were created and populated with these corrected tidal datums.

Finally, to be applicable over coastal waters, VDatum requires spatially-varying fields of the topography of sea surface (TSS) as well, which refers to the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to LMSL. The NAVD88-to-LMSL field was derived by spatially interpolating the calculated orthometric-to-tidal datum relationships at NOAA tide stations onto the structured marine grids.

This technical report is organized as follows: After an introduction in Section 1, Section 2 discusses data needed for driving and validating the hydrodynamic model. Section 3 and 4 describe the set-up and sensitivity studies of the tide model, respectively. Section 5 discusses creation of a regularly structured marine grid required for the VDatum software tool and its population with error-corrected model datums. In Section 6, creation of TSS for the area is described. Finally, a summary is given in Section 7.

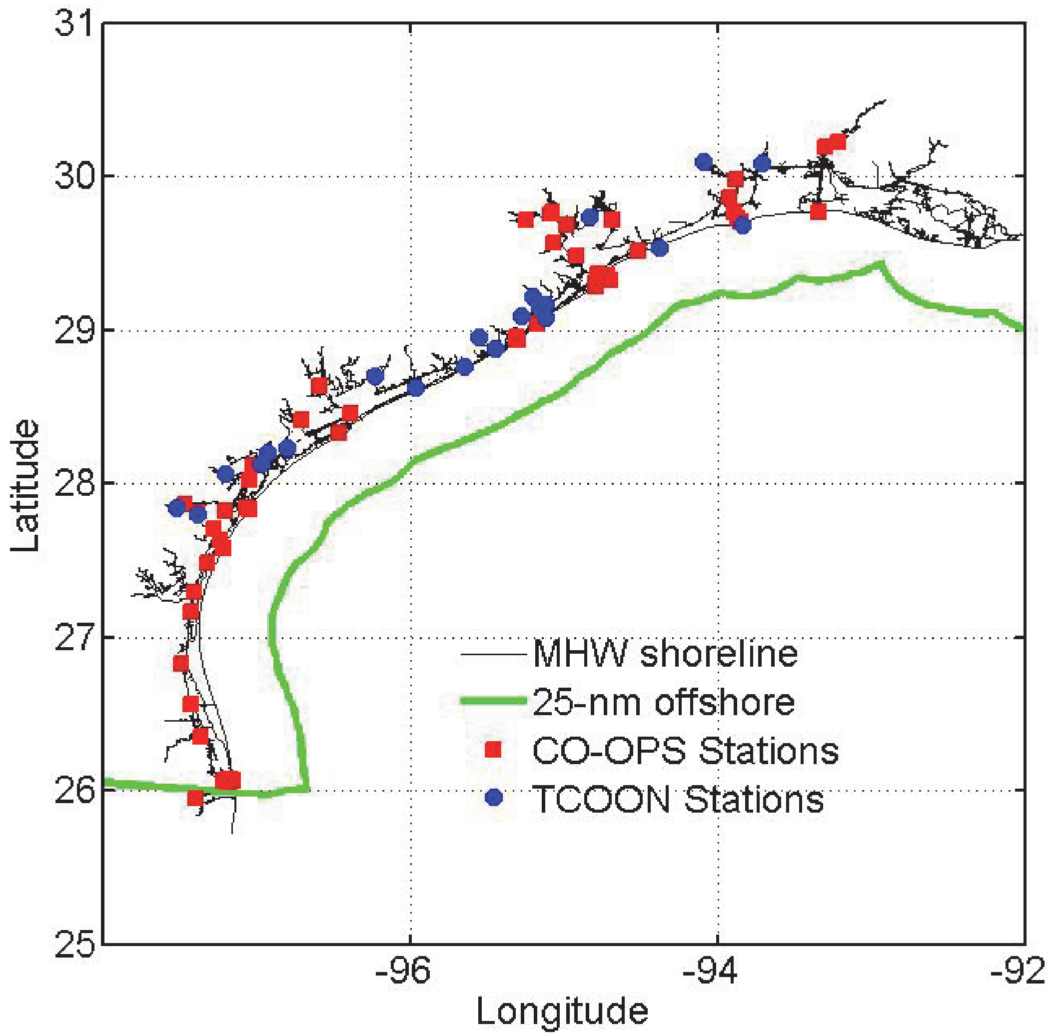

Figure 1. Map of the coastal waters for the VDatum region of interest. The black line illustrates the MHW coastline. The green line marks a distance of 25 nautical miles offshore. Red squares show the locations of the CO-OPS tide stations and blue circles show additional stations from TCOON.

2. DATA DESCRIPTION

To derive spatially varying tidal datum fields for VDatum, a hydrodynamic model was used to simulate the tidal dynamics in this region. Coastline and bathymetric data were required to build the model grid for the tidal simulation. Tidal datums derived from observations were used to validate the model results and to make corrections in the final tidal datum fields.

2.1. Digital Coastline

The MHW coastline was used to delineate the land-water boundaries. The medium resolution coastline downloaded from NOAA's National Geophysical Data Center (NGDC) was used to guide the building of the unstructured grid used in the tide model. However, a high resolution digital shoreline was produced from current NOAA Electronic Navigational Chart (ENC) and Raster Navigational Chart data and was used for interpolating the model results onto the structured marine grids used by the VDatum software. The Coastline (COALNE) and Shoreline Construction (SLCONS) ENC object classes were obtained for both the Harbor and Approach scalebands and converted from their native S57 format to shapefiles for use in ArcGIS 9.3 from the Environmental Systems Research Institute, Inc. (ESRI). The ENC data were merged and edited against NOAA charts to produce a continuous shoreline product representing the most detailed and most current information available. The charts used typically ranged in scale from 1:5,000 to 1:80,000. A commercial software package called Surface-Water Modeling System (SMS) was used to read in the shapefile and manually connect the shoreline segments together and to correct errors in the original digital coastlines. In Figure 1, the black line illustrates this final version of the coastline and is used in the generation of the VDatum marine grids (see Section 5.1).

2.2. Bathymetric Data

Bathymetric data used in this study were from three sources: NOS soundings, the NOAA ENCs, and U.S. Army Corps of Engineers (USACE) navigational channel surveys.

The NOS soundings were from the NOS/OCS hydrographic database maintained at NGDC and include surveys conducted between 1885 and 2005 (Figure 2a). As shown in Figure 2a, the majority of the coastal surveys were done in the 1930's. More recent surveys from the 1960's to early 2000's updated the bathymetric data in some of the coastal open waters and embayments. The bathymetric data on NOAA ENCs provided additional coverage in this area, notably in the Sabine Lake and southern Laguna Madre (Figure 2b).

The USACE is responsible for maintaining and dredging the navigational channels. Where available, this dataset is usually the most dense and most recent. However, USACE's bathymetry surveys are only conducted for the major ports and harbors. In the studied area, this dataset covers the major shipping channels and the IntraCoastal Waterways (ICWs) (Figure 2b).

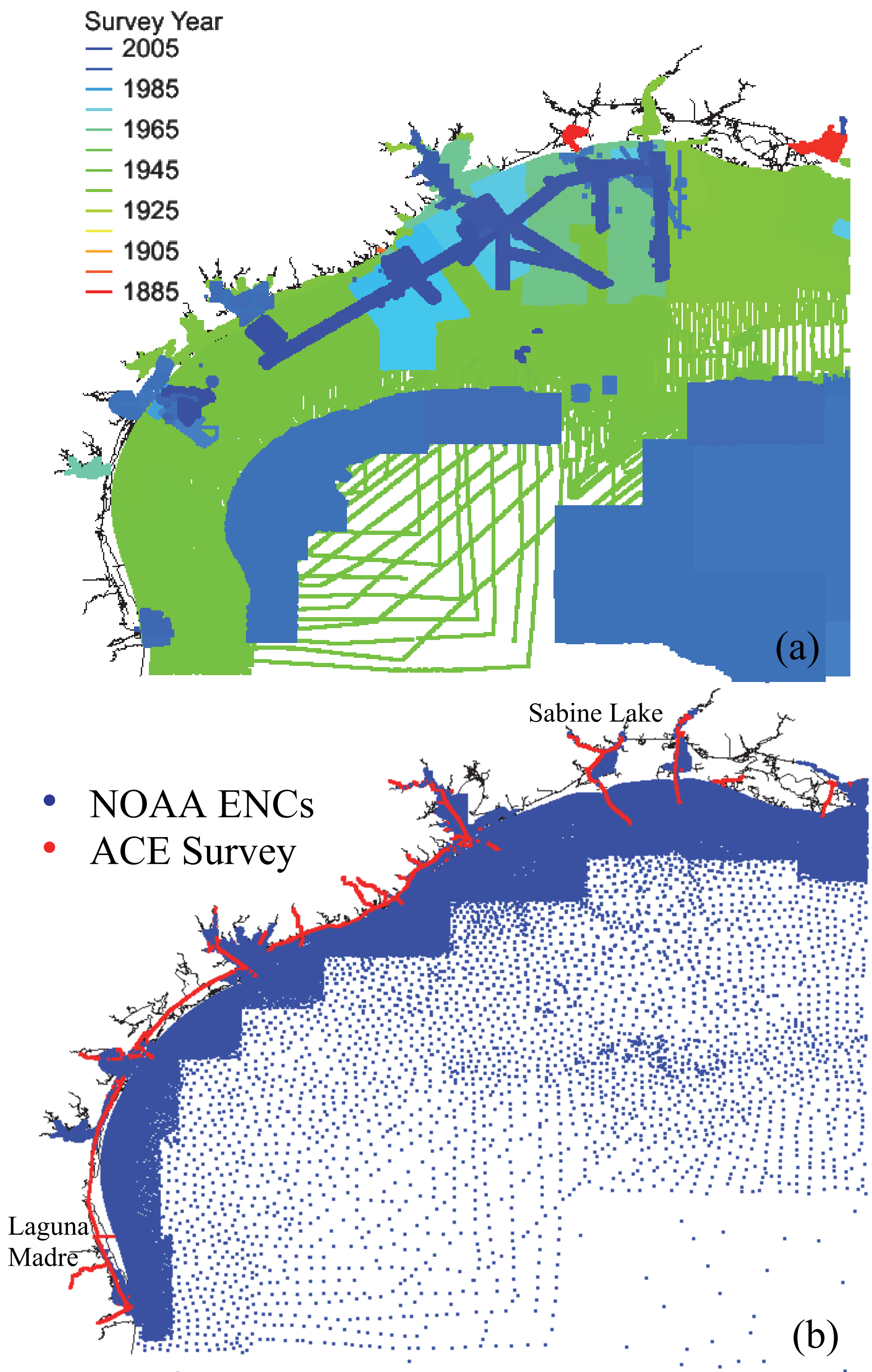

Figure 2. (a) Dates and locations of NOS sounding surveys. (b) The distribution and coverage of the Army Corps of Engineers (ACE) bathymetric survey data (in red) and the NOAA ENC bathymetric data (in blue).

All sources of bathymetric data were used for the best regional coverage. However, they were prioritized based on the data quality as follows: USACE dredging/survey data, NOS sounding, and ENC bathymetric data, from highest to lowest resolution.

2.3. Water level station data

Tidal datums derived from NOAA tide station water level observations were used to validate and correct model results. There are a total of 52 stations in the planned VDatum coverage area from western Louisiana to Texas. The station locations are shown as red squares in Figure 1. In addition, the State of Texas maintains the TCOON, which consists of a number of water level stations along the Texas coast. The 21 stations with accepted tidal datums in addition to the NOAA stations are shown as blue circles in Figure 1. Table A1 in Appendix A lists the NOAA stations and Table A2 lists the additional TCOON stations. Tidal datums are usually listed relative to the present National Tidal Datum Epoch (1983-2001). However, the tidal datums at a number of stations in this region are computed based on the Modified Procedure for Tidal Datum Computation for a reduced 5-year period to account for the fast-changing LMSL due to land subsidence (CO-OPS, personal communication) and these stations are marked with either an ‘a’ (for computation period of 1997-2001) or ‘b’ (for computation period of 2002-2006) in Table A1.

3. TIDAL DATUM SIMULATION

3.1. Hydrodynamic model

The ADvanced CIRCulation (ADCIRC) model (Luettich et al., 1992; Westerink et al., 1994) is a finite element hydrodynamic model which is run on unstructured grids. The ADCIRC model solves the shallow water equations utilizing the Generalized Wave Continuity Equation (GWCE) formulation. It was developed to simulate water level and hydrodynamic circulation along shelves, coastal ocean and within estuaries and has been applied to model tides (Westerink et al., 1993; Luettich et al., 1999; Mukai et al., 2002; Spargo et al., 2004), storm surge (Blain et al., 1998; Westerink et al., 2008; Demirbilek et al., 2008), inundation, and other applications. More detailed information about the model can be found at its website http://www.adcirc.org/.

3.2. Model grid

ADCIRC model utilizes an unstructured triangular grid. The unstructured mesh with variable horizontal resolution allows accurate representation of complex shoreline and bathymetry. The model domain for this project extends from Vermilion Bay, Louisiana, to just south of the U.S.-Mexico border and its adjacent coastal waters, as well as many embayments along the western Louisiana and Texas coasts (Figure 3). The SMS software (http://www.aquaveo.com/sms) was used to generate the high resolution unstructured model grid extending from the MHW shoreline to beyond the continental shelf break offshore (Figure 3a). The grid has a total of 284,217 nodes and 523,047 elements. Generally speaking, the grid resolution increases from the open ocean to coasts and embayments to better represent the complexity in the shorelines and shallow water tidal dynamics. Efforts have been made to include most of the ICWs and resolve the major navigational channels and barrier islands. The grid sizes range from around 40 m for channels/islands, 300 m along the coasts and in the embayments, and to about 30 km in the deeper waters of the open Gulf (Figure 3b).

3.3. Bathymetry on model grid

The bathymetric datasets described in Section 2.2 were used to specify the model grid bathymetry. Bathymetry at each node is specified by the arithmetic mean of data points within the node's surrounding elements. Since element size changes throughout the model domain, the searching ranges for bathymetric data points vary from node to node. As the element size is smaller in coastal waters and increases towards deep oceans, bathymetry for nodes near the coastline were from more locally distributed data points compared to those in deep waters and thus were better resolved. Where the bathymetry is not set by interpolation from data points, the extrapolation is done iteratively by arithmetic mean of the neighboring nodes with valid bathymetric values.

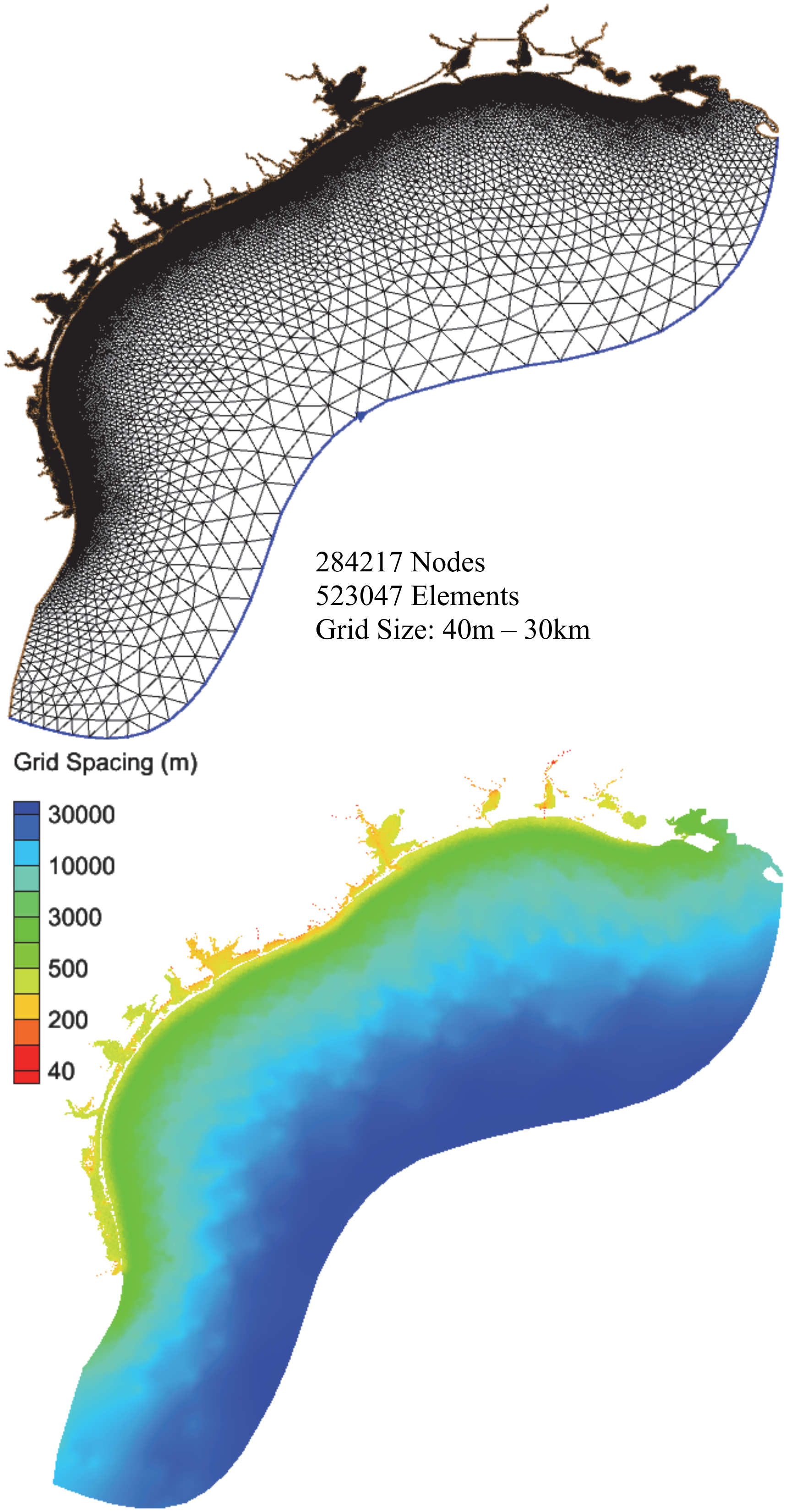

Figure 3. (a) The triangular element model grid for the Texas and western Louisiana coastal waters, and (b) the grid spacing in the model domain.

The original bathymetric data were referenced to either MLLW or MLW. An initial guess of 20 cm and 16 cm for transformation of MLLW and MLW to mean sea level (MSL), respectively, based on the tidal datums at the stations, was used to reference all bathymetric data to MSL. After a stable model run was achieved, the model bathymetry was furthered adjusted based on the modeled tidal datum fields and referenced to the model zero, itself a geopotential surface. This process was repeated iteratively until the tidal datums converged.

The final model bathymetry is shown in Figure 4. The contour intervals are not of equal values so that the shallow regions along the coast and the continental shelf break can be better resolved. In the model domain, the southern Texas shelf has a much steeper slope while approaching Louisiana the shelf becomes broader and has a gentler slope in the northeast. Because semidiurnal tides tend to get amplified across a wide shelf (whereas diurnal tides do not) (Clarke and Battisti, 1981), the difference in the shelf geometry will be manifested in the tidal characteristics. Figure 4b shows a close-up view of the bathymetry in Galveston Bay (GB). The resolutions of both the bathymetric data and model grid were fine enough to represent the shipping channels in GB and the ICWs connecting GB to its adjacent water bodies in the model.

3.4. Model Configurations

The ADCIRC model can be run in either two- or three- dimensional mode. To simulate tides for computing tidal datums, the model was run in the two-dimensional barotropic mode with wetting and drying.

Tidal potential body force of eight major diurnal and semidiurnal constituents (K_1, O_1, P_1, Q_1, M_2, S_2, N_2 and K_2) was included in the model. Water elevations constructed from the same eight constituents were also applied at the open ocean boundary. Various global and regional tidal databases can be used to provide the open boundary conditions. We examined the ADCIRC EC2001 (Jesse Feyen, per. comm.; see also Mukai et al., 2002), and Oregon State University's (OSU's) TPXO global tide solution and the Gulf of Mexico (GOM) regional model using OSU's tide prediction software (OTPS) (Xu and Myers, 2010). The amplitudes of the two major diurnal tidal constituents K_1 and O_1 in EC2001 are about 2 cm greater than the OSU-GOM solution (Figure 5), which is consistent with the amplitude error of K_1 and O_1 in EC2001 at the National Data Buoy Center DART buoy station 42409 in eastern GOM (Figure 6). Based on the comparisons of different databases along the open boundary and the model responses (results not shown), the OSU-GOM model was used to force this model at the open ocean boundary.

A series of model sensitivity studies on the GWCE weighting factor TAU0 and different bottom friction formulation and coefficients were carried out for better tuning of the model for a more realistic simulation of the tidal dynamics in the studied region (Xu and Myers, 2010). For each test run, the model was evaluated against observed major harmonic constants and tidal datum fields. A spatially uniform TAU0 of 0.02 and quadratic bottom friction coefficient of 0.002 were used in the final model runs.

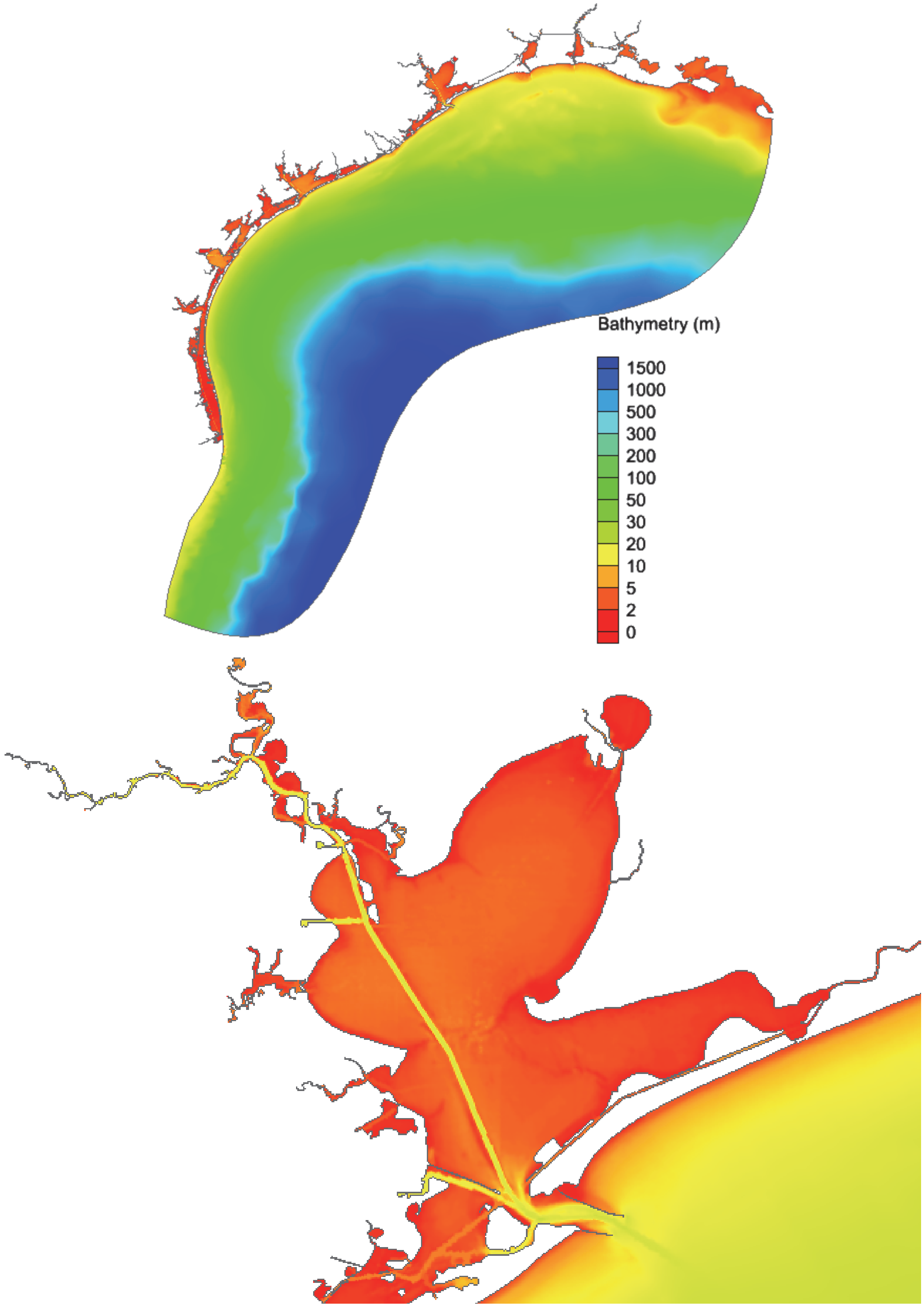

Figure 4. (a) The model bathymetry for the whole domain. (b) A close-up view of bathymetry in Galveston Bay.

Neither atmospheric forcing nor river flow was imposed. Lateral viscosity was set as a constant, 5.0 ms^{-2}, throughout the model domain. A 3-second time step was used for computational efficiency and model stability. The final model set-up including all model input files are archived along with modeled tidal datums output, correction and quality control tests in the VDatum project archive.

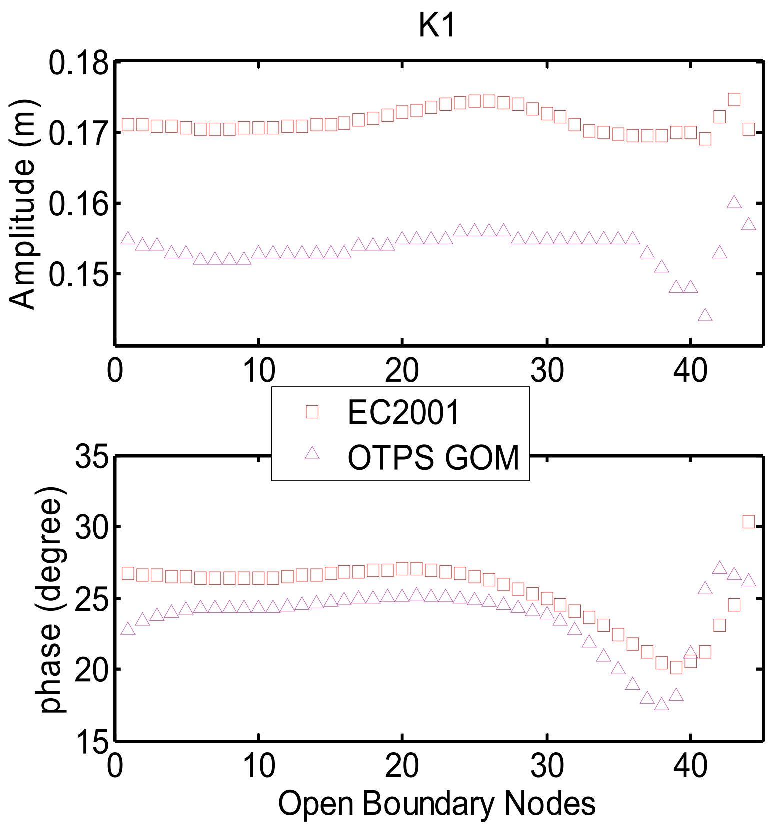

Figure 5. The K_1 amplitude and phase comparison between EC2001 and OTPS GOM model along the open ocean boundary. The OSU-GOM model values were selected to force the model at the open ocean boundary.

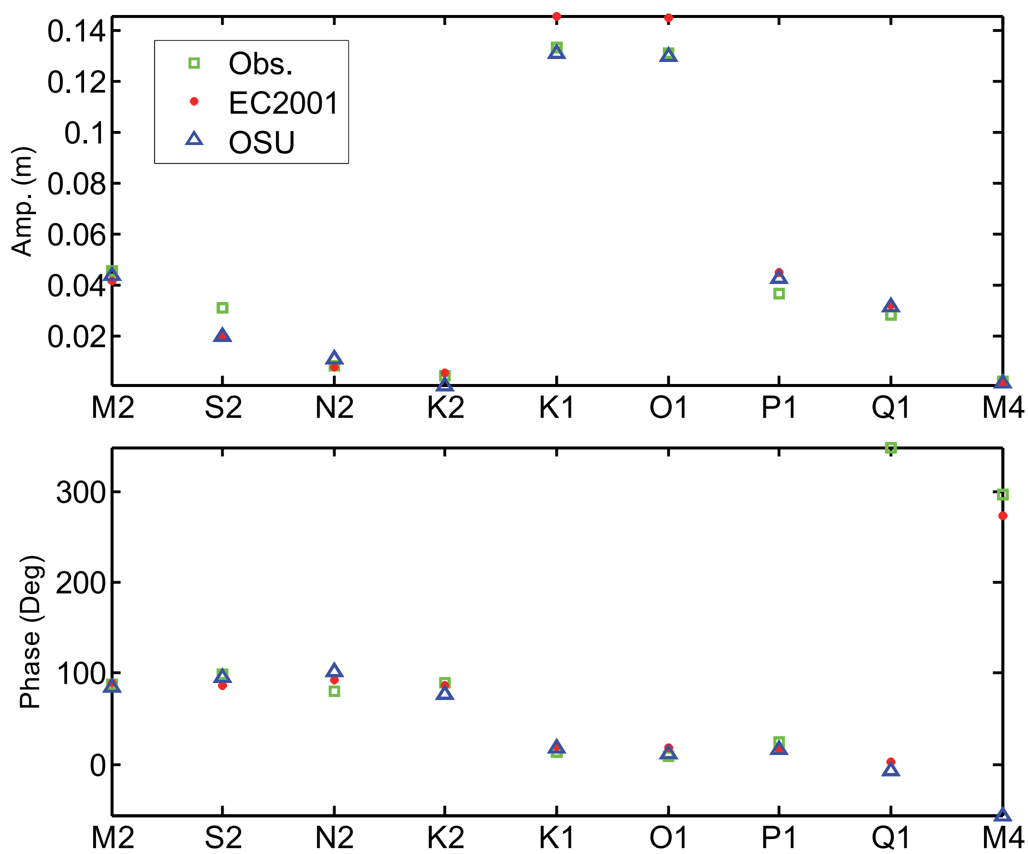

Figure 6. The comparison of the common harmonic constants between the EC2001 and OSU GOM models and from the NDBC buoy 42409, at the location of the buoy.

4. MODEL RESULTS, VALIDATION AND CORRECTION

The model was run for 67 days with a 7-day ramping using a hyperbolic tangent function. The 6-minute water level time series were stored for the last 60 days for computing tidal datums and harmonic analysis.

4.1. Harmonic constituents

Figure **7** shows the amplitude and phase distribution in the whole domain for K_1 and M_2. Both K_1 and M_2 propagate through the region in a counter clockwise manner. K_1 amplitudes are somewhat uniform across the southern Texas shelf, with a slight increase over the broader shelf towards the entrances to the Sabine and Calcasieu Lakes in the north. M_2 amplitudes are generally stronger approaching the shoreline and are amplified by over 10cm crossing the wider shelf in the north. Both K_1 and M_2 are damped in the numerous embayments along the coasts. In Calcasieu Lake, Sabine Lake, Galveston Bay, Matagorda Bay and Corpus Christi Bay there are still sizeable tides. However, a large portion of Laguna Madre shows very small water level variations in our tidal simulations and is classified as non-tidal by CO-OPS.

Harmonic constants of the 37 NOS standard tidal constituents are available at 34 of the 52 NOAA and TCOON tide stations in the model domain (marked by * in Table A.1). The comparison between the modeled and observed harmonic constants from two major diurnal constituent (K_1 and O_1) and two major semi-diurnal constituents (M_2 and S_2) displays reasonably good agreements for both amplitude and phase (Figure 8). Note that the constituents K_1 (red squares) and O_1 (blue asterisks) are of similar magnitude and are the dominant tidal components at most stations. However, the amplitudes of M_2 (green triangles) vary considerably among the stations and are comparable to K_1 and O_1 at some stations. S_2 (magenta diamonds) amplitudes are quite small (<5 cm) at all stations. The amplitude errors of all constituents are within 5cm. The spatial distribution of the amplitude errors for K_1 and M_2 are shown in Figure 9. The color scale indicates the magnitude of the error and model overestimation is shown as a circle and underestimation as a triangle. For both the diurnal and semidiurnal constituents, no particular spatial pattern is observed in the error distribution over the whole model domain. However, there is a fairly consistent underestimation of both K_1 and M_2 in Galveston Bay. Imposing a smaller bottom friction coefficient for the whole domain improved the results in Galveston Bay but compromise the results in other places, so it was not applied in the final model runs. A more reasonable and complicated approach utilizing the bottom type determined Manning formulation for bottom friction may be necessary to further improve the overall model performance. The mean absolute amplitude errors at all stations are 1.4, 1.3, 0.7 and 0.3 cm for K_1, O_1, M_2 and S_2, respectively.

Modeled phases of K_1, O_1 and M_2 agree with observation very well (Figure 8b). The mean absolute phase errors are 9, 7, 13 and 23 degrees (or 0.5, 0.5, 0.4 and 0.5 hours) for the same four tidal constituents. Considerable discrepancies are shown in S_2 phases. Given the small amplitudes of S_2, the relatively larger phase errors in S_2 do not contribute much to the total tidal errors.

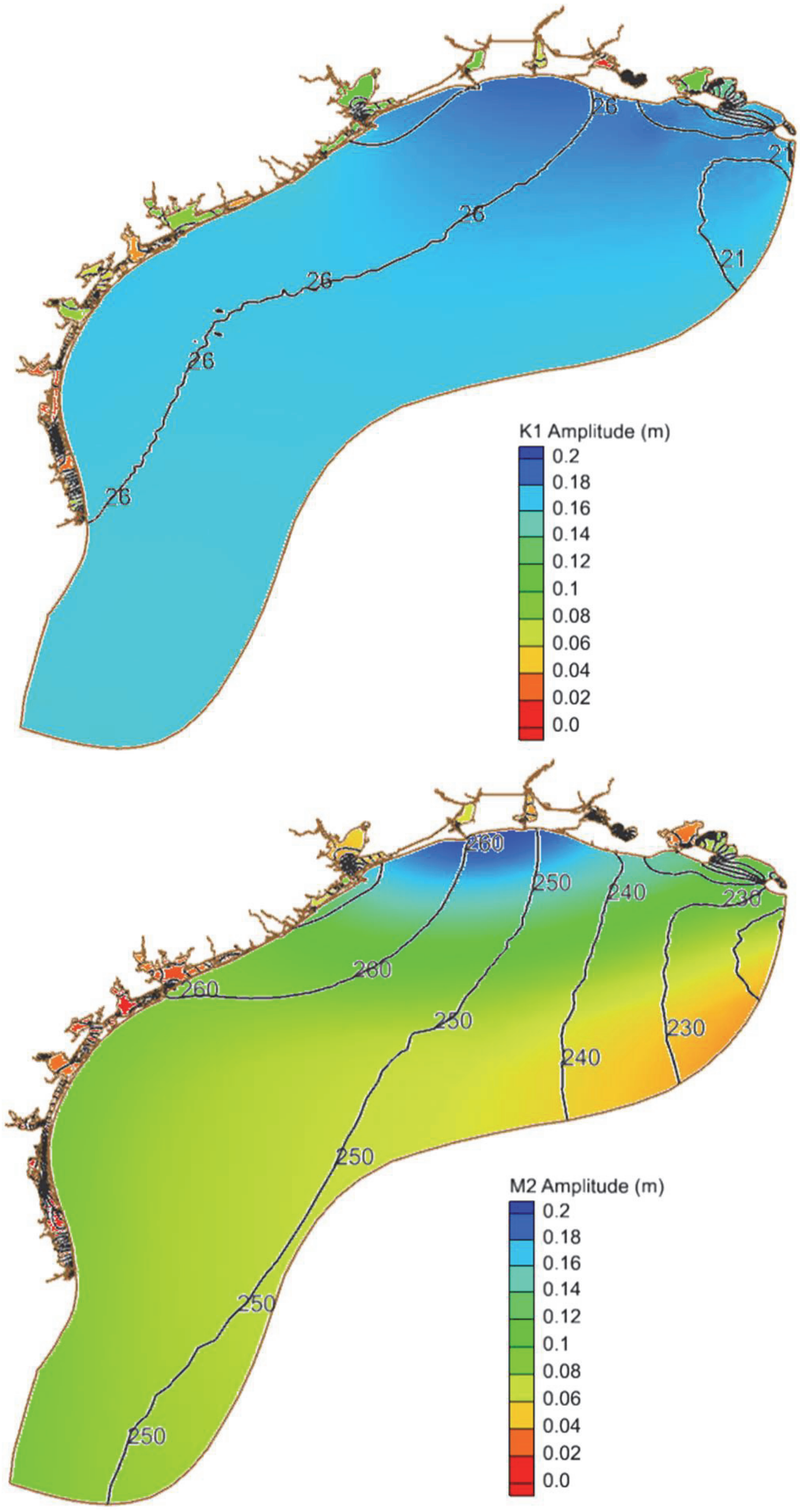

Figure 7. The Co-amplitude (in color) and co-phase (contours) charts of (a) K_1 and (b) M_2 over the whole model domain.

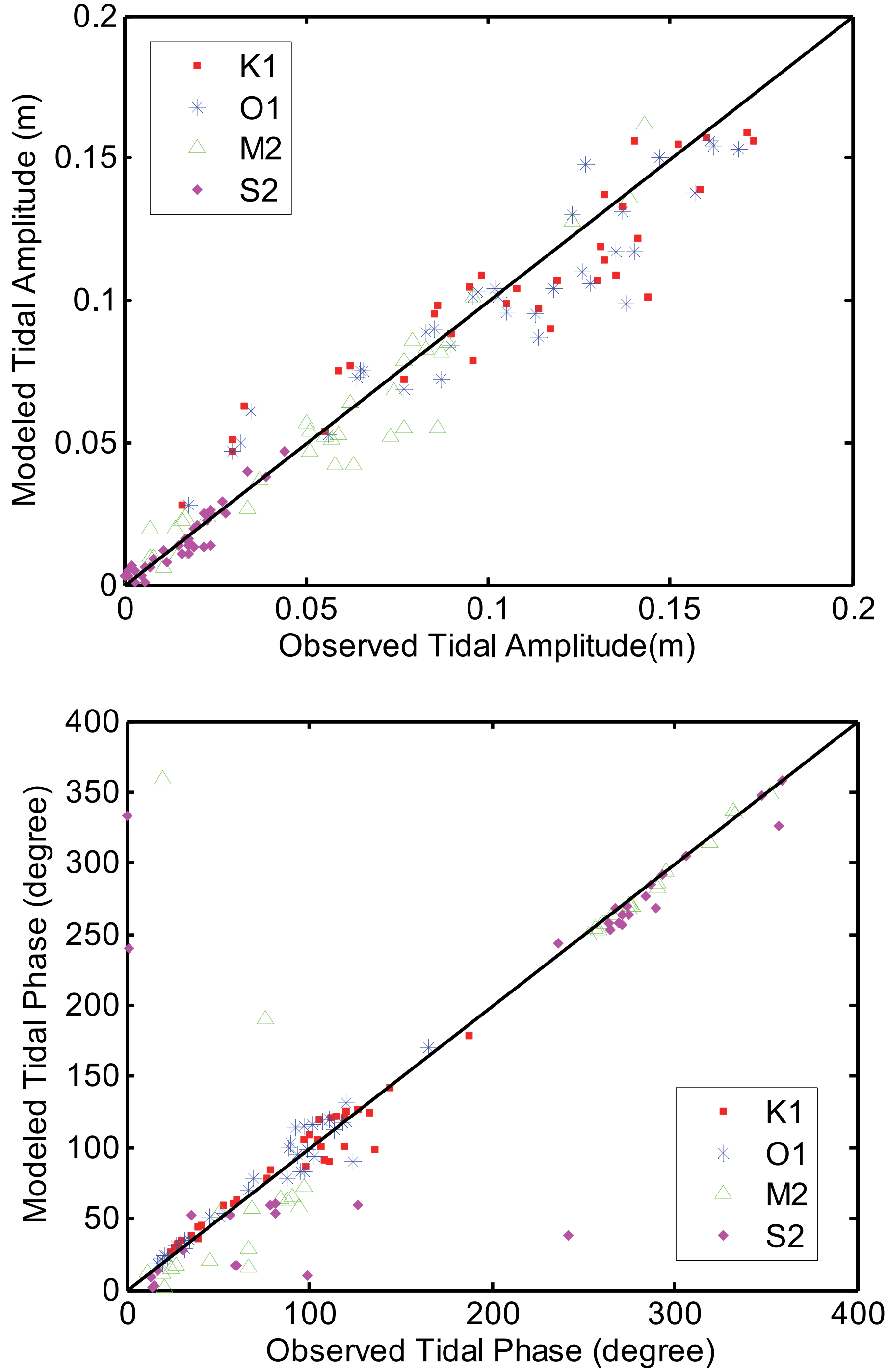

Figure 8. The modeled and observed (a) amplitudes and (b) phases of K_1 (red square), O_1 (blue asterick), M_2 (green triangle) and S_2 (magenta diamond) at 34 tide stations.

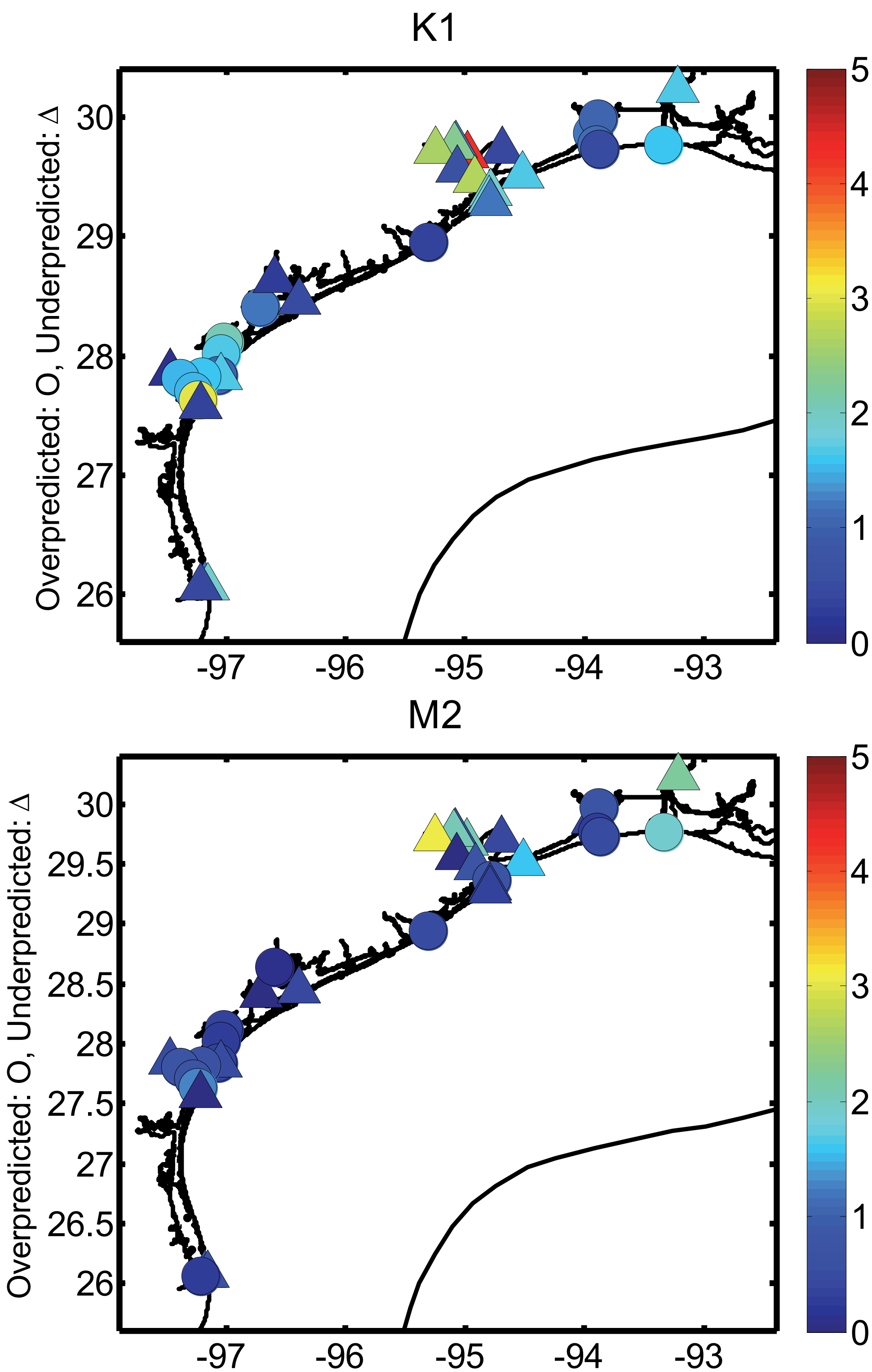

Figure 9**.** The spatial distribution of amplitude error (in cm) in K_1 and M_2 in the model domain.

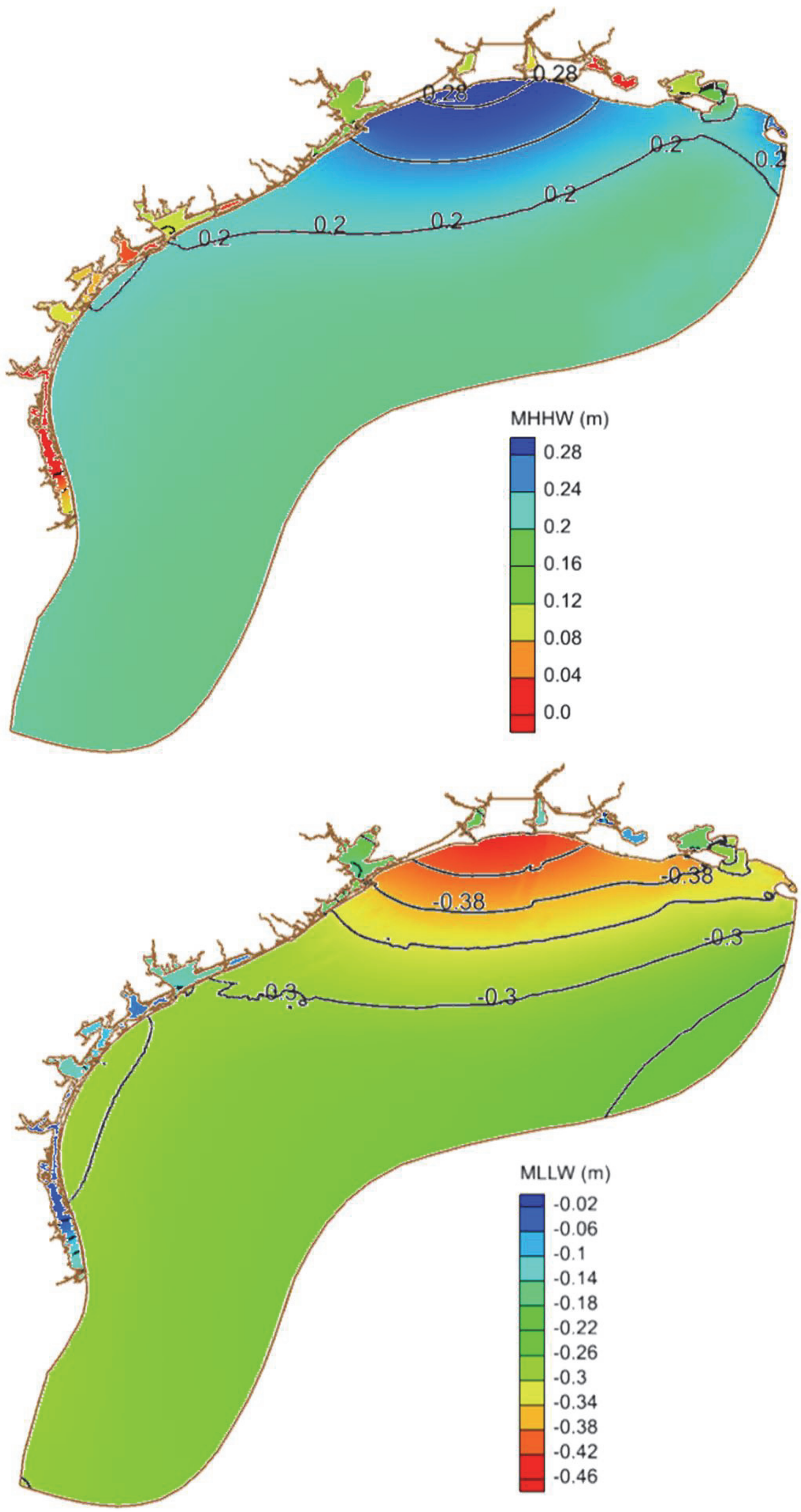

Figure 10. The modeled MHHW and MLLW (relative to MSL in m) over the whole model domain.

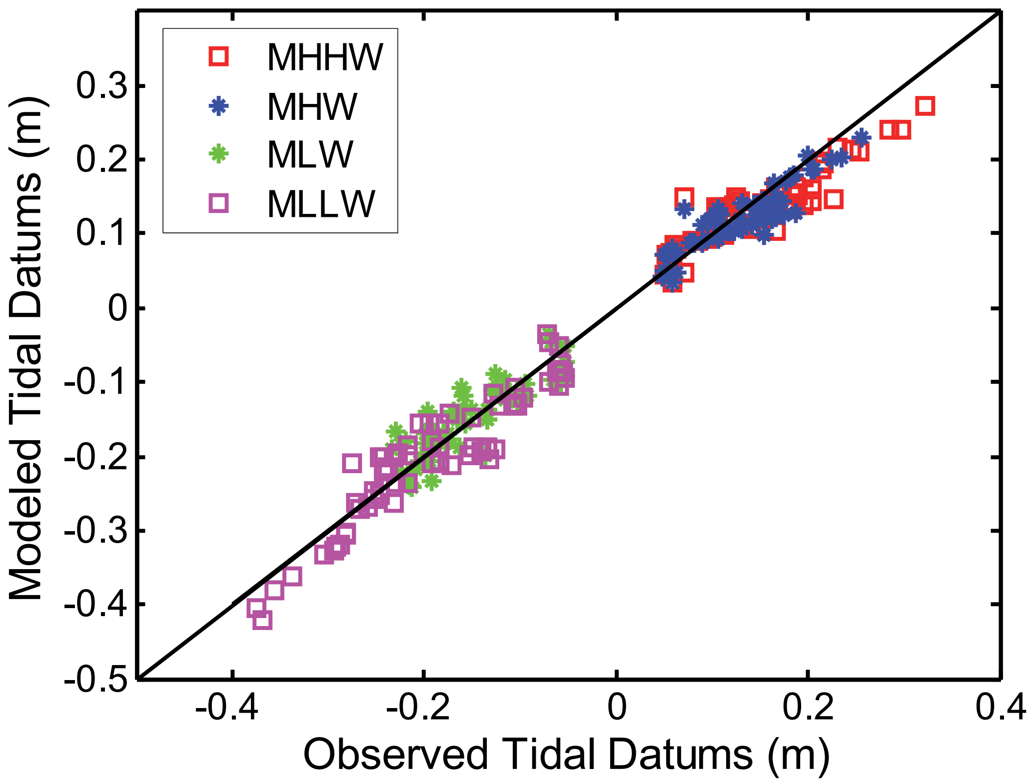

Figure 11. The modeled and observed MHHW, MHW, MLW and MLLW (all relative to MSL) at 71 stations.

4.2. Tidal datums

For the development of VDatum in this region, tidal datum fields of MHHW, MHW, MLW and MLLW are calculated from the water level time series at each node. The four tidal datum fields exhibit a similar spatial pattern. Figure 10 displays modeled MHHW and MLLW for the whole domain. Across the southern Texas shelf, tidal datums are roughly uniform. Across the northern Louisiana-Texas shelf, MHHW increase from ~0.16 m at the open boundary to 0.28 m near the coast, while MLLW changed more rapidly from -0.26 m to -0.42 m.

4.2.1. Model-observation differences

Figure 11 illustrates model-data comparisons for MHHW, MHW, MLW, and MLLW relative to MSL. The black line shows the one-to-one correlation. In general, the comparisons exhibit good model-data agreement. Due to the dominance of the diurnal signal, the difference between MHHW and MHW, and between MLW and MLLW are generally quite small and at some stations they are even identical. Over the 73 stations, magnitudes of the absolute model-data differences are averaged to be 2.46 cm, 1.89 cm, 2.18 cm, and 2.96 cm for MHHW, MHW, MLW, and MLLW, respectively. The root mean squared errors for all four tidal datums are 3.10 cm, 2.42 cm, 2.73 cm, and 3.53 cm. Of the four tidal datums, the largest discrepancy shows up in MLLW, which probably is related to the difficulty in calculating low waters from the modeled water level when ponding and drying happen over very shallow waters and the lack of accurate bathymetric data. Table 1 also lists the range (Min and Max), bias (the difference between the modeled mean and observed mean) and the standard deviation of the error fields of each tidal datum.

Table 1. Statistics of the tidal datum errors (in cm) at all stations.

Error Field	Min	Max	Mean (Bias)	Mean of absolute error	Standard Deviation	Root Mean Squared Error
MHHW	-7.68	7.81	-0.89	2.46	2.97	3.10
MHW	-5.57	6.31	-0.18	1.89	2.42	2.42
MLW	-7.51	4.47	-0.78	2.18	2.63	2.73
MLLW	-7.36	6.67	-1.29	2.96	3.30	3.53

4.2.2. Differences at the connecting boundary from the adjacent VDatum area

The model domain of the current VDatum project overlaps with the previous VDatum project for the Mississippi and eastern Louisiana coastal waters (Yang et al., 2010). To ensure a seamless VDatum coverage and smooth transition from one VDatum region to the next, the current VDatum coverage for this project will connect with the existing VDatum area, and the datum transformations along the shared boundary need to match the existing ones.

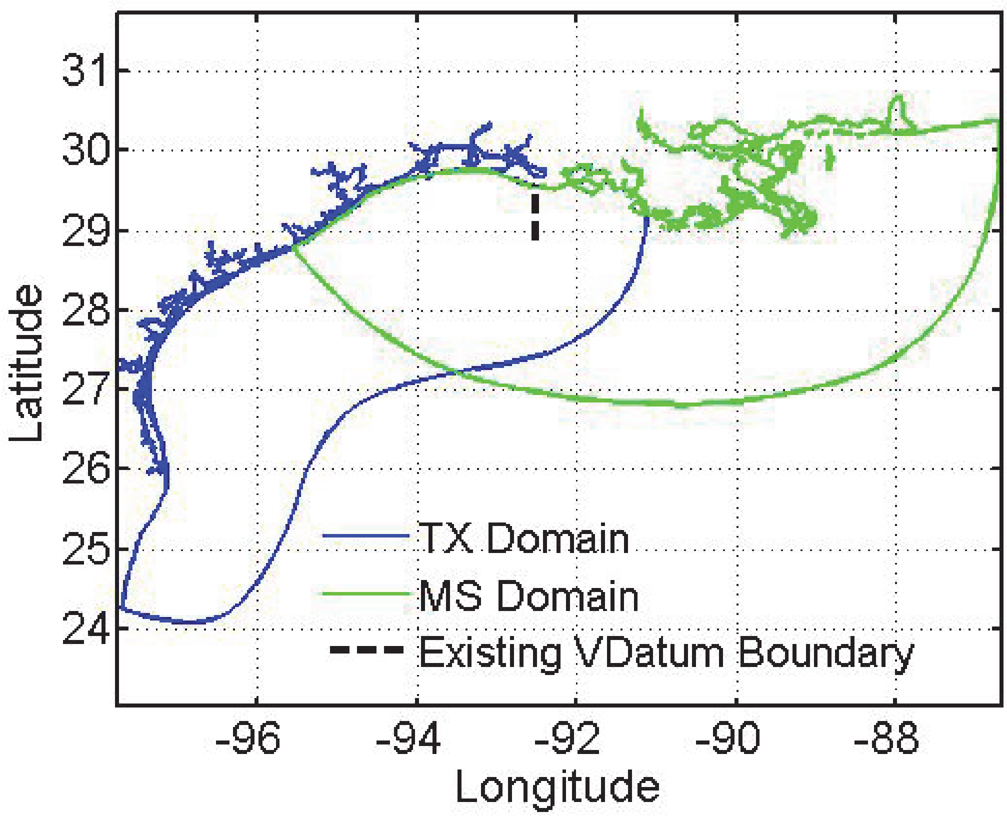

Figure 12. The ADCIRC model domains for the Texas (TX) and Mississippi (MS) VDatum projects. The dashed black line delineates the western boundary of the MS VDatum coverage.

Figure 12 illustrates the tidal model domains developed for both of these VDatum applications, as well as the shared boundary of the VDatum marine grids. We first examined the tidal datum differences between current model and existing published VDatum values at the shared boundary. The differences are then incorporated in the TCARI correction as discussed below to ensure smooth transition.

4.3. Modeled tidal datum correction

The tidal datum results from the model generally agree well with the CO-OPS water level station data at most locations. However, they are not expected to match exactly, and at certain stations the discrepancy can be up to 8 cm. The results presented above are accepted with the understanding that i) the model simulates the astronomical tides only, while the station data includes non-tidal river flow, ocean circulation and meteorological effects, ii) the bathymetric data coverage around some stations are sparse (and sometimes not available) and/or outdated, and iii) the grid resolution may not be enough in some small rivers/embayments.

To eliminate the model-data difference at the stations and to match existing VDatum tidal transformation across the project boundary, the TCARI program (Hess et al., 1999; Hess, 2002; Hess, 2003) was applied to spatially interpolate the error fields. TCARI may be run using either structured or unstructured grids. A version of TCARI written in the Python computer language and based on use of an unstructured grid (Barry Gallagher, personal comm.) was used in this application.

To run TCARI, both the observational stations and locations along the domain boundary are treated equally as control stations. For each tidal datum, both model-data differences at the tidal stations and across-boundary discrepancies between current model results and existing VDatum results for eastern Louisiana (Yang et al., 2010) were computed and input to TCARI.

The error fields for MHHW, MHW, MLW, and MLLW derived from TCARI were then added to the model results to get the final tidal datum elevations for VDatum. These TCARI-corrected results match the tide station data at the included stations and seamlessly connect to the existing adjacent VDatum region to the east.

However, with the addition of the TCARI correction fields, the final tidal datums became invalid at certain locations within the domain in the following four cases: 1) the MHHW or MHW becomes negative; 2) the MLLW or MLW becomes positive; 3) MHHW is lower than MHW; and 4) MLW is lower than MLLW. In the first two cases, all four tidal datums at that node are treated as invalid and the tidal datums at these nodes are interpolated from neighboring nodes. In the last two cases, the MHHW and MHW, and the MLW and MLLW are assigned with their averages, respectively. The issue appears to be new and unique to this region for two reasons. Firstly, the tidal range in this region is small. The first two cases usually happened over the area within the CO-OPS defined non-tidal zones, where the tidal datum transformations will be reassigned according to the hydrographic survey conventions for non-tidal regions (see discussion in Section 5.2). Secondly, because of the overall dominance of diurnal tides, the MHHW and MHW, and MLW and MLLW tend to be close to each other or even identical.

Therefore, slightly different correction fields could change the relative magnitudes of the two high or low tidal datums.

Figure 13 and Figure 14 illustrate the extent of where adding back the correction fields resulted in MHHW being lower than MHW, and MLLW being higher than MLW, respectively, and their magnitudes. In the corrected tidal datum fields, MHHW could be below MHW by up to 0.2 cm (Figure 13) and MLW could be below MLLW by up to 3 cm (Figure 14). In Figure 14a, the nodes located in the open ocean have MLW below MLLW by less than 1 cm and are of less concern because they reside outside of the marine grid bounding polygon (See Section 5.1) and will not affect the final tidal datums defined on the marine grids. Inside Calcasieu Lake (Figure 14b) the corrected MLW is lower than MLLW by 0.2 to 2 cm. Figure 15 shows that the difference between MLW and MLLW is quite small for most of the areas within the model domain. The maximum difference occurs over the broader shelf off Sabine Lake and Calcasieu Lake due to the greater amplification of semidiurnal tides. Within Calcasieu Lake, the modeled MLW is only about 0.2 to 1 cm above MLLW. The decision of assigning the averages to the two tidal datums is based on the small differences between the MHW and MHHW, and MLLW and MLW fields in both corrected and the original modeled results. As a result, the final tidal datum fields used to populate the marine grid will have identical MHW/MHHW or MLW/MLLW in the areas where adding back the TCARI correction fields caused inversion. Using averaged values also ensures a smooth transition from the areas with normal corrections to the areas discussed above.

Note that the other two tidal datum fields, the MTL and DTL, were produced in a different way. They were derived from the four corrected datums by taking the averages between MHW and MLW and between MHHW and MLLW, respectively. This is the accepted procedure for determining these datum elevations (Gill and Schultz, 2001).

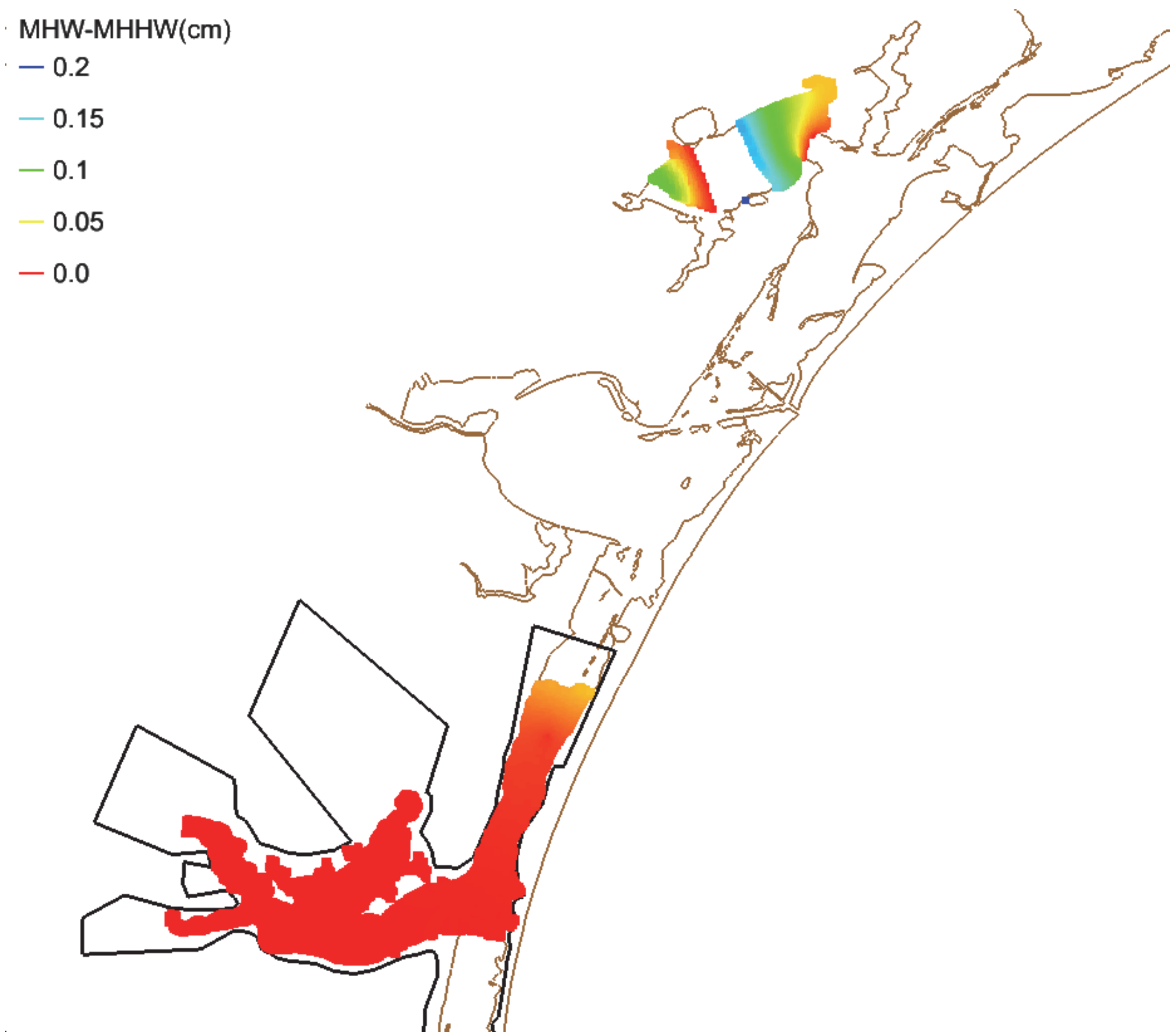

Figure 13. The differences (in cm) between corrected MHHW and MHW when MHW>MHHW. The maximum is about 0.2 cm.

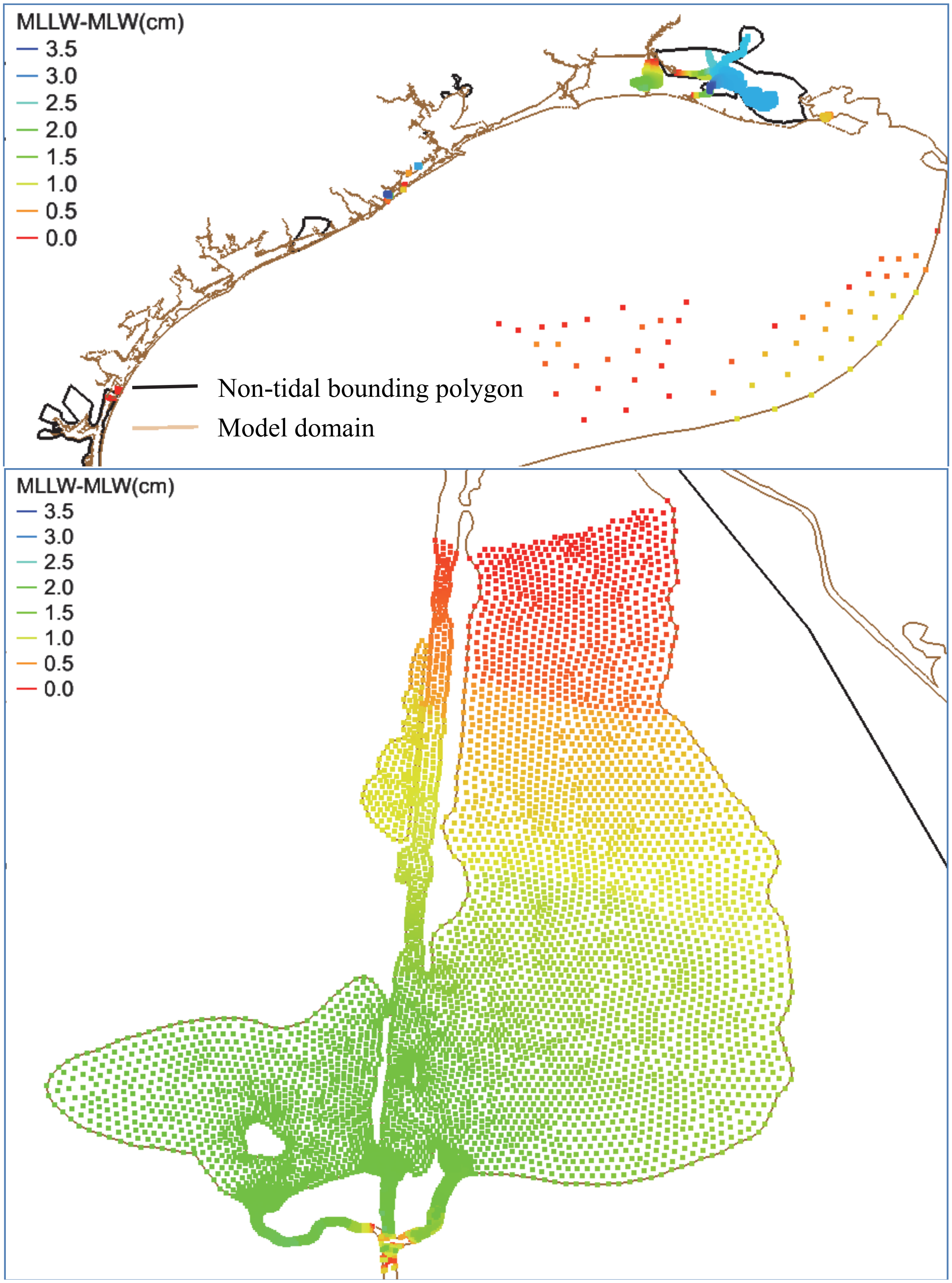

Figure 14. (a) The differences (in cm) between corrected MLLW and MLW when MLLW>MLW. (b) A close-up view of Cacalsieu Lake, Louisiana. The maximum difference inside the Lake is about 2 cm.

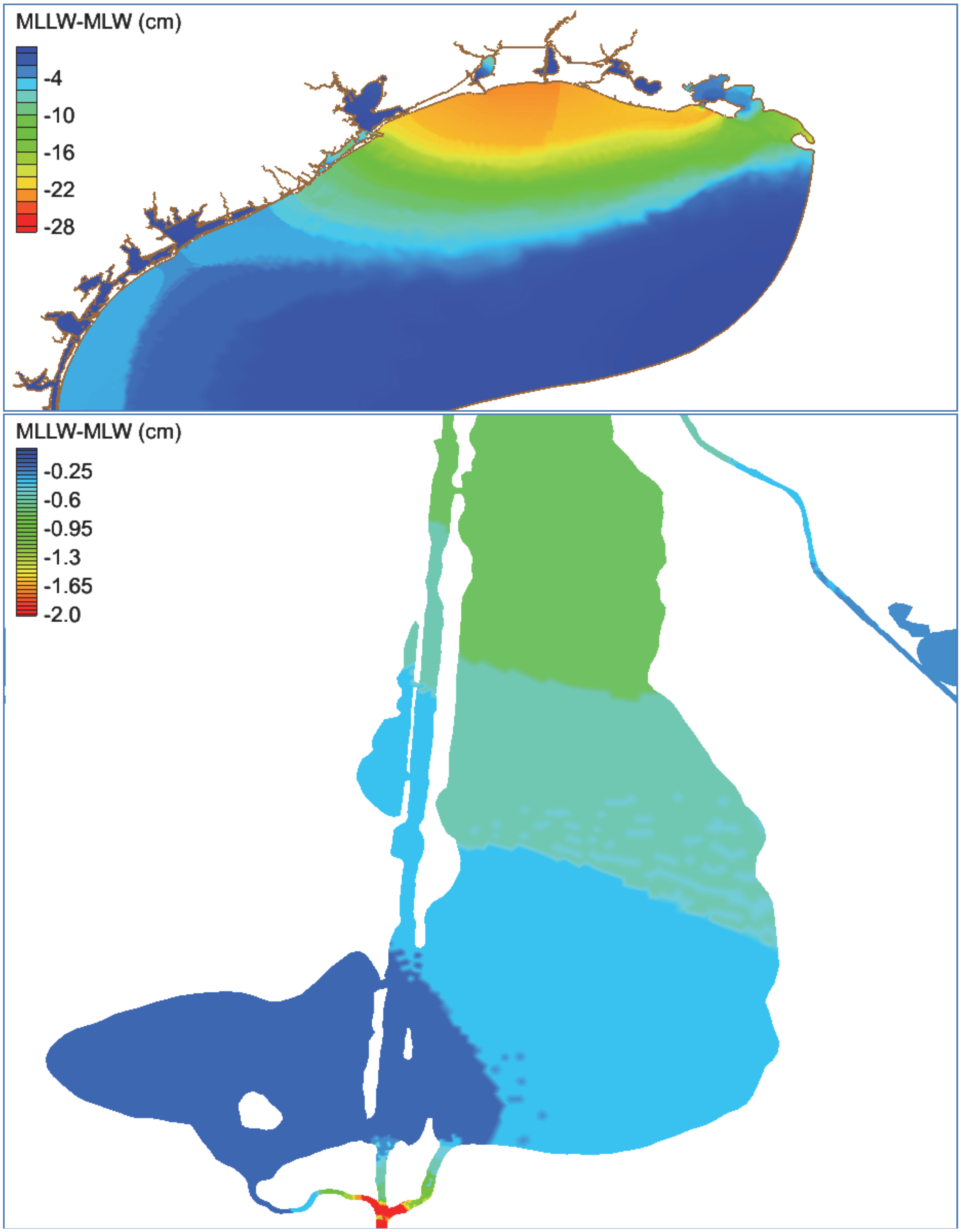

Figure 15. (a) The differences (in cm) between modeled MLLW and MLW. (b) Close up view of Calcasieu Lake, Louisiana (inside the Lake, the differences range from 0.2 to 1 cm).

5. CREATION AND POPULATION OF THE MARINE GRID

5.1. Creation of VDatum marine grid

Tidal datums in the VDatum software are defined on a regularly structured grid called the VDatum marine grid. Due to the large size of the domain and the existence of extensive barrier islands in this region, a set of five marine grids was generated to cover the whole region (Figure 16). Each node in the marine grid is designated as either a water node or a land node based on the high resolution coastline described in Section 2.1 and the bounding polygons. The bounding polygons are designed not to interfere with the water-land designation based on the actual shoreline but to constrain model extrapolation of tidal datums to regions where the results cannot be validated and/or published with sufficient accuracy. Examples of such areas include upper reaches of rivers and narrow waterways, as well as areas that are not included or sufficiently resolved in the tide model. The bounding polygon may also be used to restrict, where necessary, the extra padded zone which normally extends inland a certain distance (Figure 16) from the shoreline.

Three extra layers of VDatum coverage (extending from the shoreline inland) were padded along the shorelines initially when creating the marine grids. All nodes outside the bounding polygon were treated as land nodes. However, NGS further padded two extra layers along all peripherals of the valid marine cells to assist their work on determining shoreline from aerial imagery and lidar. Close examinations were made to determine if ambiguity exists in extending the VDatum transformation coverage while accommodating NGS' requirements.

The water nodes of the marine grid are populated with valid tidal datum values and the land nodes are assigned null values. Even though the marine grid coverage for each region may overlap with each other, the marine cells normally are not valid in more than one region. Exceptions were made along the narrow barrier islands where valid cells are allowed to go beyond the bounding polygon boundary (Figure 17). In Figure 17, the blue and red dot-dashed lines represent the bounding polygons which seamlessly cover the intended area but allow no overlap of adjacent regions. The black and green solid lines delineate the actual boundaries of the valid (water) marine cells for region 2 and 3, respectively, which extend slightly beyond the corresponding bounding polygons. Therefore, for these regions, there could be two different sets of tidal datum values over the cells around the boundaries defined by the adjacent bounding polygons. Therefore, it is possible for NGS to get slightly more yet necessary coverage beyond the stringent constraints of bounding polygons over the narrow barrier islands. However, the bounding polygons are enforced in the VDatum software to determine the appropriate marine grid region for datum transformations.

Marine grid points are equally spaced within each region. The resolution of each marine grid is set to be 0.001 degree in both zonal and meridional directions, which is the same resolution as the existing VDatum marine grid for the adjacent Louisiana region to the east. Details of each marine grid boundary limits and grid size information are listed in Table 2.

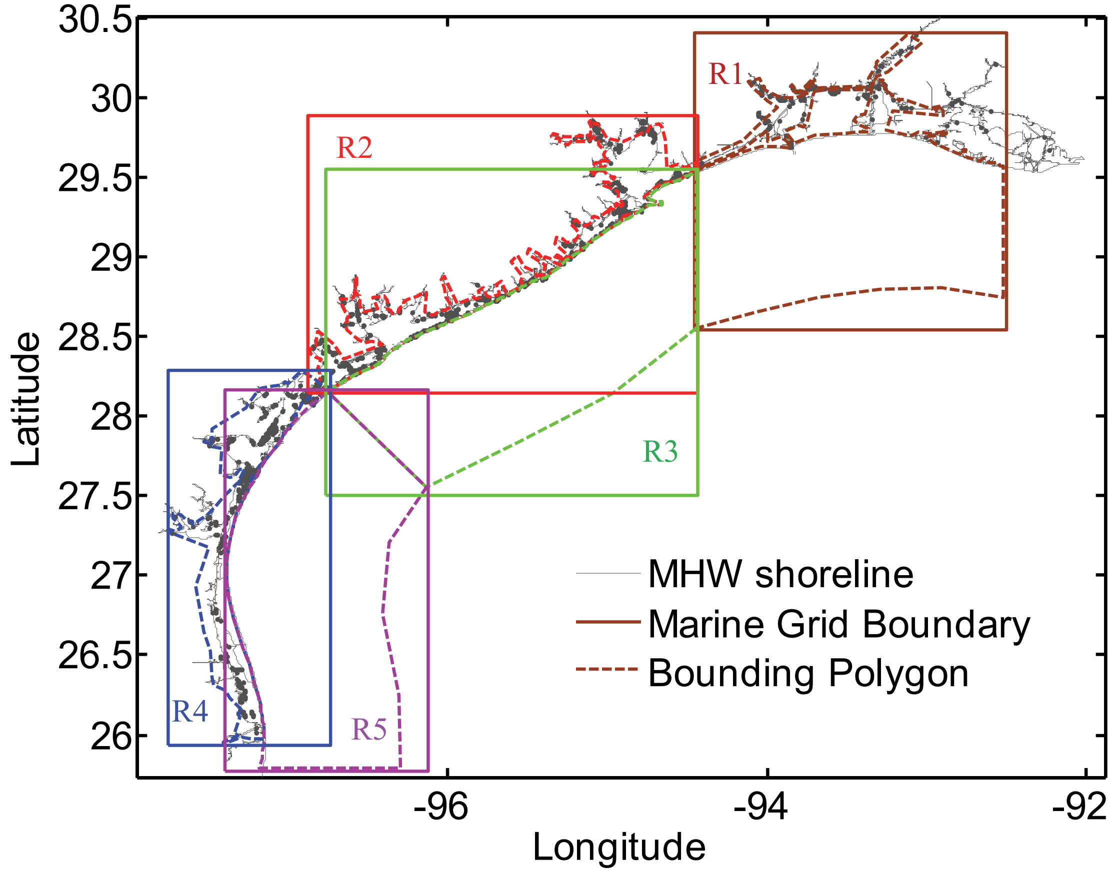

Figure 16. The delineation of the five marine grid regions and their corresponding bounding polygons.

Table 2. VDatum marine grid information for the five regions.

VDatum Region	Lon.-Lat Window	Horiz. Spacing (deg)	Vertical Spacing (deg)	No. of Horiz. Nodes	No. of Vertical Nodes
R1	[-94.45 -92.499 28.54 30.406]	0.001	0.001	1952	1867
R2	[-96.875 -94.43 28.149 29.89]	0.001	0.001	2446	1742
R3	[-96.765 -94.43 27.5 29.55]	0.001	0.001	2336	2051
R4	[-97.76 -96.739 25.93 28.288]	0.001	0.001	1022	2359
R5	[-97.4 -96.125 25.77 28.167]	0.001	0.001	1276	2398

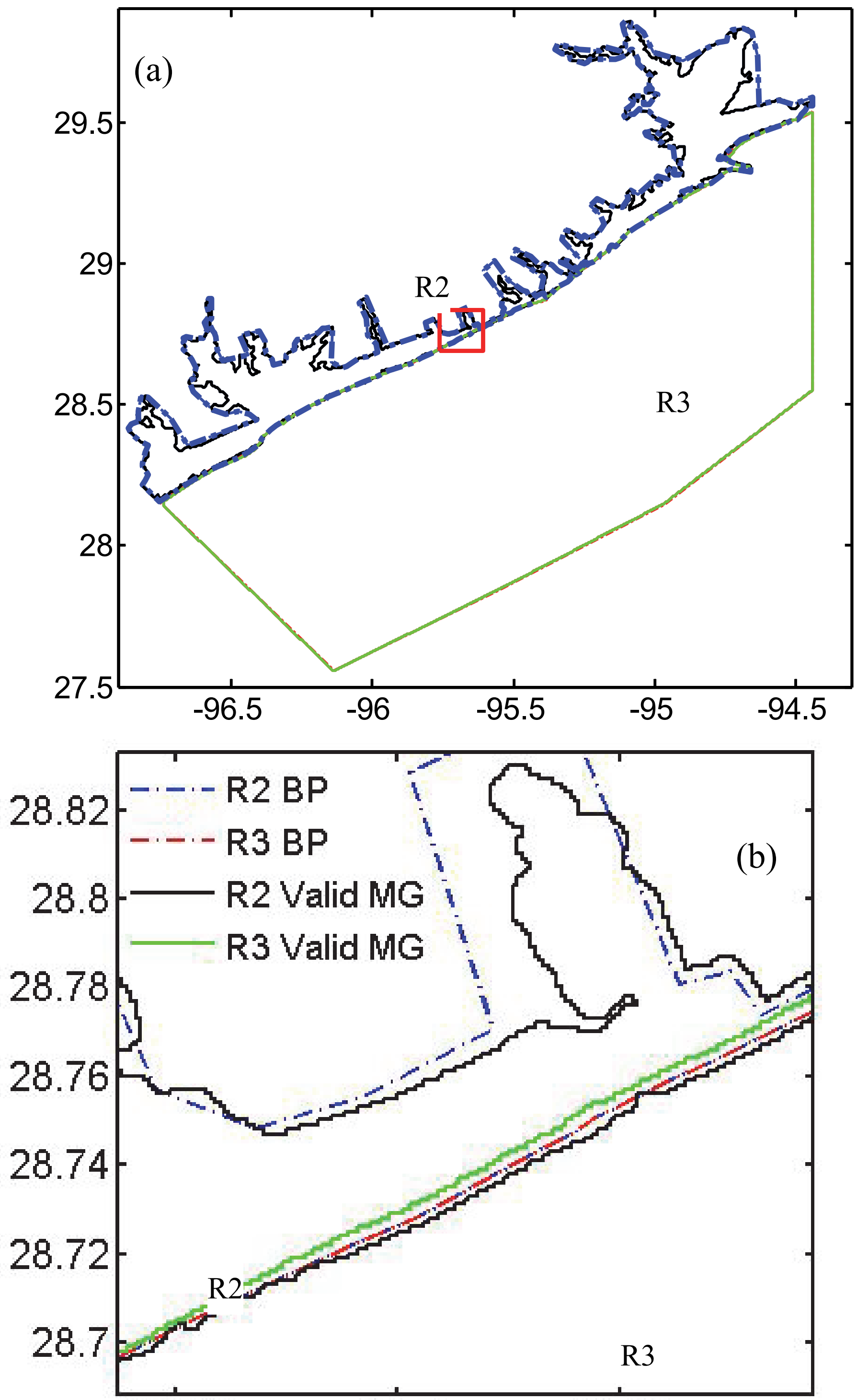

Figure 17. (a) The bounding polygons (dot dashed lines) and boundaries of valid marine grid cells (solid lines) for Regions 2 and 3. (b) A close-up view of the area shown in red square in (a) showing the overlap of valid marine grid cells over the narrow barrier island.

5.2. Incorporation of non-tidal zones in VDatum

CO-OPS defines an area as non-tidal if the Great Diurnal Tide Range (GT) falls below 0.09 m (0.3 feet) (Gill et al., 1995) or the tidal signals are masked out by non-tidal forcings. In non-tidal areas, MLLW is no longer used as the official Chart Datum. Instead, Low Water Datum (LWD) is used and is defined as 0.50 feet below Mean Water Level (MWL) (which is used in areas of little or no range of tides and calculated analogously as MSL). It was decided that in VDatum, the difference between each tidal datum and the MWL will be set to zero. It is also planned that a message will inform VDatum users that MWL is actually used when attempts are made to transform data within non-tidal area to any tidal datums.

A set of non-tidal bounding polygons for U.S. coastal waters were provided by CO-OPS. The non-tidal areas within the current VDatum project are shown as blue bounding polygons in Figure 18. These non-tidal zones include the Grand Lake and White Lake in western Louisiana, and a few areas off Galveston Bay, part of East Matagorda Bay, and Laguna Madre in Texas.

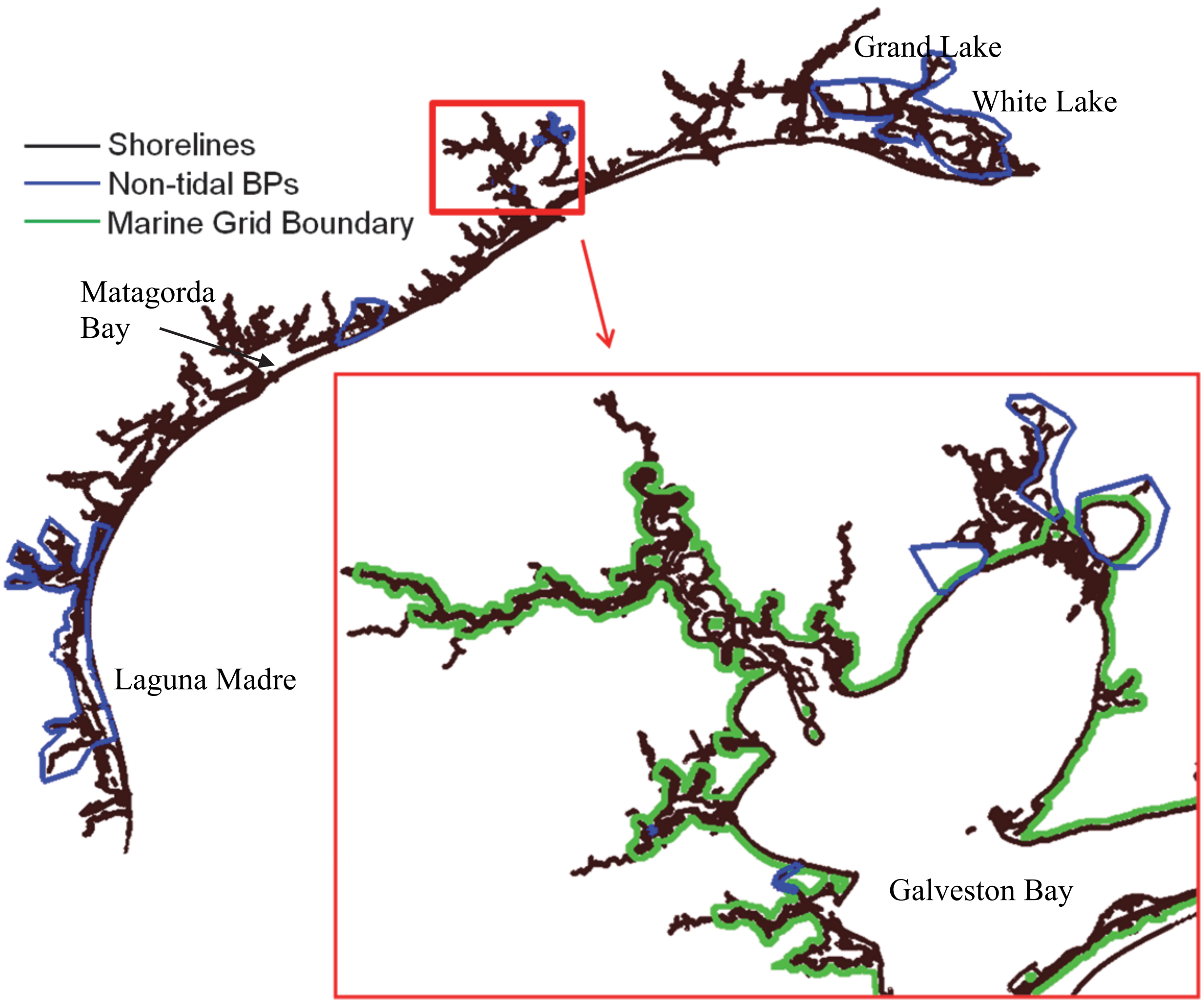

Figure 18. Non-tidal bounding polygons in Texas and western Louisiana. The inlet shows a close-up on Galveston Bay, Texas, with marine grid water cells boundary (green line).

The inset of Figure 18 shows a close-up view of the Galveston Bay area, and the green lines show the tidal datum coverage of the marine grid. The non-tidal bounding polygons that mostly fall out of the marine grid water-cell coverage were not taken into account during the process of populating the marine grid because these areas were not included in the tide model and were already designated as land cells in the marine grid generation. This also avoids conflict with the inshore extension of bay-side marine grid coverage requested by VDatum users.

5.3. Population of VDatum grid with tidal datums

Tidal datums on the VDatum marine grid were populated by interpolating TCARI-corrected tidal datums (Section 5.3) according to the algorithm of Hess and White (2004). Datums at each VDatum marine grid point were computed by averaging or linearly interpolating those values within a user-specified search radius or the closest user-specified number of points. In the present case, the interpolation was accomplished using the FORTRAN program vpop19.f. It populates marine points differently depending on whether the point is inside/outside of the ADCIRC model grid elements. If the point was inside an element, datums were calculated using an interpolation of the three nodes of the element; if the point was outside any elements, datums were computed using the inverse distance weighting of the closest two node values. Bounding polygons were also used in the program to determine the portion of model grid being used in the populating process, so that no values are taken from the opposite side of the barrier islands and no averaging will be made across the narrow barrier islands between the outer coast and inshore bay. The program also checks for the existence of non-tidal zones as defined by non-tidal bounding polygons in the specific marine grid region. A LWD file is created in each region with the fixed value of 0.50 feet below MWL on the marine grid cells inside the non-tidal zone and the default value for invalid transformation elsewhere.

The exceptions made in the marine grid generation over the narrow barrier islands resulted in overlapping of valid cells from the two adjacent marine grids along the barrier islands. The inclusion of the bounding polygon when populating the marine grids prevents any averaging of values between the outer coast and inshore bays. Therefore, two sets of different values were written onto the overlapping grids over the narrow barrier islands for the two adjacent marine grid regions. Within the VDatum software, the bounding polygons determine the appropriate marine grid region to use for the requested transformation. However, users need to take precautions in deciding which marine grid region is appropriate for their specific applications when using the datum transformation files on their own.

Two types of verifications were conducted for the tidal datums populated on the marine grids: comparison with observations from the CO-OPS tidal stations and examining the match across its boundaries with the existing New Orleans VDatum regimes. For each of the four datums (MHHW, MHW, MLW, and MLLW), the model-data error is mostly less than 0.002 m and the biggest error is less than 0.01 m. The differences between current and previous VDatum project are less than 0.002 m over the connecting boundary.

The consistency between datum fields across the boundaries of different regions of this VDatum project was also evaluated. Because the datum fields on these regions were extracted and interpolated from the same model results, they were practically identical across all boundaries except for certain places over the barrier islands as described above where the coastal values meet with the estuarine values. For each of MHHW, MHW, MLW, and MLLW, maximum differences are less than 0.001 m over the majority of the boundaries. The differences in MLLW over the narrow barrier islands with overlapping valid marine grid cells are up to 0.265 m between R2 and R3 and 0.198 m between R4 and R5, which is the difference between the two distinct tidal regimes of outer coast and inshore bay. The final tidal datum fields on the marine grids (Figure B1) are shown in Appendix B.

5.4. Estimation of tidal datum transformation uncertainty

As discussed above, the tidal datum transformation errors at tide stations are negligible as defined on the marine grids due to the TCARI correction. However, at locations away from the stations used in the TCARI corrections, it is more difficult to determine the errors. These errors are affected by a variety of factors, including variations in the tidal range, tidal phase differences, bathymetric and coastal features, the density and proximity of nearby stations used in the corrections, and more. As an initial step in assessing the tidal datum transformation uncertainties, the original errors between the modeled and observed tidal datums were used as an approximation of potential errors away from the stations.

Table 3 lists the statistics of the modeled tidal datum errors in each region.

The VDatum team is currently investigating better approximations of these spatially varying errors. These methods include selective removal of data to determine the sensitivity of the corrected fields and various spatial interpolation methods that are guided by the results of the underlying hydrodynamic model of the tides.

Table 3. Statistics of the tidal datum errors (in cm) for each marine grid region.

Region	Field	Min	Max	Mean (Bias)	Mean of absolute error	Standard Deviation	Root Mean Squared Error	No. of Stations
R1	MHHW	-5.07	3.04	-0.80	2.13	2.54	2.63	12
R1	MHW	-3.98	3.93	0.15	1.97	2.39	2.36	12
R1	MLW	-4.10	4.47	1.68	2.73	2.50	2.98	12
R1	MLLW	-7.36	6.67	-2.11	4.29	4.36	4.79	12
R1	MTL	-2.25	3.08	0.91	1.55	1.56	1.79	12
R1	DTL	-5.13	1.24	-1.46	1.85	1.71	2.23	12
R2	MHHW	-7.68	7.81	-1.50	3.45	3.65	3.93	31
R2	MHW	-5.42	6.31	-0.61	2.52	2.92	2.97	31
R2	MLW	-4.93	4.11	-0.39	1.75	2.26	2.28	31
R2	MLLW	-7.12	6.25	-0.61	3.35	3.75	3.78	31
R2	MTL	-2.83	3.33	-0.50	1.21	1.38	1.46	31
R2	DTL	-3.38	0.95	-1.06	1.18	1.02	1.47	31
R3	MHHW	-4.71	0.30	-3.03	3.12	2.04	3.59	3
R3	MHW	-2.50	1.13	-1.24	1.74	1.52	1.90	3
R3	MLW	-1.73	2.60	0.60	1.65	1.86	1.85	3
R3	MLLW	-4.48	-1.13	-2.97	2.97	1.32	3.22	3
R3	MTL	-2.08	0.85	-0.32	0.94	1.21	1.19	3
R3	DTL	-3.73	-2.09	-3.00	3.00	0.65	3.06	3
R4	MHHW	-6.18	4.74	0.14	1.43	2.06	2.05	27
R4	MHW	-5.57	4.74	0.36	1.26	1.81	1.84	27
R4	MLW	-7.51	1.57	-2.13	2.30	2.14	3.01	27
R4	MLLW	-5.80	3.81	-1.46	2.08	2.22	2.65	27
R4	MTL	-3.25	0.00	-0.88	0.88	0.88	1.24	27
R4	DTL	-2.13	0.47	-0.66	0.69	0.62	0.90	27
R5	MHHW	-3.00	-1.75	-2.21	2.21	0.42	2.25	3
R5	MHW	-2.01	-0.19	-0.80	0.80	0.73	1.05	3
R5	MLW	-4.12	-3.13	-3.84	3.84	0.38	3.85	3
R5	MLLW	-2.30	-0.22	-1.68	1.68	0.83	1.86	3
R5	MTL	-2.65	-2.11	-2.32	2.32	0.20	2.33	3
R5	DTL	-2.29	-1.60	-1.95	1.95	0.27	1.96	3

6. TOPOGRAPHY OF THE SEA SURFACE

The topography of the sea surface is defined as the elevation of the North American Vertical Datum of 1988 relative to local mean sea level. This grid provides compensation for the local variations between a mean sea level surface and the NAVD88 geopotential surface over the Lake Charles, Louisiana to South Padre Island, Texas VDatum regions. A positive value specifies that the NAVD88 reference value is further from the center of the Earth than the local mean sea level surface.

The direct method of obtaining NAVD 88-to-LMSL values includes calculating orthometric-to-tidal datum relationships at NOAA tide stations where elevation information has been compiled. Data for the direct method were supplied by CO-OPS and NGS. All data are based on the most recent National Tidal Datum Epoch (1983-2001). The locations of tide stations used are illustrated in Figure 19.

Next, a mesh covering the entire area of benchmarks and water level stations with a spatial resolution similar to that of the tidal marine grids is created. Breaklines are inserted to represent the influence of land. A sea surface topography field is generated using the Surfer© software's minimum curvature algorithm to create a surface that honors the data as closely as possible. The maximum allowed departure value used was 0.0001 meters. To control the amount of bowing on the interior and at the edges of the grid, an internal and boundary tension 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 sea-surface topography for the current VDatum region is illustrated in Figure 20.

The data used to compile TSS grids was compared against the TSS grid product, to generalize internal consistency. The mean difference (delta) between NAVD88 and LMSL for each tide station utilized for creation of the TSS is depicted for the Lake Charles, Louisiana to South Padre Island, Texas VDatum in Table 4. The mean and standard deviations for these values between NAVD88 to LMSL relationships for the Lake Charles, Louisiana to South Padre Island, Texas regions are listed in Table 5.

Figure 19. Location of tide stations used to compute the TSS grid for the Texas and western Louisiana VDatum region.

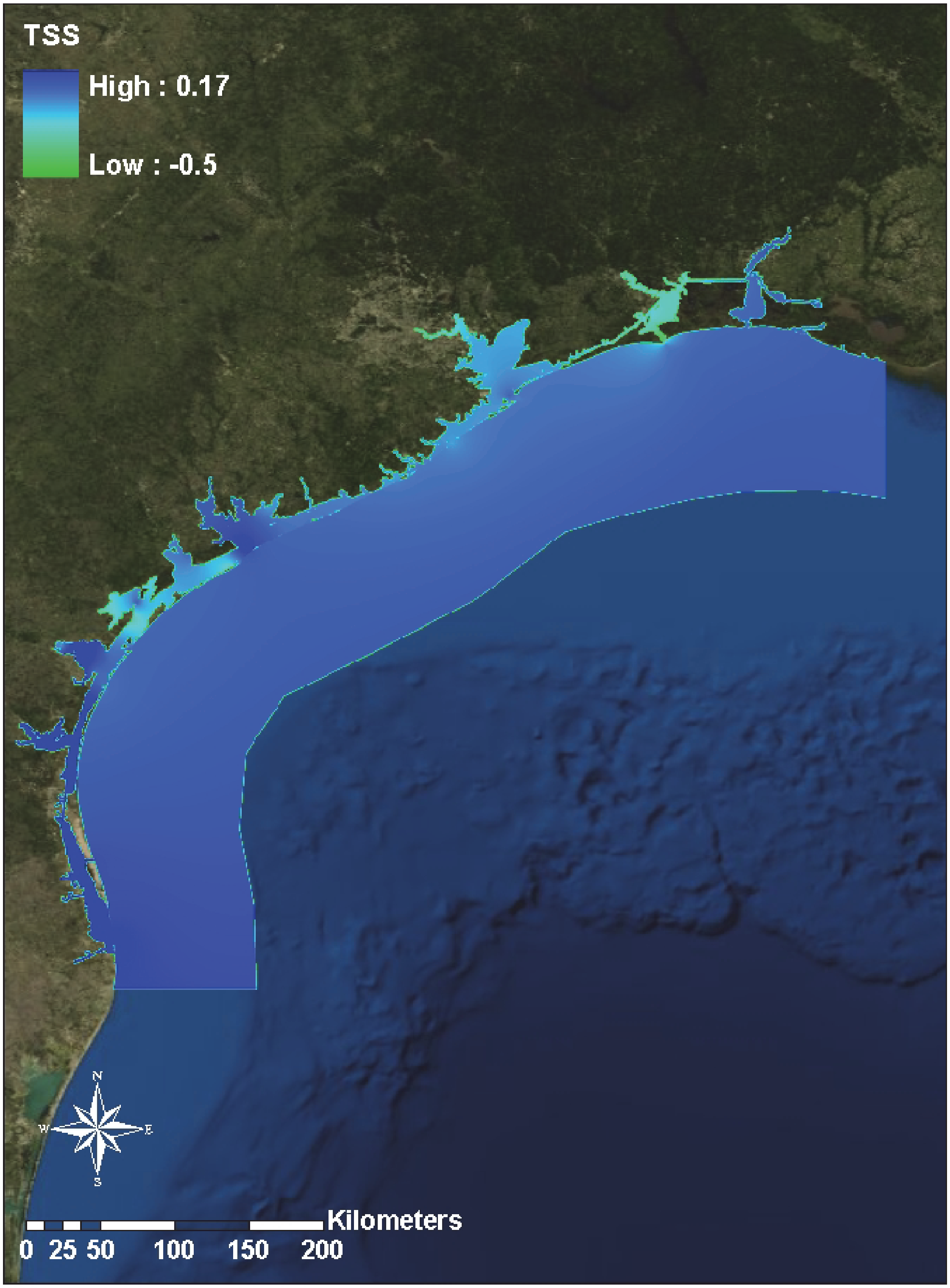

Figure 20. Topography of the Sea Surface for the Texas and western Louisiana VDatum region.

Table 4. Tide station data utilized for TSS creation and deltas computed against the TSS grid.

ID	Latitude (deg)	Longitude (deg)	NAVD 88 to LMSL (m)	TSS Derived Value (m)	Delta (m)
90037	28.20230	-96.92800	-0.258	-0.258	0.000
8767816	30.22500	-93.22167	-0.094	-0.094	0.000
8768094	29.76500	-93.34333	-0.128	-0.128	0.000
8770475	29.86670	-93.93000	-0.254	-0.254	0.000
8770520	29.98000	-93.88170	-0.312	-0.312	0.000
8770559	29.71330	-94.69000	-0.206	-0.206	0.000
8770570	29.72840	-93.87010	-0.424	-0.423	-0.001
8770590	29.70500	-93.85330	-0.466	-0.464	-0.002
8770595	30.09500	-94.09000	-0.325	-0.325	0.000
8770597	30.08480	-93.71720	-0.299	-0.299	0.000
8770613	29.68170	-94.98500	-0.201	-0.201	0.000
8770733	29.76500	-95.07830	-0.246	-0.246	0.000
8770743	29.75670	-95.09000	-0.261	-0.261	0.000
8770777	29.72628	-95.26581	-0.322	-0.322	0.000
8770822	29.67833	-93.83722	-0.153	-0.157	0.004
8770923	29.53830	-94.38500	-0.153	-0.153	0.000
8770933	29.56330	-95.06670	-0.205	-0.205	0.000
8770971	29.51500	-94.51330	-0.185	-0.185	0.000
8771013	29.48000	-94.91830	-0.207	-0.207	0.000
8771328	29.36500	-94.78000	-0.112	-0.112	0.000
8771341	29.35733	-94.72483	-0.185	-0.173	-0.012
8771450	29.31000	-94.79330	-0.209	-0.209	0.000
8771510	29.28530	-94.78940	-0.152	-0.152	0.000
8771972	29.07570	-95.12257	-0.211	-0.210	-0.001
8772132	29.04170	-95.17500	-0.168	-0.168	0.000
8772440	28.94830	-95.30830	-0.151	-0.151	0.000
8772447	28.94331	-95.30250	-0.158	-0.158	0.000
8772689	28.87780	-95.45460	-0.200	-0.200	0.000
8773037	28.40830	-96.71170	-0.129	-0.129	0.000
8773118	28.71330	-95.88670	-0.186	-0.186	0.000
8773156	28.69670	-96.23170	-0.196	-0.196	-0.001
8773259	28.64000	-96.59500	-0.108	-0.108	0.000
8773701	28.45170	-96.38830	0.021	0.019	0.002
8773963	28.33330	-96.46170	-0.327	-0.325	-0.002
8774513	28.11830	-97.02170	-0.100	-0.102	0.002
8774522	28.12670	-96.97830	-0.211	-0.210	-0.001
8774652	28.06670	-97.20330	-0.316	-0.316	0.000
8774770	28.02170	-97.04670	-0.342	-0.341	-0.001
8775188	27.85830	-97.47500	-0.200	-0.199	-0.001
8775222	27.84623	-97.52090	-0.120	-0.120	0.000
8775237	27.83830	-97.07330	-0.115	-0.116	0.001
8775270	27.82670	-97.05000	-0.122	-0.122	0.000
8775283	27.82170	-97.20330	-0.140	-0.139	-0.001

8775296	27.81170	-97.39000	0.187	0.185	0.002
8775421	27.70500	-97.28000	-0.141	-0.141	0.000
8775792	27.63330	-97.23670	-0.141	-0.141	0.000
8775870	27.58000	-97.21670	-0.146	-0.146	0.000
8776139	27.48000	-97.32170	0.037	0.037	0.000
8776604	27.29500	-97.40500	0.059	0.059	0.000
8776639	27.27500	-97.70830	-0.082	-0.082	0.000
8777812	26.82500	-97.49170	-0.035	-0.035	0.000
8778490	26.56500	-97.43000	-0.020	-0.020	0.000
8779724	26.07830	-97.17000	0.114	0.112	0.001
8779739	26.07170	-97.19170	0.029	0.029	0.000
8779748	26.07670	-97.17670	0.063	0.064	-0.001
8779750	26.06830	-97.15670	0.008	0.007	0.001
8779768	26.05170	-97.18170	0.024	0.024	0.000
8779770	26.06000	-97.21500	0.012	0.012	0.000
8779977	25.95170	-97.40170	0.080	0.080	0.000

Table 5. Mean and stand deviations of delta values (meters) for the five marine grids in the Texas and western Louisiana VDatum region.

	Mean Delta Value (m)	**Standard Deviation (m)**
Region 1 (Western Mississippi to Sabine Pass)	0.00008	0.001454
Region 2 (Galveston Bay Vicinity Coastal Embayments)	-0.00063	0.002558
Region 3 (Galveston / Gulf of Mexico Vicinity)	-0.00417	0.006536
Region 4 (Corpus Christi Vicinity Coastal Embayments)	0.00000	0.000783
Region 5 (Padre Island / Gulf of Mexico Vicinity)	0.00023	0.000586

7. SUMMARY

In support of the development of the national datum transformation software tool, VDatum, a tide model for the coastal waters extending from Vermillion Bay, Louisiana, to just south of the U.S.-Mexico border was development in this project. Tidal dynamics in the study area were simulated using the two-dimensional mode of ADCIRC. Tidal datum fields, including mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and mean higher high water (MHHW), were calculated from modeled water level time series. Modeled results were validated against observation-derived tidal datum fields at NOAA tide stations. The TCARI program was used to generate the interpolated error fields from the model-data discrepancies at these water level stations. The errors in the modeled tidal datums were compensated for by subtracting the interpolated error fields, and the resulting VDatum values match the CO-OPS database closely at the stations.

VDatum software requires that tidal datum fields be defined on regular grids. Due to the large size of the studied area and the existence of narrow barrier islands, five VDatum marine grids were built to cover the whole domain and separate the different tidal regime in the bays from outer shore open water. Tidal datums defined on the unstructured grid were interpolated onto the regular grids to be used as input to the VDatum software tool.

Non-tidal areas, where the astronomical tide is practically absent, were incorporated into the VDatum tool for the first time. Bounding polygons for non-tidal zones were initially obtained from CO-OPS and modified based on the tidal simulation results when necessary. The time-averaged elevation of the water in these areas was defined as the Mean Water Level (MWL), and the differences between the other tidal datums and MWL were set to zero.

The TSS field was derived by using the Surfer software to create a surface that honors the calculated orthometric-to-tidal datum relationships at the NOAA tide stations as closely as possible.

Along with the previously-developed VDatums for central Louisiana, the northeast Gulf, and the west Florida shelf, this project extends VDatum coverage to all U.S. coastal waters in the Gulf of Mexico region.

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APPENDIX A. WATER LEVEL STATIONS

Table A1. NOS water level stations along the western Louisiana and Texas coasts in the model domain.

No.	Station ID	Latitude	Longitude	Station Name
1	8767816[a*]	30.2250	-93.2217	LAKE CHARLES, CALCASIEU R
2	8768094[a*]	29.7650	-93.3433	CALCASIEU PASS, EAST JETT
3	8770475[a*]	29.8667	-93.9300	PORT ARTHUR, SABINE NACHE
4	8770520[a*]	29.9800	-93.8817	RAINBOW BRIDGE, NECHES RI
5	8770539[a*]	29.7667	-93.8950	MESQUITE POINT
6	8770559[*]	29.7133	-94.6900	ROUND POINT, TRINITY BAY
7	8770570[a*]	29.7300	-93.8700	SABINE PASS NORTH
8	8770590[a]	29.7050	-93.8533	SABINE PASS
9	8770613[a*]	29.6817	-94.9850	MORGANS POINT, BARBOURS C
10	8770733[a*]	29.7650	-95.0783	LYNCHBURG LANDING, SAN JA
11	8770743[*]	29.7567	-95.0900	BATTLESHIP TEXAS S.P, HOU
12	8770777[a*]	29.7183	-95.2517	MANCHESTER, HOUSTON SHIP
13	8770933[a*]	29.5633	-95.0667	CLEAR LAKE
14	8770971[a*]	29.5150	-94.5133	ROLLOVER PASS
15	8771013[a*]	29.4800	-94.9183	EAGLE POINT, GALVESTON BA
16	8771328[a*]	29.3650	-94.7800	PORT BOLIVAR, BOLIVAR ROA
17	8771341[a]	29.3573	-94.7248	GALVESTON BAY ENTRANCE, N
18	8771416[a]	29.3267	-94.6933	GALVESTON BAY ENTRANCE, S
19	8771450[a*]	29.3100	-94.7933	GALVESTON PIER 21, GALVES
20	8771510[a*]	29.2853	-94.7894	GALVESTON PLEASURE PIER,
21	8772132[a]	29.0417	-95.1750	CHRISTMAS BAY
22	8772440[a*]	28.9483	-95.3083	FREEPORT, DOW BARGE CANAL
23	8772447[a]	28.9333	-95.3000	USCG FREEPORT, FREEPORT E
24	8773037[b*]	28.4083	-96.7117	SEADRIFT, SAN ANTONIO BAY
25	8773259[b*]	28.6400	-96.5950	PORT LAVACA, LAVACA CAUSE
26	8773701[b*]	28.4517	-96.3883	PORT O'CONNOR, MATAGORDA
27	8773963[b]	28.3333	-96.4617	NORTH MATAGORDA
28	8774513[b*]	28.1183	-97.0217	COPANO BAY STATE FISHING
29	8774770[b*]	28.0217	-97.0467	ROCKPORT, ARANSAS BAY
30	8775188[b*]	27.8583	-97.4750	WHITE POINT BAY
31	8775237[b*]	27.8383	-97.0733	PORT ARANSAS
32	8775270[*]	27.8267	-97.0500	PORT ARANSAS, H. CALDWELL
33	8775283[b*]	27.8217	-97.2033	PORT INGLESIDE, CORPUS CH
34	8775296[b*]	27.8117	-97.3900	TEXAS STATE AQUARIUM, COR
35	8775421[b*]	27.7050	-97.2800	CORPUS CHRISTI NAVAL AIR
36	8775792[b*]	27.6333	-97.2367	PACKERY CHANNEL
37	8775870[*]	27.5800	-97.2167	CORPUS CHRISTI, GULF OF M
38	8776139	27.4800	-97.3217	BIRD ISLAND

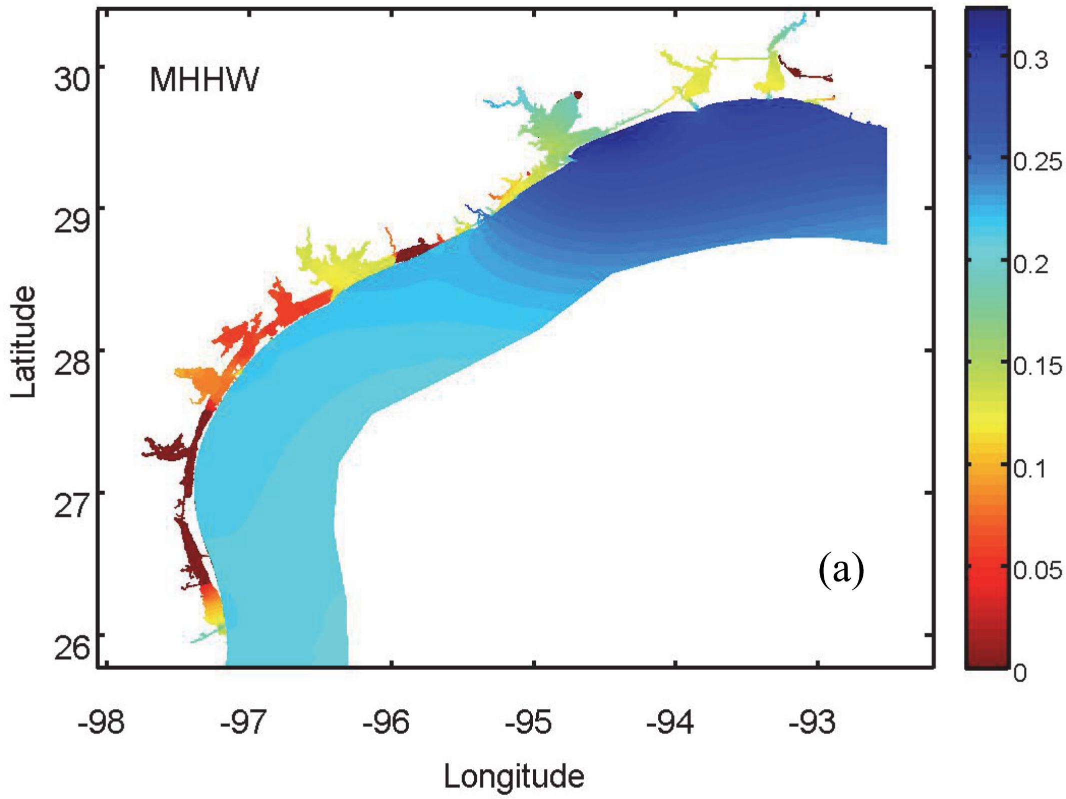
39	8776604	27.2950	-97.4050	BAFFIN BAY
40	8776687	27.1667	-97.4333	YARBROUGH PASS
41	8777812	26.8250	-97.4917	RINCON DEL SAN JOSE
42	8778490	26.5650	-97.4300	PORT MANSFIELD
43	8779038	26.3483	-97.3650	ARROYO COLORADO
44	8779724	26.0783	-97.1700	QUEEN ISABELLA CAUSEWAY,
45	8779739	26.0717	-97.1917	W QUEEN ISABELLA CAUSEWAY
46	8779748*	26.0767	-97.1767	SOUTH PADRE ISLAND C.G. S
47	8779750*	26.0683	-97.1567	PADRE ISLAND, BRAZOS SANT
48	8779768	26.0517	-97.1817	SOUTH BAY
49	8779770*	26.0600	-97.2150	PORT ISABEL, LAGUNA MADRE
50	8779977	25.9517	-97.4017	PORT OF BROWNSVILLE

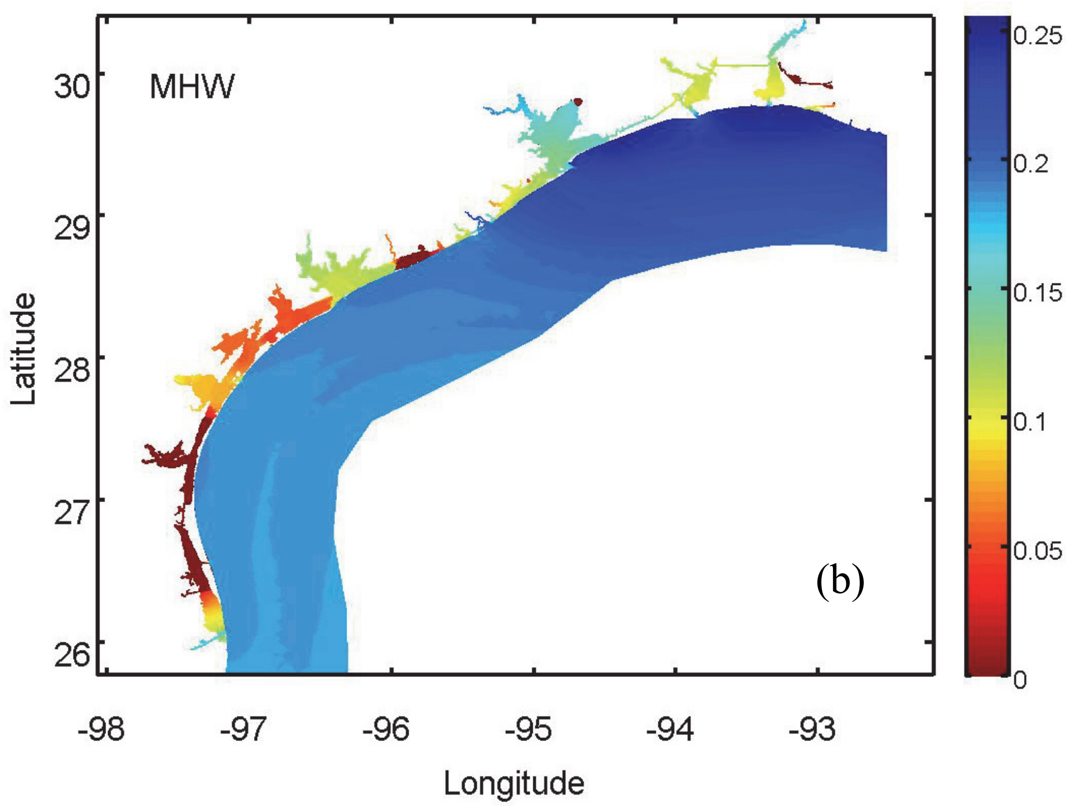
[a]Tidal Datums computed using Modified Procedure for Tidal Datum Computation on a reduced 5-year period of 1997-2001
[b]Tidal Datums computed using Modified Procedure for Tidal Datum Computation on a reduced 5-year period of 2002-2006
*Stations with harmonic constants

Table A2. The 21 additional TCOON stations with tidal datums from observation.

No.	Station ID	Latitude	Longitude	Station Name
1	87753511	27.7947	-97.3876	Lawrence St. T-Head
2	87746521	28.0667	-97.2033	Bayside
3	87730011	28.7617	-95.6533	East Matagorda Bay
4	87731561	28.6967	-96.2317	Palacios
5	87745221	28.1267	-96.9783	Goose Island
6	CBI90037	28.2023	-96.9280	Indian Head Point
7	CBI90038	28.2315	-96.7990	False Live Oak
8	87726891	28.8778	-95.4546	San Bernard Rivers End
9	CBI90050	28.9498	-95.5553	Churchill - San Bernard
10	87733041	28.6233	-95.9700	Rawlings
11	87708221	29.6783	-93.8372	Texas Point
12	87752221	27.8462	-97.5209	Viola Turning Basin
13	87718011	29.1667	-95.1250	Alligator Point
14	87709231	29.5383	-94.3850	High Island
15	87705951	30.0950	-94.0900	Beaumont
16	87705971	30.0848	-93.7172	Orange
17	87717081	29.2117	-95.2067	Chocolate Bayou
18	87719841	29.0900	-95.2817	Bastrop Bayou
19	87719721	29.0757	-95.1226	San Luis Pass
20	87705571	29.7405	-94.8318	Point Barrow
21	87718541	29.1443	-95.1596	West Bay

APPENDIX B. Tidal Datums on the Marine Grids





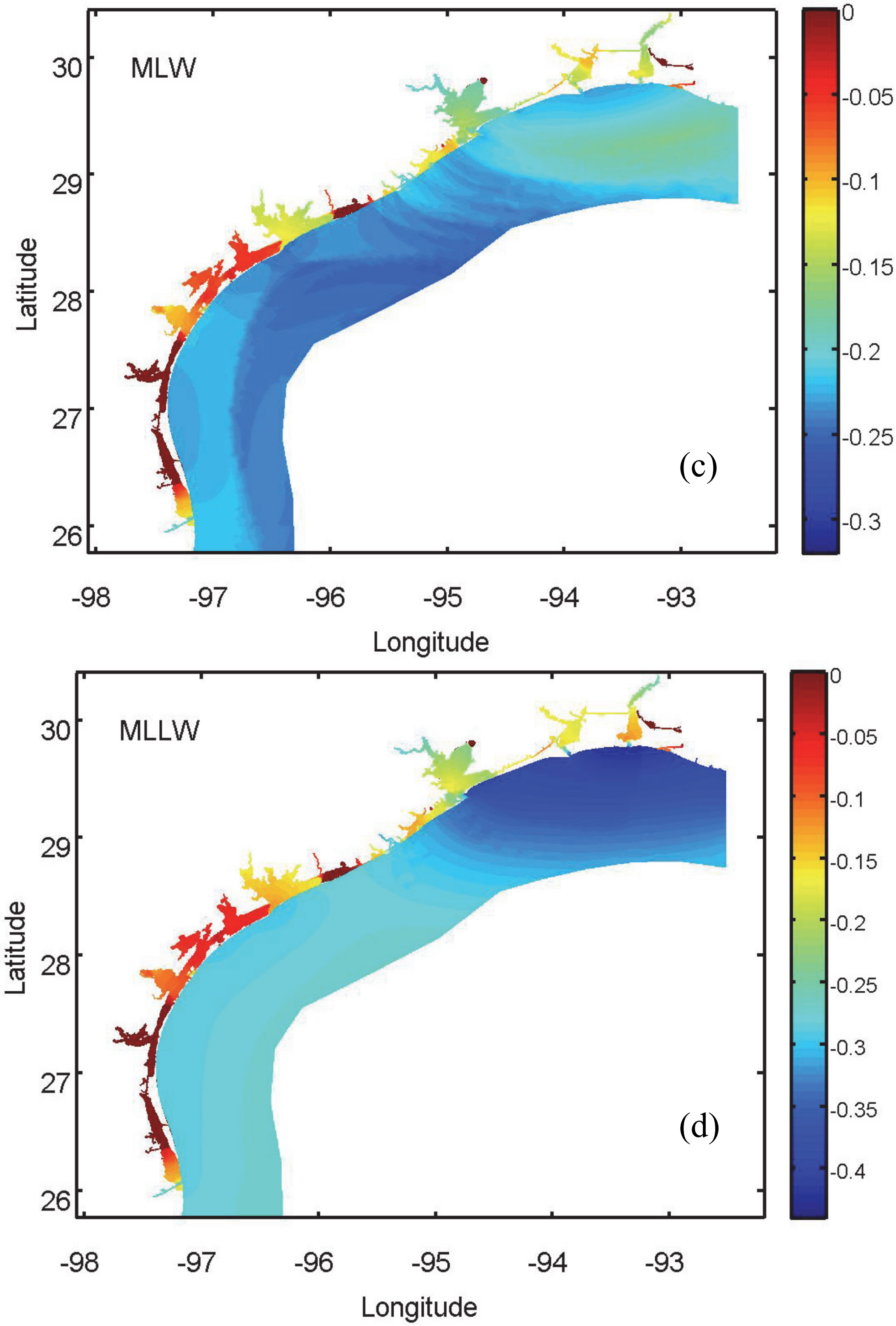


Figure B1. The final, corrected (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW fields relative to LMSL defined on VDatum marine grids.