NOAA Technical Report NOS CS 19

VDATUM FOR THE CALCASIEU RIVER FROM LAKE CHARLES TO THE GULF OF MEXICO, LOUISIANA: TIDAL DATUM MODELING AND POPULATION OF THE GRID

Silver Spring, Maryland
March 2005

noaa National Oceanic and Atmospheric Administration

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

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

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ABSTRACT

The goal of the VDatum, vertical datum transformation tool, project is to provide transformations between tidal, orthometric and three-dimensional datums for all areas of the contiguous United States. This paper chronicles the continuing work on this project in the Lake Charles and Calcasieu Lake area of Louisiana. A VDatum marine grid was created and populated for this area. The tidal datum fields were created using a two-dimensional finite element hydrodynamic model of the area. The tidal datum results from this model were corrected to match existing NOAA tide gauge data in the region using a spatial interpolation scheme. The sea surface topography, or difference between local mean sea level and the NAVD 88 geopotential surface, was defined as a constant over the domain based on data at one tide gauge.

Key Words: tides, tidal datums, Lake Charles, Lake Calcasieu, finite element model, hydrodynamic model, ADCIRC, bottom friction, North American Vertical Datum of 1988, mean sea level, spatial interpolation, coastline

1. INTRODUCTION

The National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) requires tidal datum information such as Mean High Water (MHW) and Mean Lower Low Water (MLLW) to support nautical charting, navigational safety, shoreline photogrammetry, and marine boundary determination. In addition, tidal datum information is needed for referencing NOS' bathymetric data (which is typically referenced to MLLW) to any one of the other vertical elevation reference systems. A software tool under development at NOS called VDatum (Milbert, 2002; Parker, 2002) is designed to transform among approximately 30 vertical reference datums. To be applicable over coastal waters, VDatum requires tidal datum fields, where the field describes the two dimensional, horizontal variability of the datum elevation. This paper chronicles the continuing work on the VDatum software for southwestern Louisiana. The work for this project work was originally conducted for and partially funded by the FY'03 NOS Partnership, "Determining Accurate Elevations for Hurricane Evacuation Route Planning in Subsidence-threatened southern Louisiana using Integrated GPS, Inertial Measurement, and Distance Measurement Systems".

A numerical tide model was employed to determine the tidal datums along the Calcasieu River from Lake Charles, Louisiana, to the mouth of the river, and out into the Gulf of Mexico. The two-dimensional finite element hydrodynamic model, ADCIRC (Luettich et al., 1992; Luettich and Westerink, 2004) was used to calculate these datums. An unstructured mesh was developed for the tidal modeling efforts and a regular grid was developed for the final VDatum results. The unstructured mesh incorporates bathymetric data from several sources and the land-water boundary of the mesh is based on NOAA's Medium Resolution Coastline. The tidal datum results from the hydrodynamic model (on the unstructured mesh) were interpolated onto the VDatum marine grid. The VDatum marine grid was developed based on the same coastline, using programs discussed by Hess and White (2004), and is a regular, structured grid. The final tidal datum results are presented. The Topography of the Sea Surface, which relates local Mean Sea Level (MSL) to the North American Vertical Datum 1988 (NAVD88) is a spatially constant value, based on the National Geodetic Survey geodetic benchmark connections to tidal benchmarks at Lake Charles, Louisiana.

2. DATA SOURCES

2.1. Coastline Data

NOAA's Medium Resolution Digital Vector Shoreline was used for this project. The shoreline was compiled by digitizing NOAA charts. Charts with a scale of 1:80,000 were used where available, and in the few places where those charts were unavailable, higher resolution 1:60,000 scale charts were used. This coastline accurately delineates the Mean High Water (MHW) shoreline as depicted on NOAA nautical charts as a solid dark line. The coastline in the Lake Charles Calcasieu River, Louisiana, area is shown in Figure 1.

2.2. Water Level Stations

For purposes of model validation, the NOAA tide stations that exist in the region were examined. Three tide stations were found in the area. These stations are listed in Table 1 along with the location, tidal datums, and epoch. The Lake Charles station (#8767816) and the East Jetty station (#8768094) are also shown in Figure 1.

The only tide station in the survey area with a published tie between tidal datums and geodetic datum of North American Vertical Datum 1988 (NAVD88) is at Lake Charles. While the tidal epoch for the data at the Calcasieu Pass Light station is not known, the age of the data is known – it was collected from May 12, 1924 until May 16, 1924. Due to the short duration and the old date of this deployment, the data from this station was not used for this project. The station at East Jetty has had a GPS tie to one bench mark which is insufficient to produce a published tidal datum to NAVD88 relationship. GPS connections are also only accurate to 2-5 cm, where the direct leveling connections are accurate to sub-centimeter levels. Given the uncertainty, this value was also not used for this project at this time. Future repeat leveling will narrow the uncertainty. Tidal datums will also become more accurate as the data are now being collected over a long time period and the datums will be updated using a longer time series.

Table 1. List of NOAA water level stations and vertical datums in the Lake Charles Calcasieu River, Louisiana, area.

Station ID #	Station Name	Longitude (degrees)	Latitude (degrees)	MHHW (m)	MHW (m)	MLW (m)	MLLW (m)	MSL to NAVD88	Tidal Epoch
8767816	Lake Charles	-93.3450	29.7783	0.1630	0.1310	-0.1580	-0.2050	-0.354	1983 - 2001
8768094	Calcasieu Pass, East Jetty	-93.3417	29.7583	0.2420	0.1940	-0.2170	-0.3730	-0.254*	1983 – 2001
8768106	Calcasieu Pass, Light	-93.3450	29.7783	0.3050	0.2440	-0.1530	-0.3050	NA	NA

* Note – this value is preliminary based on recent GPS surveys. The entire region is undergoing readjustment using predicted vertical velocities of bench marks and the vertical time dependent positioning(VTDP) model. This value does not take into account VTDP and the estimate that matches how the value was computed at Lake Charles.

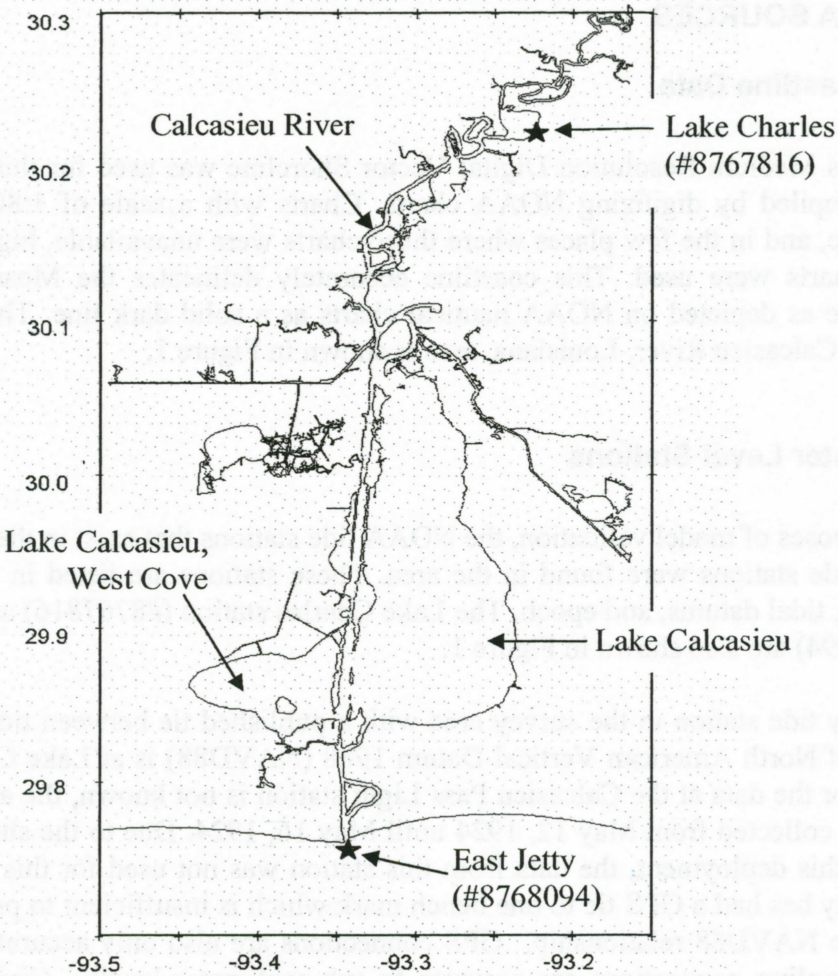

Figure 1. NOAA's Medium Resolution MHW shoreline in Calcasieu Lake, Louisiana, area with stars marking the two NOAA water level stations in the region that were used in this study.

2.3. Bathymetric Data

Bathymetric data used for this modeling effort came from four sources. Bathymetry from the National Geophysical Data Center's (NGDC) Coastal Relief Model (CRM) is available at every node in that model's grid, which has a grid cell spacing of 2 arc seconds by 2 arc seconds (about 90 m by 90 m). These bathymetric data are referenced to Mean Low Water (MLW). NOS sounding data are available in many areas of this region. The surveys were conducted between 1933 and 1994 and contain data referenced to both Mean Lower Low Water (MLLW) and MLW. The U.S. Army Corps of Engineers (USACE) has conducted surveys along the Calcasieu River, where they are responsible for dredging activities. The data are recent (from 2002), but are referenced to the Mean Low Gulf (MLG) datum, which does not match exactly with any standard NOAA tidal datums (i.e. MLLW, MLW, etc.). The final set of bathymetric data is from the NOAA charts themselves – electronic data outlining the extents of the dredged channels in the Gulf of Mexico and the listed dredged depths from the chart. The chart datum is MLLW.

3. ADCIRC MODEL SET UP AND TESTING

For this modeling effort, the two-dimensional, depth-integrated, barotropic version of the finite element model ADCIRC was employed (Luettich et al., 1992; Luettich and Westerink, 2004). This model solves the shallow water equations for water elevation and velocity on an unstructured, triangulated mesh. The following sub-sections outline the steps taken to set-up and test the ADCIRC model for this domain. First, the creation of the unstructured mesh will be outlined. Discussion of the bathymetric data and the process used to populate the mesh with depths at the nodes will follow. The model allows for a variety of hydrodynamic conditions, including wetting and drying, that are implemented through several user-specified parameters. The parameters used for this study along with details of tests done to find the best bottom friction parameters will be discussed. Finally, a description of the series of runs conducted to determine model convergence towards a physically realistic answer will conclude this section.

3.1. Creating the Unstructured Mesh

The placement of nodes in the unstructured triangulated mesh used for the ADCIRC model runs was based on the NOAA's Medium Resolution Coastline (see Figure 1). The nodes and elements in the grid were placed to follow this shoreline as closely as possible. The entire finite element mesh is shown in Figure 2(a). This mesh contains 20,575 nodes and 36,931 elements. One advantage of flexible, finite element meshes is that they easily allow different levels of resolution within one domain. Fewer nodes are needed in deeper waters in the Gulf of Mexico, but when advection begins to dominate the flow regime as the waters channel into the Calcasieu Pass at the mouth of the Calcasieu River, more nodes are needed to accurately capture the hydrodynamics. Two zoomed views of the Calcasieu Pass area (connecting Calcasieu Lake to the Gulf of Mexico) are shown in Figures 2(b) and 2(c). These figures illustrate the increasing resolution through the Calcasieu Pass area. The largest elements in the grid are just over 4 kilometers (measured as the average distance between nodes in an element) in the Gulf of Mexico and the smallest elements are about 30 meters wide in the Calcasieu River.

3.2. Adjusting and Combining Bathymetric Data

Even before the bathymetric data could be incorporated in the unstructured mesh, the depths needed to be converted to a common vertical datum. The common datum chosen was MLLW, which is NOAA's chart datum.

The USACE data are referenced to MLG. No exact relationship between MLG and MLLW has been established but the estimated relationship is that MLG is 1.2 feet below MLLW at the Port of Lake Charles and 0.8 feet below MLLW near the mouth of the Calcasieu River at Calcasieu Pass (Steve Gill, NOAA/NOS/CO-OPS, personal communication). The MLG-to-MLLW difference was assumed to be a linear function of the latitude between the station at Lake Charles and the station at Calcasieu Pass, and this relationship was used to transform from USACE data so that all sounding depths were referenced to MLLW.

The CRM data are referenced to MLW. The difference between MLW and MLLW is known to be 4.7 cm at the Lake Charles station at the northern end of the domain (station #8767816) and 15.6 cm at the mouth of the Calcasieu River at the East Jetty (station #8768094) (see Figure 1). A finite element implementation of the tidal constituent and residual interpolation (TCARI) program was used to spatially interpolate the difference between MLW and MLLW that is known at those two stations. TCARI solves Laplace's Equations and takes landforms into account (Hess, 2002). A field of the difference between MLW and MLLW was created for the finite element mesh shown in Figure 2 that exactly matched the MLW-MLLW differences listed above at the Lake Charles and East Jetty stations. Once the MLW-MLLW difference field was created (with MLW-MLLW values at each node in the mesh), values for each element could be determined as the average of the values of the three nodes that make up that element.

For the NOS data referenced to MLLW, no adjustments were made, but for survey depths referenced to MLW, each depth was adjusted to MLLW by adding the MLW-MLLW difference for the element in the MLW-MLLW difference field created using TCARI as described above. For depths outside the finite element mesh, the MLW-MLLW difference of the nearest element was used.

After all the bathymetric data were converted to MLLW, each of the four sources was processed separately. The data from each of the first three sources (CRM data, NOS soundings, and Army Corps soundings) were used to create three separate meshes; each mesh contained bathymetric depths from only one source. The data were incorporated into the mesh using a process that will be referred to as the cluster-averaging approach and is a method of filtering the bathymetric data at the grid scale. To determine the bathymetric depth for a given mesh node, this method picks out all of the bathymetric data located in the elements surrounding that node. These data values are averaged, and the result is taken as the bathymetric value for the node. If there are no bathymetric data in any of the surrounding elements, a null value of -9999 is assigned to that node. For each data set being processed (USACE, NOS, and CRM) a different mesh file, that lists the node number, latitude, longitude and bathymetric depth or the null value, was created. After each of the three meshes was created, they were combined into a final combined mesh.

The first individual mesh incorporated bathymetric data from the CRM using the cluster-averaging approach. After all of the data from the CRM (adjusted so that depths were referenced to MLLW) had been added to the mesh, the nodes marked with null values (where no CRM data was available) were located. Bathymetric information was extrapolated to these nodes using an average of the non-null value nodes on elements connected to the node of interest. Several iterations of this bathymetric extrapolation process were necessary; in the initial iteration some nodes were surrounded entirely by elements consisting of nodes with all null value data and so no bathymetric depth information was extrapolated to these points. In this process, the bathymetric information was, in a sense, propagated from the nodes with viable bathymetric information to those nodes initially containing the null value for the depth, so that in the end, no nodes had null values.

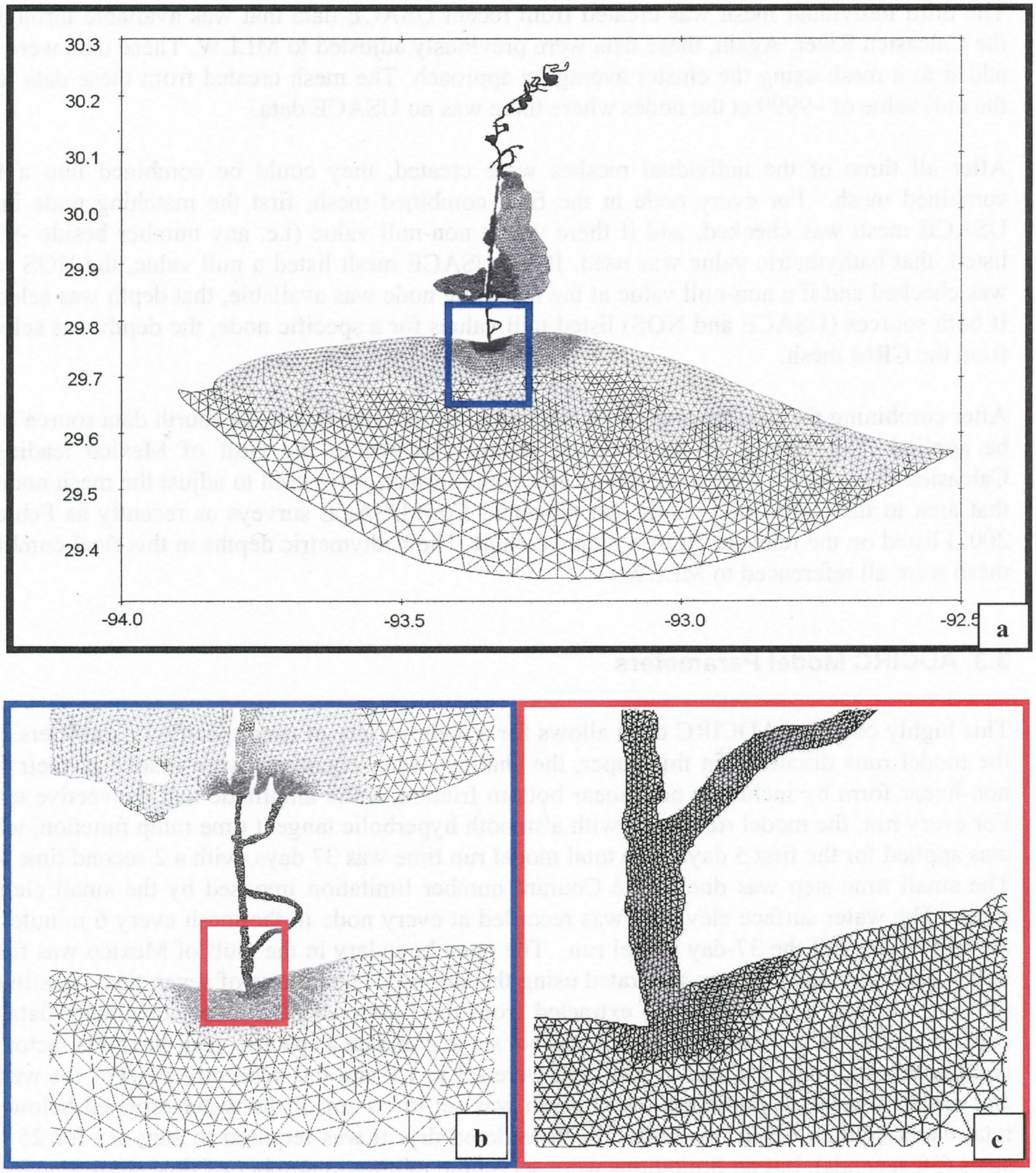

Figure 2. Finite element mesh for (a) the entire model domain following the Calcasieu River from Lake Charles to the Gulf of Mexico, and zoomed views of (b) the Calcasieu Pass, and (c) the mouth of the Calcasieu River.

The second individual mesh was created using NOS sounding data. This bathymetric data (which were all adjusted to MLLW) were incorporated into a mesh using the cluster averaging approach. Null values of -9999 were listed at the locations where no NOS data were available. Unlike the CRM data mesh, the null value nodes were not eliminated.

The third individual mesh was created from recent USACE data that was available throughout the Calcasieu River. Again, these data were previously adjusted to MLLW. These data were also added to a mesh using the cluster averaging approach. The mesh created from these data listed the null value of –9999 at the nodes where there was no USACE data.

After all three of the individual meshes were created, they could be combined into a final combined mesh. For every node in the final combined mesh, first the matching node in the USACE mesh was checked, and if there was a non-null value (i.e. any number beside -9999) listed, that bathymetric value was used. If the USACE mesh listed a null value, the NOS mesh was checked and if a non-null value at the matching node was available, that depth was selected. If both sources (USACE and NOS) listed null values for a specific node, the depth was selected from the CRM mesh.

After combining the data from the first three sources into one mesh, the fourth data source could be applied. The extents of the dredged channel located in the Gulf of Mexico leading to Calcasieu Pass, which were available in electronic format, were used to adjust the mesh nodes in that area to the controlling depths (as tabulated from USACE surveys as recently as February 2002) listed on the relevant NOAA nautical chart. The bathymetric depths in this final combined mesh were all referenced to MLLW.

3.3. ADCIRC Model Parameters

This highly complex ADCIRC code allows for a wide variety of user-specified parameters. For the model runs discussed in this paper, the shallow water equations were treated in their fully non-linear form by including non-linear bottom friction, finite amplitude and convective terms. For every run, the model run began with a smooth hyperbolic tangent time ramp function, which was applied for the first 5 days. The total model run time was 37 days, with a 2 second time step. The small time step was due to the Courant number limitation imposed by the small element sizes. The water surface elevation was recorded at every node in the mesh every 6 minutes for the last 30 days of the 37-day model run. The open boundary in the Gulf of Mexico was forced with a synthetic tide that was generated using the amplitude and phase of seven tidal constituents (K_1, O_1, Q_1, M_2, S_2, N_2, and K_2) extracted from the Eastcoast 2001 tidal constituent database (Mukai et al., 2001). Since this model was not set to simulate a specific year, the node factor and equilibrium argument for each constituent were set to 1.0 and 0.0, respectively. For the wetting and drying scheme, a minimum water depth was set to 10 cm; if the water dropped below this total water column depth, the node was considered dry. It was required to stay dry for 25 time steps (50 seconds), but no limitations were set on the minimum number of time steps a node was required to stay wet. The limitation on staying dry was set to maintain model stability. The minimum velocity required to wet a dry node was set to 0.05 m/s. The lateral eddy diffusion/dispersion coefficient was set to 2 m^2/sec, the lowest possible number that did not produce numerical instabilities. Bottom friction parameters are discussed below.

The ADCIRC model has been parallelized using domain decomposition, a conjugate gradient solver and Message Passing Interface (MPI) based message passing. This parallel version of the code was compiled and run on NOAA's Forecast Systems Laboratory (FSL) JET computer in

Boulder, Colorado. It took approximately 4 wall-clock hours to complete the 37-day run utilizing 36 processors.

3.4. Bottom Friction Formulation

The ADCIRC model allows for several different methods of implementing bottom stress. Generally, bottom stress is expressed as $\tau_{bx}=U\tau_*$ and $\tau_{by}=V\tau_*$, where U and V are the velocity terms and τ_* is the bottom friction coefficient. For the linear friction option, $\tau_* = C_f$, where C_f is the user-specified bottom friction coefficient, and that term is constant in time, but may vary in space. For the quadratic friction option, a more complex formula is used for τ_* such that $\tau_* = \frac{C_f(U^2+V^2)^{1/2}}{H}$, where H is the bathymetric depth at the node. For the so-called hybrid friction option, the same formula for τ_* as in the second option is used, but C_f is not assigned by the user, but is calculated in the code by the following formula: $C_f = C_{f\,\min}\left[1+\left(\frac{H_{break}}{H}\right)^{\theta}\right]^{\gamma/\theta}$. In this equation, H is again the bathymetric depth at a specified mesh node and H_{break} (the so-called break depth) is a depth specified by the user such that in waters deeper than H_{break} (where $H > H_{break}$), C_f approaches C_{fmin}, and in shallower waters (where $H < H_{break}$) C_f approaches $C_{fmin}(H_{break}/H)^{\gamma}$ The exponent, θ, determines how quickly C_f approaches the asymptotic limit and γ determines how quickly the friction coefficient increases as the water depth decreases. The user is required to specify C_{fmin}, H_{break}, θ, and γ. This formulation allows for increased bottom stress in very shallow water.

For the bottom friction test discussed here, the H_{break}, θ, and γ values were set to relatively low values so that the value specified for C_{fmin} would approximately equal C_f even in very shallow waters. (Basically, the parameters were set to mimic quadratic bottom friction.) These parameters were: H_{break} = 1m, $\theta = 10$, and $\gamma = 1/3$. With these parameters held constant, the differences in changing C_{fmin} could be examined. Runs were conducted using C_{fmin} = 0.002, 0.0025, 0.003, 0.0035, and 0.004. These C_{fmin} values fall in the range of the generally accepted values for a bottom friction drag coefficient and are near the ADCIRC recommended valued of 0.0025 (Luettich and Westerink 2004). Although the ADCIRC model is much more sensitive to changes in bathymetry and node configuration, this study of bottom friction parameters was conducted to confirm that the bottom friction coefficients generally chosen for large scale deep ocean to shelf water scale models are also appropriate for this near-shore coastal water model.

4. ADCIRC MODEL RESULTS

Fifteen different model runs were conducted for this study. These runs were conducted on three meshes (each with the same node and element configuration, but with different bathymetric depths at the nodes) for five different values of C_{fmin} (0.002, 0.0025, 0.003, 0.0035, and 0.004). The different meshes will be referred to as the initial mesh, the second mesh, and the third mesh. While the combined final mesh, described in the above Section 3.1, is referenced to MLLW, the initial, second and third meshes are all referenced to the ADCIRC "model zero" (MZ) elevation, which is an equipotential surface.

For the initial model set up, the depths at every node in the final combined mesh were adjusted from MLLW to MSL based on a spatial interpolation of the MSL-MLLW differences at Lake Charles (-20.5 cm) and the East Jetty station (-37.3 cm) using the before mentioned TCARI model. The local MSL can vary from MZ, but for the initial mesh, MSL and MZ were assumed to be equal. The model was run using all five of the different C_{fmin} values with the initial mesh. The absolute average error between the model results and the station data at Lake Charles (station #8767816) and the East Jetty (station #8768094) for four datums (MHHW, MHW, MLW, and MLLW all relative to MSL) was calculated for each run. These results are shown in Figure 3 and are listed as "initial mesh" results. The best run (i.e. the lowest absolute average error) was with $C_{fmin} = 0.003$, producing an absolute average error of 1.19 cm.

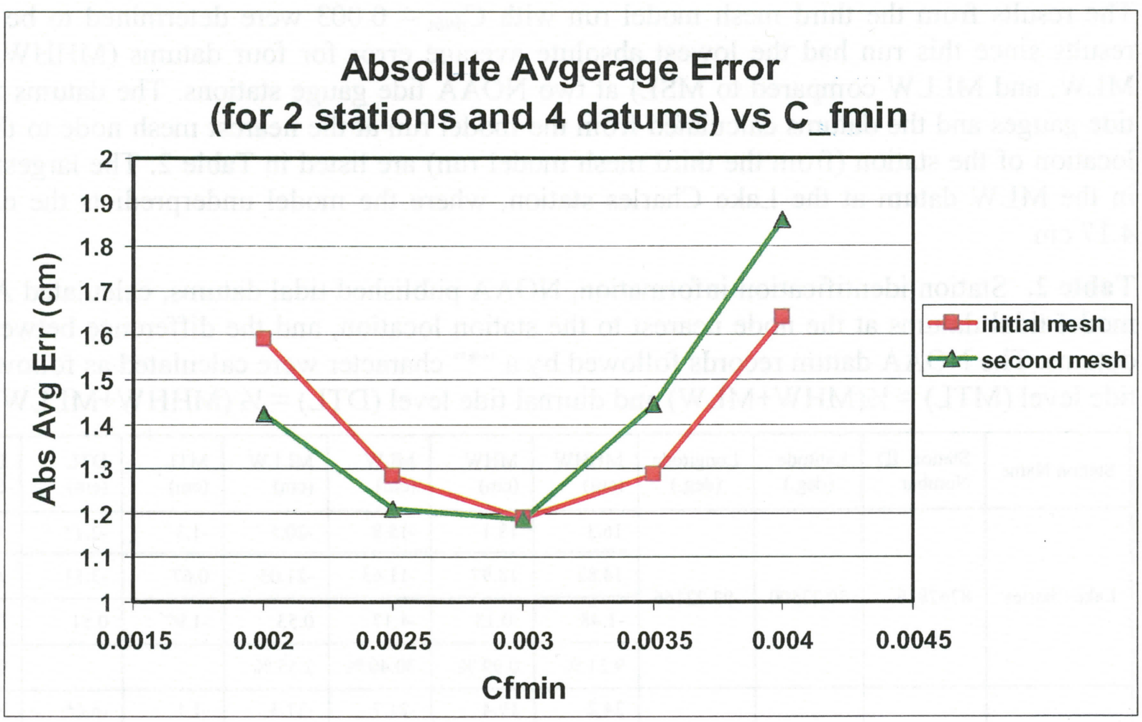

Figure 3. Absolute Average Error for modeled MHHW, MHW, MLW, and MLLW datums at the location of the Lake Charles station #8767816 and the East Jetty station #8768094.

The results from the best run with the initial mesh were used to make the second mesh. Instead of using the TCARI interpolation of data at the NOAA tide gauges, the MSL-MLLW results from the best initial mesh model run were used to convert the bathymetry in the combined final mesh (referenced to MLLW) to MSL and then the model results of the difference between MSL and MZ were used to convert the bathymetry to MZ. It should be noted that the MSL-MZ difference was less than 2 cm throughout the domain and there was no difference in the Gulf of Mexico. The mesh with the newly adjusted bathymetry was called the second mesh, which had nodes and elements in the same location as the initial mesh, but with different bathymetric values at each node. Another series of runs were conducted on this second mesh with C_{fmin} = 0.002, 0.0025, 0.003, 0.0035, and 0.004. The run with the lowest absolute average error between the station data and the model results was again the run with C_{fmin} = 0.003, with an error of 1.19 cm. The absolute average error results from all tests on this mesh are shown in Figure 3 and listed as "second mesh" results.

The MSL-MLLW results from the best second mesh model run were used to convert the combined final mesh bathymetry (referenced to MLLW) to MSL and then the model results of the difference between MSL and MZ were used to convert the bathymetry to MZ. This mesh was called the third mesh. Another series of runs were conducted on this third mesh with the same C_{fmin} values. The absolute average error results from these runs are not shown in Figure 3 since the error points and the line connecting these points falls on top of the line delineating the same error calculations from the second mesh run. The best run was with C_{fmin} = 0.003, with an absolute average error of 1.18 cm. These results for every datum and C_{fmin} test value are listed in Appendix A.

The results from the third mesh model run with C_{fmin} = 0.003 were determined to be the best results since this run had the lowest absolute average error for four datums (MHHW, MHW, MLW, and MLLW compared to MSL) at two NOAA tide gauge stations. The datums from the tide gauges and the datums calculated from the model run at the nearest mesh node to the actual location of the station (from the third mesh model run) are listed in Table 2. The largest error is in the MLW datum at the Lake Charles station, where the model underpredicts the datum by 4.17 cm.

Table 2. Station identification information, NOAA published tidal datums, calculated ADCIRC model tidal datums at the node nearest to the station location, and the difference between these datums. The NOAA datum records followed by a "*" character were calculated as follows: mean tide level (MTL) = ½(MHW+MLW) and diurnal tide level (DTL) = ½ (MHHW+MLLW).

Station Name	Station ID Number	Latitude (deg.)	Longitude (deg.)	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)	MTL (cm)	DTL (cm)	Data Origin
Lake Charles	8767816	30.22500	-93.22166	16.3	13.1	-15.8	-20.5	-1.3	-2.1*	NOAA
				14.82	12.97	-11.63	-21.03	0.67	-3.11	ADCIRC
				-1.48	-0.13	-4.17	0.53	-1.97	0.51	Difference
				9.51 %	0.99 %	30.40 %	2.55 %			% Diff
Calcasieu Pass, East Jetty	8768094	29.75833	-93.34167	24.2	19.4	-21.7	-37.3	-1.1	-6.6*	NOAA
				24.04	19.55	-19.59	-38.02	-0.02	-6.99	ADCIRC
				-0.16	0.15	-2.11	0.72	-0.54	0.20	Difference
				0.66 %	0.77 %	10.22 %	1.91 %			% Diff

While the results from the model runs could be compared to the NOAA tide gauge records, the modeled datums (at locations other than the Lake Charles and East Jetty stations) had no reference data. The change in the MSL-MLLW difference was evaluated between the different model runs to look for a general pattern of convergence. The initial MSL-MLLW difference field, developed from a TCARI spatial interpolation of the datum records at the Lake Charles and East Jetty stations, is shown in Figure 4(a). This field does not reflect the hydrodynamics that the ADCIRC model simulates. The first ADCIRC model run produced a MSL-MLLW field that showed more realistic variations in that datum field with smaller values in very shallow regions (like the West Cove) and larger values in deep channels (like the main Calcasieu River channel). These results are shown in Figure 4(b). The spatially interpolated MSL-MLLW difference field and the MSL-MLLW results from the initial model run were compared on a node by node basis and the maximum absolute difference and the average absolute difference were calculated. These comparisons are listed in Table 3. The model results from the second model run are shown in Figure 4(c). The results from the second model run were compared to the first model run and the maximum absolute difference and the average absolute differences are listed in Table 3. The MSL-MLLW model results from the third model run are shown in Figure 4(d). The maximum absolute difference and the average absolute difference between the MSL-MLLW fields from the second model run the and third model run are listed in Table 3.

Table 3. Maximum absolute and average absolute difference between MSL-MLLW results from two sources.

MSL-MLLW Source 1	MSL-MLLW Source 2	Maximum Difference (cm)	Average Difference (cm)
TCARI Spatial Interpolation	Initial Mesh Model Run	20.77	6.65
Initial Mesh Model Run	Second Mesh Model Run	2.11	0.62
Second Mesh Model Run	Third MeshModel Run	1.01	0.02

Two conclusions can be made from this analysis. First, it can be seen in Figure 4 that the hydrodynamic model results reflect a more physically accurate picture of the tidal datum fields compared to a TCARI interpolation. Second, the average and maximum differences between the model runs decreases not only between the TCARI interpolation and the ADCIRC model results, but also between modeled outputs over the iteration process. The average difference between the last two model runs is negligible: only two-hundredths of a centimeter. This leads one to believe that the model results are converged to a physically accurate solution.

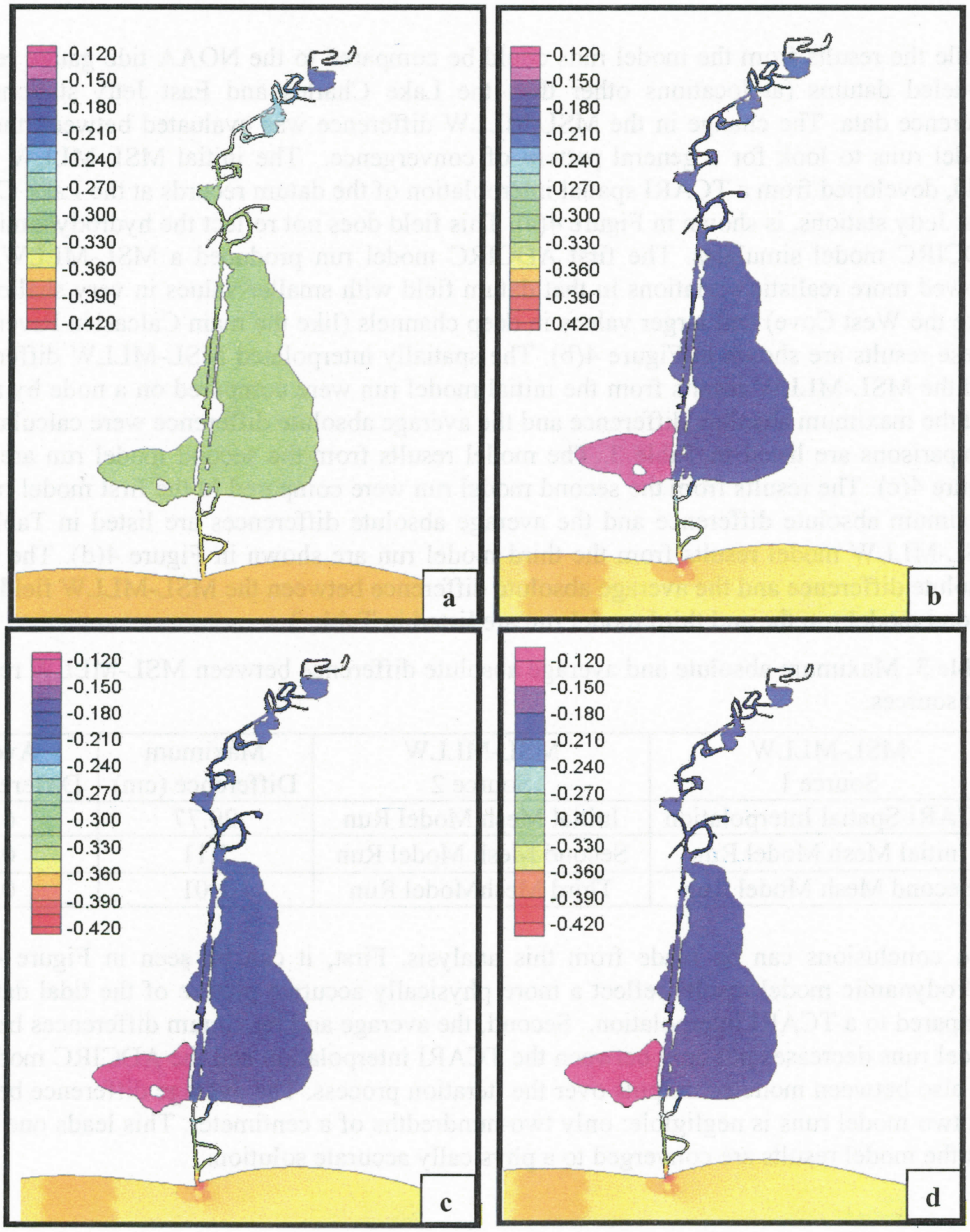

Figure 4. The MSL-MLLW difference (m) from (a) a Laplacian interpolation of the datums at the Lake Charles and East Jetty NOAA tide gauges, (b) the output from the initial model run, (c) the output from the second model run, and (d) the output from the third model run.

5. INTERPOLATION OF ERRORS

Even though the model results very closely matched the tide gauge data and appeared to converge to the correct hydrodynamic solution throughout the domain, it was important to ensure that the final results used in the VDatum marine grid matched the NOAA tide gauge data exactly. This match was guaranteed by using the finite element implementation of TCARI to spatially interpolate the error between the tide gauge data and the ADCIRC model results. This error field (for each datum) was then added to the ADCIRC model results, which produced an exact match of the datums at the tide gauge stations. Figure 5 shows the TCARI interpolation of the MSL-MLW errors and the final corrected MSL-MLW tidal datum results (chosen since that was the datum with the highest errors). From the corrected MHHW, MHW, MLW and MLLW tidal datum fields, the Mean Tide Level (MTL) and Diurnal Tide Level (DTL) were computed such that MTL = ½(MHW+MLW) and DTL = ½ (MHHW+MLLW). These six final tidal datum fields were used for the population of the VDatum marine grid and are shown in Appendix B.

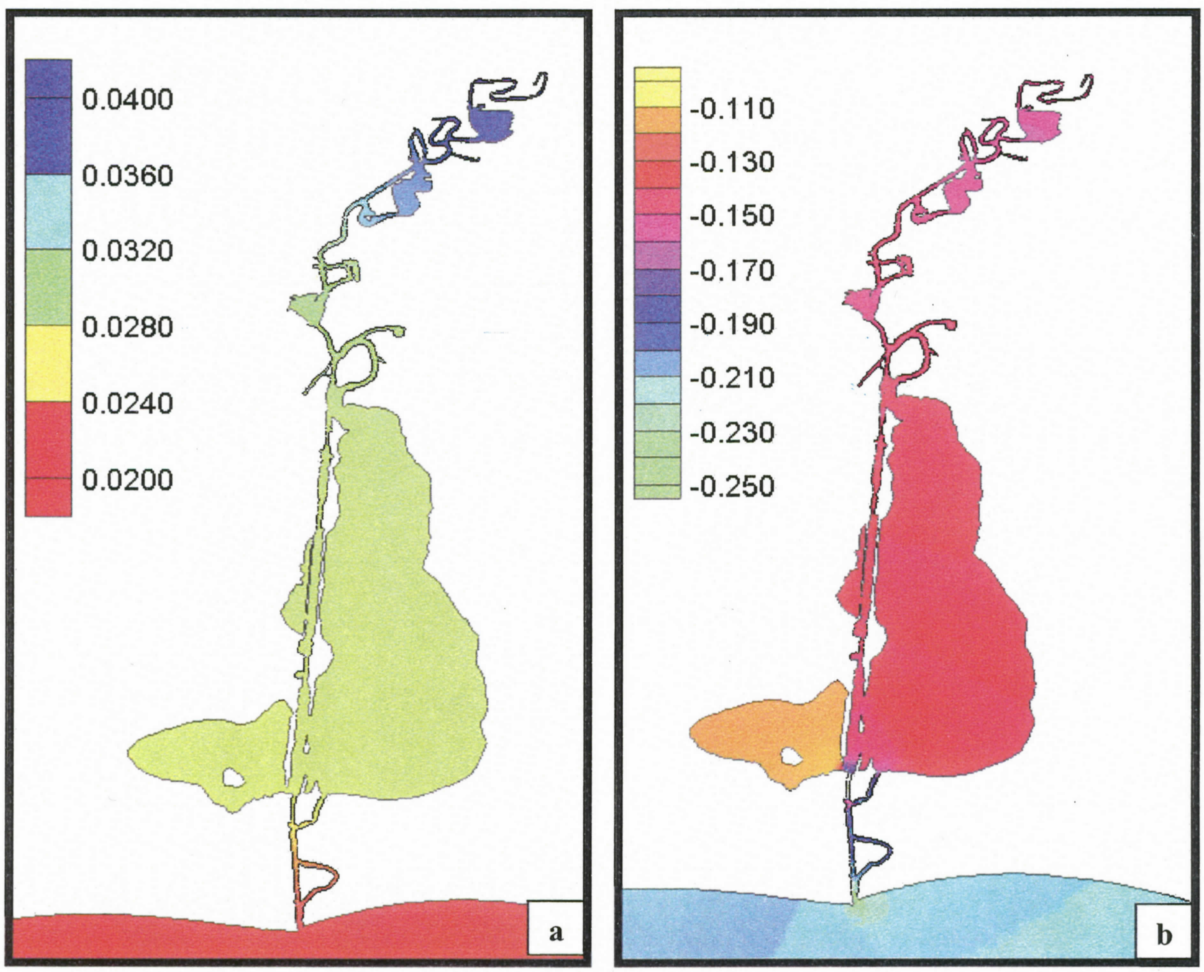

Figure 5. (a) TCARI MSL-MLW error correction results (m) using two forcing stations (Lake Charles station #8767816 and East Jetty station #8768094) and (b) the final corrected MSL-MLW model results (m).

6. THE VDATUM MARINE GRID

The VDatum software requires a regularly girded data, so the unstructured mesh used for the ADCIRC and TCARI model runs could not be used. Therefore, a new VDatum marine grid was generated with a Δx of 0.0021 degrees and Δy of 0.0018 degrees, resulting in the spacing between points of about 200 m (0.1 nmi). The grid resulting from this process has a width of 109 points and a height of 501 points, totaling 54,609 points. The grid is bounded between the latitudes 29.34° in the south and 30.24° in the north, and the longitudes -93.445° in the west and -93.218333° in the east.

The VDatum marine grid was populated using the Fortran program vpop5.f. This program interpolates the corrected ADCIRC model results onto the VDatum marine grid. The basic program is described by Hess and White (2004), but changes to the program were made to interpolate the final tidal datum results from an unstructured mesh onto the regular VDatum marine grid. The vpop5.f program finds a value for each marine point by averaging all of the ADCIRC mesh points within a user-specified radius or the closest user-specified number of points. The program was set to use the 10 closest points. However, looking only at the 10 closest points, the program does not account for landforms that affect the hydrodynamics of the model. For example, the West Cove area (see Figure 1) has a very small tide range, but the main channel of the Calcasieu River, which is on the other side of a long island separating the two bodies of water, has a much larger tide range. When selecting only the 10 closest points, the program averages the high values of the river with the low values in West Cove to get an average datum value, which makes the values in the West Cove area of the VDatum marine grid too large and the values of the Calcasieu River area of the VDatum marine grid too small. To remedy this problem, the area was divided into three separate regions contained within three different bounding polygons. Three separate VDatum marine grids were created to correspond to these regions, where all areas outside the associated bounding polygon were designated as land. For each region, only ADCIRC mesh nodes within the bounding polygon were used to populate the VDatum marine grid. One bounding polygon restricts the selection process to only the West Cove, another region restricts the selection process to only the main area of the Calcasieu Lake and the final bounding polygon covers the rest of the domain. The boundary lines that divide the main area of the Calcasieu Lake and the Calcasieu River were selected so that there are no discontinuities between the different regions (i.e. the boundary was selected in a region where the tidal datums are slowly varying). The regional VDatum marine grids and associated bounding polygons are shown in Figure 6.

A final check was done to compare the final corrected datums in the VDatum marine grid with the NOAA tide gauge data. The VDatum marine grid used for this analysis was the marine grid that contains the Gulf of Mexico and Calcasieu River channel since bounding polygon defining this region contains both the East Jetty and Lake Charles stations. Table 4 lists the station information for the two stations in the domain and the final root mean square error (RMSE) (cm) error, which was calculated as the RMSE for MHHW, MHW, MLW, and MLLW at each station.

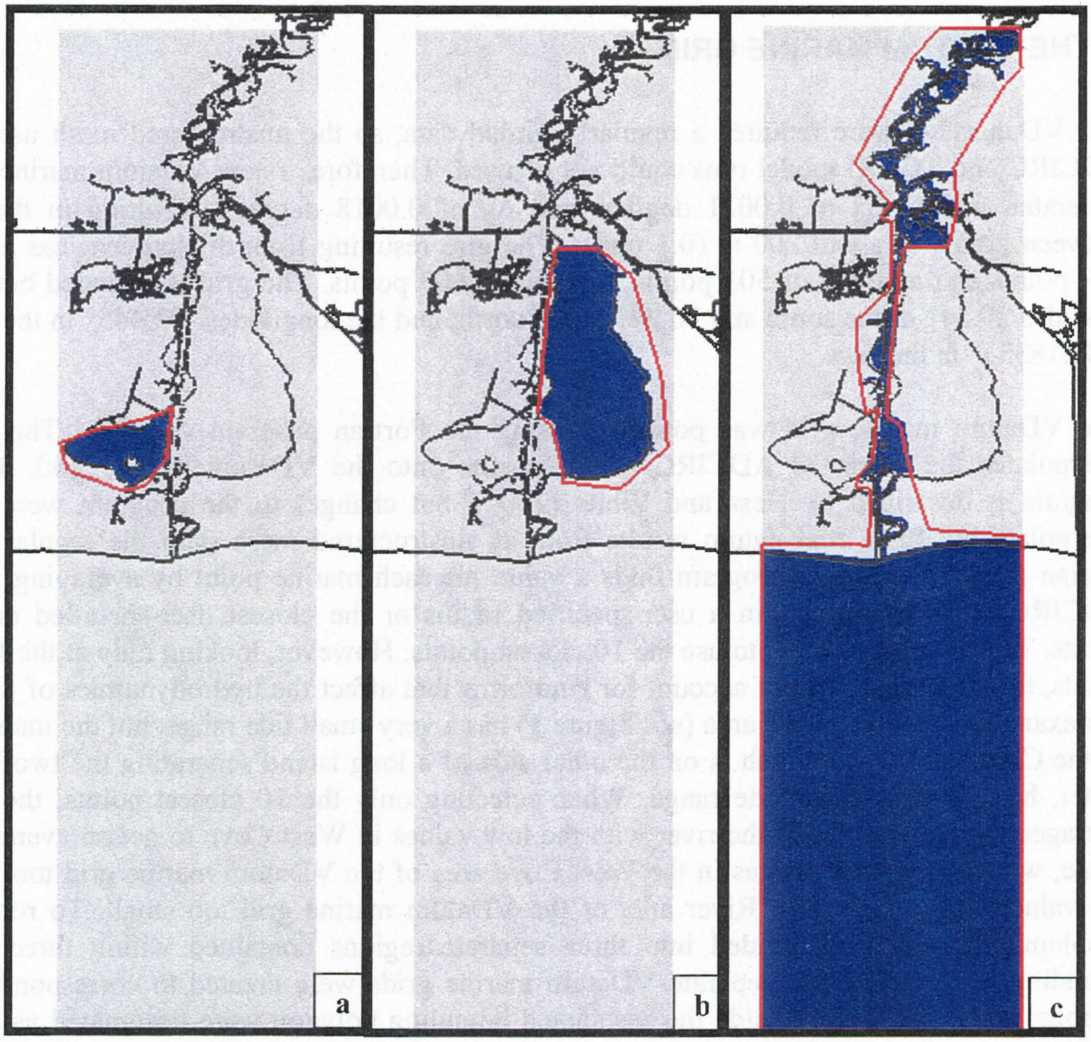

Figure 6. VDatum marine grid (blue) and land grid (grey) with the MHW shoreline (black) and bounding polygons (red) for (a) the West Cove region, (b) the main Lake Calcasieu region, and (c) the main region of the Lake Charles/Calcasieu River/Gulf of Mexico region.

Table 4. Station identification information and the RMSE (cm) calculated for four tidal datums (MHHW, MHW, MLW, and MLLW) in the VDatum grid compared to the NOAA tide gauge station datums.

Station Name	Station ID Number	Latitude	Longitude	RMSE (cm)
Lake Charles	8767816	30.22500	-93.22166	0.000
Calcasieu Pass, East Jetty	8768094	29.75833	-93.34167	0.373

7. SEA SURFACE TOPOGRAPHY

The sea surface topography defines the difference between the elevation of NAVD88 and local mean sea level (LMSL). The sea surface topography is based on the relationship between these datums at NOAA tide gauges. Only one tide station with benchmark ties to NAVD88 exists in the Lake Charles VDatum area: Lake Charles (NOAA station #8767816). At this station, the difference between NAVD88 and LMSL is – 0.354 m (i.e. NAVD88 is 0.354 m below MSL). Since there is only one station, the sea surface topography was defined as a constant value of –0.354 m over the entire domain. Based on other estuaries, one would expect some variation in the NAVD88 to MSL difference as one progresses up the system from the Gulf of Mexico entrance up into Lake Charles, but with no other published data, no adjustments to the sea surface topography constant can be made. Recent GPS work at the East Jetty suggests a NAVD88 to LMSL difference of -0.254, but this is based only on a GPS occupation of one benchmark for a short time period. NGS is continuing to refine the NAVD88 reference system for all of Louisiana by taking into account rates of vertical movement using repeat GPS surveys over time (Tronvig et al, 2003). Changes to the VDatum sea surface topography field may be made in the future when studies of the NAVD88 reference system in Louisiana are completed.

ACKNOWLEGEMENTS

Kurt Hess of CSDL provided support in evaluating ADCIRC model results and generating the VDatum marine grids. Bathymetric data was supplied by Adeline Wong of CSDL. The tide datum information used for model validation and interpolation of the errors was supplied by NOS' CO-OPS.

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APPENDIX A. RESULTS FROM BOTTOM FRICTION TESTING

Table A.1. Model run tidal datum results compared to NOAA datums at Lake Charles, Louisiana (Station #8767816) for a series tests using three meshes (with different bathymetry) and five different bottom friction parameters. Negative error values mean that the model was underpredicting and positive error values mean the model was overpredicting.

Mesh/Run Name	Cfmin	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)	
Initial Mesh Runs	0.002	16.30	13.10	-15.80	-20.50	NOAA
		17.37	15.09	-14.26	-24.86	Model
		1.07	1.99	-1.54	4.36	Difference
		6.36%	14.12%	10.25%	19.22%	% Diff
	0.0025	16.30	13.10	-15.80	-20.50	NOAA
		16.15	14.07	-13.23	-23.29	Model
		-0.15	0.97	-2.57	2.79	Difference
		0.92%	7.14%	17.71%	12.74%	% Diff
	0.003	16.30	13.10	-15.80	-20.50	NOAA
		15.12	13.23	-11.90	-21.50	Model
		-1.18	0.13	-3.90	1.00	Difference
		7.51%	0.99%	28.16%	4.76%	% Diff
	0.0035	16.30	13.10	-15.80	-20.50	NOAA
		14.30	12.55	-11.24	-20.43	Model
		-2.00	-0.55	-4.56	-0.07	Difference
		13.07%	4.29%	33.73%	0.34%	% Diff
	0.004	16.30	13.10	-15.80	-20.50	NOAA
		13.87	11.96	-10.69	-19.10	Model
		-2.43	-1.14	-5.11	-1.40	Difference
		16.11%	9.10%	38.58%	7.07%	% Diff
Second Mesh Runs	0.002	16.30	13.10	-15.80	-20.50	NOAA
		17.02	14.81	-13.94	-24.32	Model
		0.72	1.71	-1.86	3.82	Difference
		4.32%	12.25%	12.51%	17.05%	% Diff
	0.0025	16.30	13.10	-15.80	-20.50	NOAA
		15.82	13.79	-12.93	-22.79	Model
		-0.48	0.69	-2.87	2.29	Difference
		2.99%	5.13%	19.98%	10.58%	% Diff
	0.003	16.30	13.10	-15.80	-20.50	NOAA
		14.81	12.96	-11.63	-21.03	Model
		-1.49	-0.14	-4.17	0.53	Difference
		9.58%	1.07%	30.40%	2.55%	% Diff
	0.0035	16.30	13.10	-15.80	-20.50	NOAA
		14.01	12.30	-10.98	-19.99	Model
		-2.29	-0.80	-4.82	-0.51	Difference
		15.11%	6.30%	36.00%	2.52%	% Diff

Table A.1. CONTINUED

Mesh/Run Name	Cfmin	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)	
Second Mesh Runs	0.004	16.30	13.10	-15.80	-20.50	NOAA
		13.34	11.72	-10.43	-18.69	Model
		-2.96	-1.38	-5.37	-1.81	Difference
		19.97%	11.12%	40.95%	9.24%	% Diff
Third Mesh Runs	0.002	16.30	13.10	-15.80	-20.50	NOAA
		17.02	14.81	-13.95	-24.33	Model
		0.72	1.71	-1.85	3.83	Difference
		4.32%	12.25%	12.44%	17.09%	% Diff
	0.0025	16.30	13.10	-15.80	-20.50	NOAA
		15.83	13.80	-12.93	-22.78	Model
		-0.47	0.70	-2.87	2.28	Difference
		2.93%	5.20%	19.98%	10.54%	% Diff
	0.003	16.30	13.10	-15.80	-20.50	NOAA
		14.82	12.97	-11.63	-21.03	Model
		-1.48	-0.13	-4.17	0.53	Difference
		9.51%	1.00%	30.40%	2.55%	% Diff
	0.0035	16.30	13.10	-15.80	-20.50	NOAA
		14.02	12.30	-10.98	-19.99	Model
		-2.28	-0.80	-4.82	-0.51	Difference
		15.04%	6.30%	36.00%	2.52%	% Diff
	0.004	16.30	13.10	-15.80	-20.50	NOAA
		13.34	11.72	-10.44	-18.69	Model
		-2.96	-1.38	-5.36	-1.81	Difference
		19.97%	11.12%	40.85%	9.24%	% Diff

Table A.2. Model run tidal datum results compared to NOAA datums at Calcasieu Pass East Jetty (Station #8768094) for a series tests using three meshes (with different bathymetry) and five different bottom friction parameters. Negative error values mean that the model was underpredicting and positive error values mean the model was overpredicting.

Mesh/Run Name	Cfmin	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)	
Initial Mesh Runs	0.002	24.20	19.40	-21.70	-37.30	NOAA
		23.00	19.18	-19.91	-37.85	Model
		-1.20	-0.22	-1.79	0.55	Difference
		5.08%	1.14%	8.60%	1.46%	% Diff
	0.0025	24.20	19.40	-21.70	-37.30	NOAA
		23.46	19.26	-19.41	-37.91	Model
		-0.74	-0.14	-2.29	0.61	Difference
		3.11%	0.72%	11.14%	1.62%	% Diff

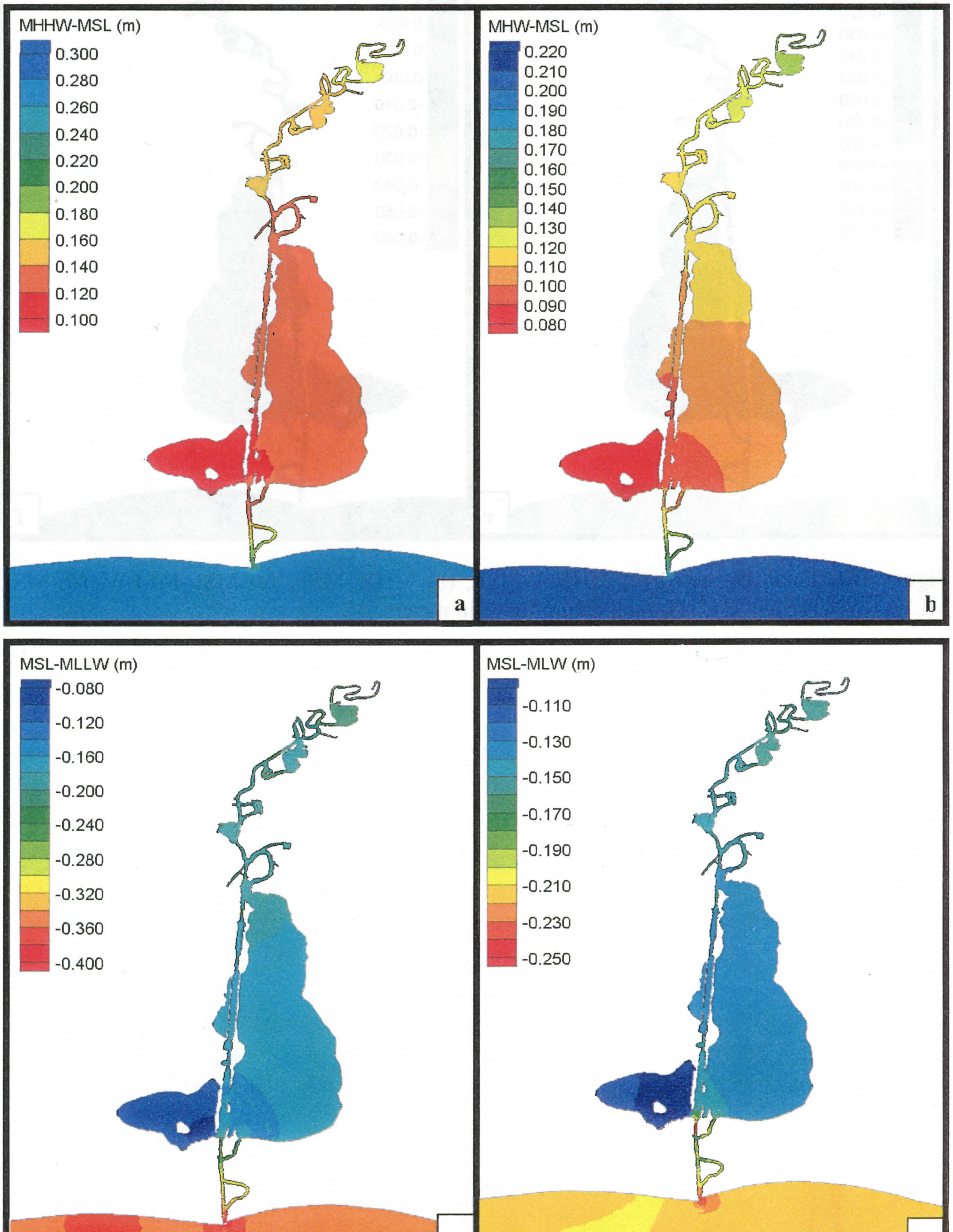
Table A.2. CONTINUED

Mesh/Run Name	Cfmin	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)	
Initial Mesh Runs	0.003	24.20	19.40	-21.70	-37.30	NOAA
		23.79	19.43	-19.50	-37.95	Model
		-0.41	0.03	-2.20	0.65	Difference
		1.71%	0.15%	10.68%	1.73%	% Diff
	0.0035	24.20	19.40	-21.70	-37.30	NOAA
		24.04	19.55	-19.58	-37.98	Model
		-0.16	0.15	-2.12	0.68	Difference
		0.66%	0.77%	10.27%	1.81%	% Diff
	0.004	24.20	19.40	-21.70	-37.30	NOAA
		24.24	19.64	-19.63	-37.98	Model
		0.04	0.24	-2.07	0.68	Difference
		0.17%	1.23%	10.02%	1.81%	% Diff
Second Mesh Runs	0.002	24.20	19.40	-21.70	-37.30	NOAA
		23.31	19.34	-20.00	-37.93	Model
		-0.89	-0.06	-1.70	0.63	Difference
		3.75%	0.31%	8.15%	1.67%	% Diff
	0.0025	24.20	19.40	-21.70	-37.30	NOAA
		23.73	19.40	-19.50	-37.98	Model
		-0.47	0.00	-2.20	0.68	Difference
		1.96%	0.00%	10.68%	1.81%	% Diff
	0.003	24.20	19.40	-21.70	-37.30	NOAA
		24.04	19.55	-19.58	-38.02	Model
		-0.16	0.15	-2.12	0.72	Difference
		0.66%	0.77%	10.27%	1.91%	% Diff
	0.0035	24.20	19.40	-21.70	-37.30	NOAA
		24.27	19.66	-19.65	-38.04	Model
		0.07	0.26	-2.05	0.74	Difference
		0.29%	1.33%	9.92%	1.96%	% Diff
	0.004	24.20	19.40	-21.70	-37.30	NOAA
		24.46	19.75	-19.69	-38.04	Model
		0.26	0.35	-2.01	0.74	Difference
		1.07%	1.79%	9.71%	1.96%	% Diff
Third Mesh Runs	0.002	24.20	19.40	-21.70	-37.30	NOAA
		23.31	19.34	-20.00	-37.93	Model
		-0.89	-0.06	-1.70	0.63	Difference
		3.75%	0.31%	8.15%	1.67%	% Diff
	0.0025	24.20	19.40	-21.70	-37.30	NOAA
		23.74	19.41	-19.49	-37.97	Model
		-0.46	0.01	-2.21	0.67	Difference
		1.92%	0.05%	10.73%	1.78%	% Diff
	0.003	24.20	19.40	-21.70	-37.30	NOAA
		24.04	19.55	-19.59	-38.02	Model
		-0.16	0.15	-2.11	0.72	Difference
		0.66%	0.77%	10.22%	1.91%	% Diff

Table A.2. CONTINUED

Mesh/Run Name	Cfmin	MHHW (cm)	MHW (cm)	MLW (cm)	MLLW (cm)	
	0.003	24.20	19.40	-21.70	-37.30	NOAA
		24.04	19.55	-19.59	-38.02	Model
		-0.16	0.15	-2.11	0.72	Difference
		0.66%	0.77%	10.22%	1.91%	% Diff
	0.0035	24.20	19.40	-21.70	-37.30	NOAA
		24.27	19.66	-19.65	-38.04	Model
		0.07	0.26	-2.05	0.74	Difference
		0.29%	1.33%	9.92%	1.96%	% Diff
	0.004	24.20	19.40	-21.70	-37.30	NOAA
		24.45	19.75	-19.69	-38.04	Model
		0.25	0.35	-2.01	0.74	Difference
		1.03%	1.79%	9.71%	1.96%	% Diff

APPENDIX B. FINAL, CORRECTED TIDAL DATUM FIELDS



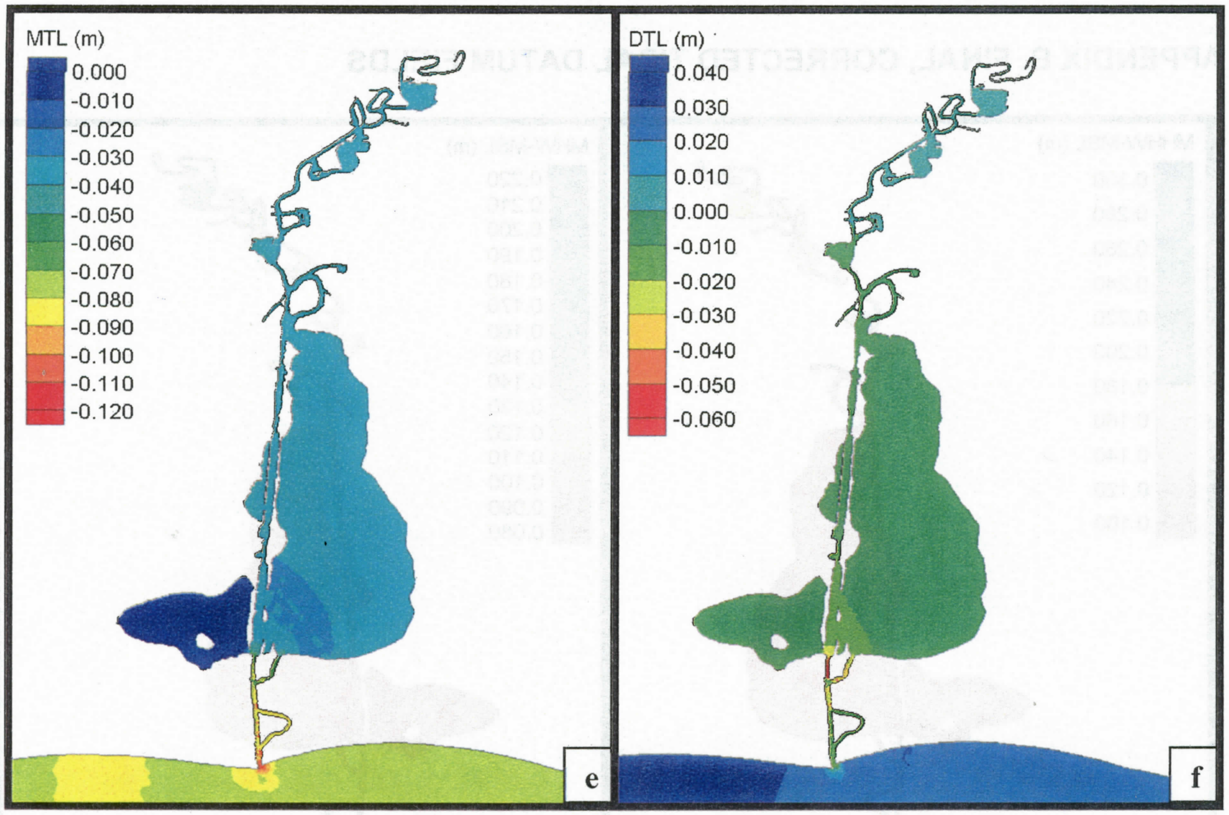


Figure B.1. Final, corrected (a) MHHW-MSL, (b) MHW-MSL, (c) MSL-MLLW, (d) MSL-MLW, (e) MTL, and (f) DTL tidal datum fields in meters.