NOAA Technical Memorandum NOS CS 33

VDATUM FOR THE COASTAL WATERS OF PUERTO RICO AND THE U.S. VIRGIN ISLANDS: TIDAL DATUMS, MARINE GRID, AND SEA SURFACE TOPOGRAPHY

Silver Spring, Maryland
December 2013

noaa **National Oceanic and Atmospheric Administration**

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

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

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ABSTRACT

VDatum, a software tool for vertical datum transformations, is developed for providing spatially-varying conversions between tidal, orthometric, and ellipsoid-based three-dimensional reference frames. The present study is focused on establishing vertical datum transformations for an area covering the coastal waters of Puerto Rico and the U.S. Virgin Islands.

To support VDatum, gridded fields with the conversions among various tidal datums, mean sea level and the Puerto Rico Vertical Datum of 2002 (PRVD02) or the Virgin Island Vertical Datum of 2009 (VIVD09) were generated. The tidal datums were derived from tidal simulations using the finite element hydrodynamic model ADCIRC. An unstructured triangular grid consisting of 274,885 nodes and 522,334 cells was created for the model simulations. The model was forced by a reconstructed tide at the ocean boundary using the harmonic constants of nine tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, and M_4) from the global tidal model TPXO7.2. Hydrodynamic conditions were simulated for 40 days. The 6-minute water level time series from the last 32 days of the simulation were used to derive various tidal datum fields, including Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Low Water (MLW), and Mean Lower Low Water (MLLW). Model-derived tidal datums were compared with the observations at 33 water level gages maintained by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS). The root mean square error (RMSE) for all tidal datums was 1.2 cm. To reduce this error, a two-dimensional correction field was constituted by spatially interpolating the error values at each tide station onto the model grid using Tidal Constituent And Residual Interpolation (TCARI), a spatial interpolation tool based on solution of Laplace's equation. The correction fields were then added to the modeled tidal datums to derive the corrected tidal datums on the model grid. These corrected tidal datums were further interpolated from the unstructured triangular grid onto a regularly structured marine grid to be used by the VDatum software.

The Topography of the Sea Surface (TSS), defined as the elevation of PRVD02/VIVD09 relative to mean sea level (MSL), was derived by interpolating orthometric-to-MSL relationships at NOAA tide gauges. The final TSS field on the marine grid was created using minimum curvature interpolation algorithm.

Key Words: vertical datum, tides, tidal datums, Puerto Rico, the U.S. Virgin Islands, circulation model, mean sea level, bathymetry, coastline, spatial interpolation, Puerto Rico Vertical Datum of 2002, Virgin Island Vertical Datum of 2009

1. INTRODUCTION

The National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) has developed a software tool called VDatum allowing users to transform elevation and bathymetry data among approximately 30 vertical datums (Gill and Schultz, 2001; Hess et al., 2003; Milbert, 2002; Parker, 2002; Myers et al., 2005). For example, using VDatum, the data sets referenced to different vertical datums can be transformed into those referenced to a common vertical datum through the inherent geoidal, ellipsoidal, and tidal datum relationships (Parker et al., 2003; Hess et al., 2005).

VDatum requires two-dimensional gridded fields of the tidal datums and the Topography of the Sea Surface (TSS). The tidal datums include Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Low Water (MLW), and Mean Lower Low Water (MLLW) referenced to mean sea level (MSL). The TSS refers to the elevation of the geodetic datum relative to MSL. The North American Vertical Datum of 1988 (NAVD88) referenced to MSL is used as the TSS in the U.S. continental coast regions. The Puerto Rico Vertical Datum of 2002 (PRVD02) and the Virgin Island Vertical Datum of 2009 (VIVD09) referenced to MSL is defined as the TSS for Puerto Rico and the U.S. Virgin Islands, respectively.

Each VDatum application covers a particular coastal region since the tides and the TSS vary widely. Tidal datum and TSS fields have so far been available throughout the coastal regions in the continental U.S., including Tampa Bay (Hess, 2001), Puget Sound (Hess and Gill, 2003; Hess and White, 2004), central/northern North Carolina (Hess et al., 2005), the Strait of Juan de Fuca (Spargo et al., 2006a), Delaware and Chesapeake Bays (Yang et al., 2008a), Long Island Sound and New York Bight and Harbor (Yang et al., 2008b; Yang et al., 2010b), the northeast Gulf of Mexico (Dhingra et al., 2008), southern California (Yang et al., 2009), the eastern Louisiana and Mississippi coastal waters (Yang et al., 2010a), the Pacific Northeast region (Xu et al., 2010), the Texas coast (Xu et al., 2013), the Florida coast (Yang et al., 2012) and the Gulf of Maine (Yang et al., 2013).

This report describes the development of VDatum for an area covering the coastal waters of Puerto Rico and the U.S. Virgin Islands (Figure 1). The tidal datums were derived from tidal simulations using the finite element hydrodynamic model ADCIRC (Westerink et al., 1993). Various tidal datum fields (MHHW, MHW, MLW, and MLLW) were calculated using the simulated water level time series and verified by comparing with the observations at the water level stations along the coasts of Puerto Rico and the U.S. Virgin Islands. The error values at each station were spatially interpolated onto model grid using Tidal Constituent and Residual Interpolation (TCARI) (Hess, 2002; Hess, 2003) to derive the correction fields. The corrected tidal datum fields were then populated onto the regularly structured marine grid directly used by VDatum. In addition, the TSS (i.e. PRVD02/VIVD09-to-MSL) field was derived by spatially interpolating the TSS value at each station onto the marine grid using minimum curvature scheme.

This technical report is organized as follows: After an introduction in Section 1, Section 2 describes the data sources used for hydrodynamic model setup and validation. The data include digital coastline, bathymetry, and tidal datums derived from observational data. Section 3 discusses model grid development, model setup and validation, and tidal datum calculation and correction. Section 4 discusses creation of the regularly structured marine grid required for the VDatum software tool and population of error-corrected model datums onto the marine grid. In Section 5, creation of the TSS field for the area is described. Finally, a summary is given in Section 6.

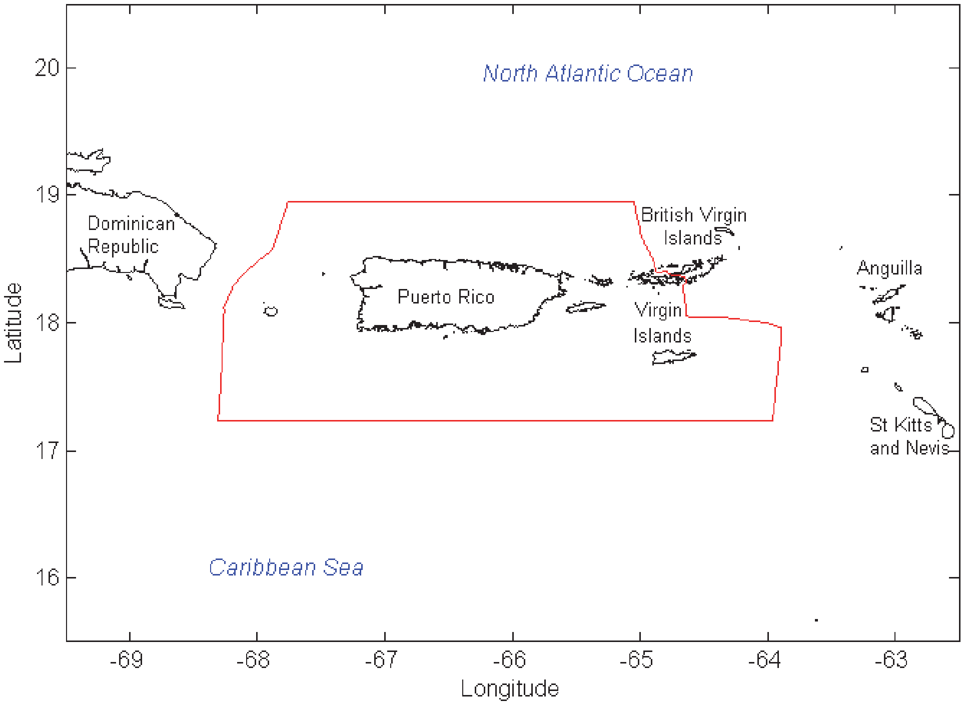


Figure 1. Map of the coastal areas of Puerto Rico and the U.S. Virgin Islands. The black lines are the MHW shoreline. The red line is the VDatum bounding polygon.

2. DATA DESCRIPTION

Development of the hydrodynamic model used for deriving tidal datum fields in this region requires three types of data: coastline, bathymetry, and water level observations. Coastline and bathymetric data are used to construct the model grid for tidal simulations. Tidal datums calculated from water level observations provide verification and correction of the model-derived datum fields.

2.1. Digital Coastline

Two MHW vector shoreline datasets were used in this study to delineate the land-water boundaries and to guide development of the hydrodynamic model grid. The shoreline of Puerto Rico and the U.S. Virgin Islands was compiled from the Electronic Navigational Chart (ENC) data (http://ocs-spatial.ncd.noaa.gov/encdirect/viewer.htm) from the NOS Office of Coast Survey (OCS) and was verified with the most up to date NOAA Raster Navigational Charts (http://www.csc.noaa.gov/digitalcoast/tools/chartreprojector). The shoreline of other Caribbean and South American regions was from Prototype Global Shoreline Data developed by National Geospatial-Intelligence Agency (NGA) (http://msi.nga.mil/NGAPortal/DNC.portal). In Figure 1, the black line illustrates the integrated MHW coastline.

2.2. Bathymetric Data

Two bathymetric datasets used in this study were obtained from National Geophysical Data Center (NGDC) (http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html): (1) the Digital Elevation Models (DEMs) of Puerto Rico (Taylor et al., 2008) and the U.S. Virgin Islands (Grothe et al., 2010); (2) the one arc-minute global relief model ETOPO1 (Amante and Eakins, 2009) for the surrounding Caribbean Sea and Atlantic Ocean. The DEMs were integrated from the NOS sounding, multibeam, and LiDAR data (Figure 2) and were adjusted to be referenced to MHW.

2.3. Tidal Datum Elevations

Tidal datums derived from CO-OPS water level observations were used for verifying and correcting the model datum fields. There are a total of 33 stations with available tidal datum values relative to the 1983-2001 National Tidal Datum Epoch (NTDE). Tables A.1 and A.2 in Appendix A list the station information and the corresponding tidal datum values.

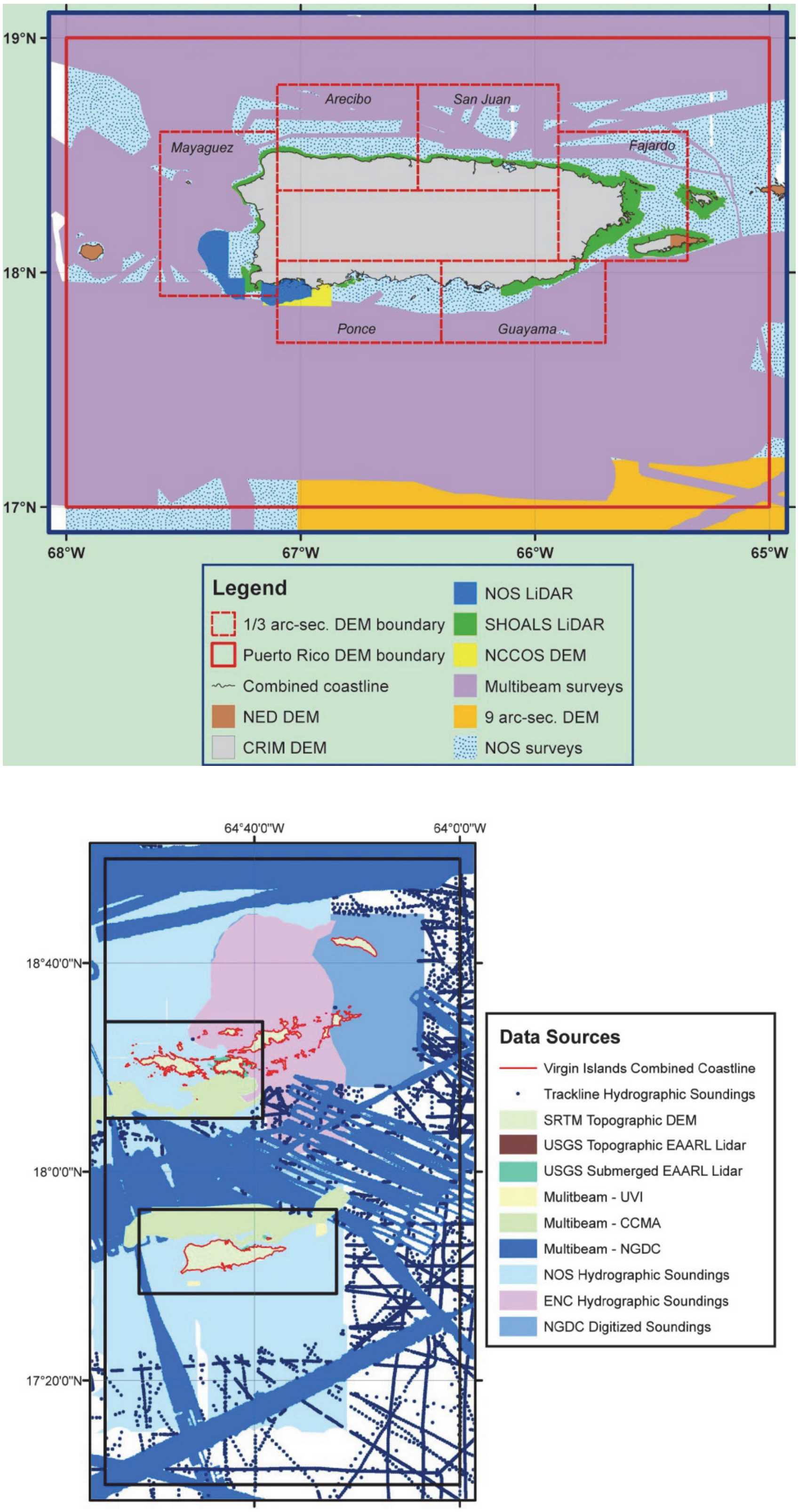


Figure 2. Source and coverage of datasets used in compiling bathymetry for Puerto Rico (top panel, from Taylor et al., 2008) and the U.S. Virgin Islands (bottom panel, from Grothe et al., 2010) DEMs.

3. TIDAL SIMULATION AND DATUM COMPUTATION

3.1. Hydrodynamic Model

The ADCIRC (ADvanced CIRCulation) model was employed to simulate tidal water levels within the study domain. The ADCIRC model was designed to solve time-dependent, free surface circulation and hydrodynamic problems in two and three dimensions using a finite element scheme on an unstructured grid (Luettich et al., 1992; Westerink et al., 1994). The ADCIRC Two-Dimensional Depth Integrated (2DDI) version used for this study is the barotropic version of the model. The ADCIRC model has been extensively applied in simulating tides (Westerink et al., 1993; Luettich et al., 1999; Mukai et al., 2002) and storm surge (Blain et al., 1998; Westerink et al., 2008; Demirbilek et al., 2008) in ocean and coastal waters. The details of model grid development and model setup for the present study are described in the following sections.

3.2. Model Grid Development

At the initial stage of this project, we had discussions with Juan Gonzalez and Aurelio Mercado in University of Puerto Rico, who did substantial modeling work for Puerto Rico and the U.S. Virgin Islands. They kindly provided us with useful experience and information as well as a triangular mesh that they developed for coastal circulation modeling. However their mesh does not have the VDatum-required resolution at the coastal waters around Puerto Rico and the U.S. Virgin Islands. Thus we decided to develop a new triangular mesh with relatively high resolution for the coastal waters. We also incorporated updated shoreline and bathymetry data into building the new mesh.

Three main steps were required to develop the model grid for the VDatum tidal simulations: determination of model domain, generation of triangular mesh, and population of model grid with bathymetric data.

It was a challenge to determine the model domain for this VDatum application given the unique features of geography, ocean bathymetry (Figure 4) and tides (Appendix B) around Puerto Rico and the U.S. Virgin Islands (PRVI). PRVI includes hundreds of islands, lying at the boundary between the Caribbean and North American plates. The Puerto Rico Trench, as subduction zone, is located about 120 km north of Puerto Rico, with a maximum depth of 8,380 m. There are extremely sharp shelf breaks to both the northern and southern sides of PRVI (Figure 5). There is also an M_2 tidal amphidromic point to the southeast of PRVI (Figure B.1 in Appendix B). The M_2 tidal amplitude increases abruptly from the south to the north across the coastal waters in between the PRVI islands. Thus it is necessary to make the model open boundaries far away from the PRVI coastal waters for model stability. In addition, other Caribbean islands to the southeast of PRVI may have significant effects on the tides around PRVI. It is also necessary to include the ocean waters around these islands in the model domain. Based on the above analyses and some preliminary modeling tests, two open boundaries were determined to define the model domain as shown in Figure 3. The locations where the open boundaries cross onto the land were carefully selected and tested to avoid the model instability at these regions.

An unstructured triangular mesh (Figure 3) was generated over the prescribed domain for the ADCIRC model utilizing the Surface-water Modeling Solution (SMS) software package (http://www.aquaveo.com/sms). The shoreline data (section 2.1) were imported into SMS and were modified for easier mesh paving. The shoreline modification is usually the most time-consuming work during grid development, including removing unnecessary features, redistributing arc nodes to represent a certain resolution, and reconnecting arcs to build polygons. The polygons with the edited shoreline and open boundaries representing ocean waters were then paved by triangular elements with linearly scaled resolutions. The final mesh has 522,334 triangular elements and 274,885 nodes. The resolution of the final mesh ranged from ~55 km in the open ocean down to ~15 m in the PRVI coastal waters. The larger elements in the deep ocean are sufficient for capturing the tide propagation there and allow for computational efficiency. The smaller elements in the coastal waters are able to represent small geographical features (such as inlets, channels and bays) that are important to the local tides. Figure 6 shows the close-up views of the grid around San Juan and in the channels and bays in between St. Thomas and St. John Islands.

The triangular mesh was then populated with the bathymetric data described in Section 2.2. The depths on the grid nodes were calculated using linear triangle interpolation from the surrounding scattered data points. As a result, the grid depths derived from the bathymetric data of the PRVI DEMs were referenced to MHW. The model bathymetry were then adjusted to the model zero (MZ), a geopotential surface by an iterative process. The model zero is assumed to be equal to the mean sea level (MSL) at the observational stations. Initially, a MHW-to-MSL difference of 12 cm was estimated from the mean of 33 stations and was applied elsewhere to the grid depths. After a 40-day tide simulation, the computed spatially-varying MHW-to-MSL field was applied to the original grid depths to derive the new grid depths. This process was repeated until depth adjustments at most grid nodes converged to within 1 cm of their final values. Given the low tidal range around Puerto Rico and the U.S. Virgin Islands, only three simulations were needed to fulfill the requirement for depth adjustment. The final grid bathymetry is shown in Figure 4 and 5.

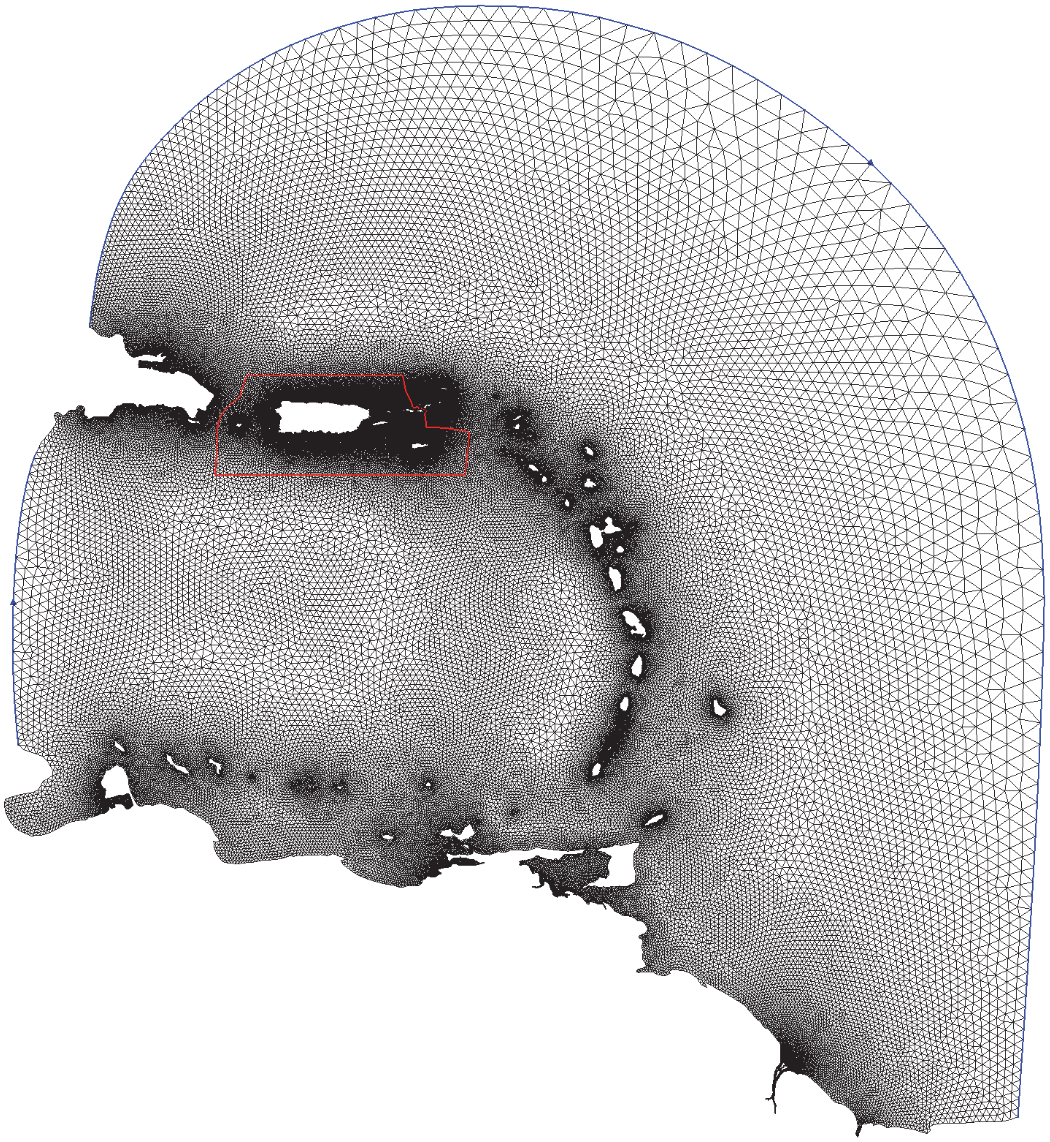


Figure 3. Finite element triangular grid for the entire model domain. The blue lines are the open ocean boundaries for tidal simulation. The red line is the VDatum bounding polygon.

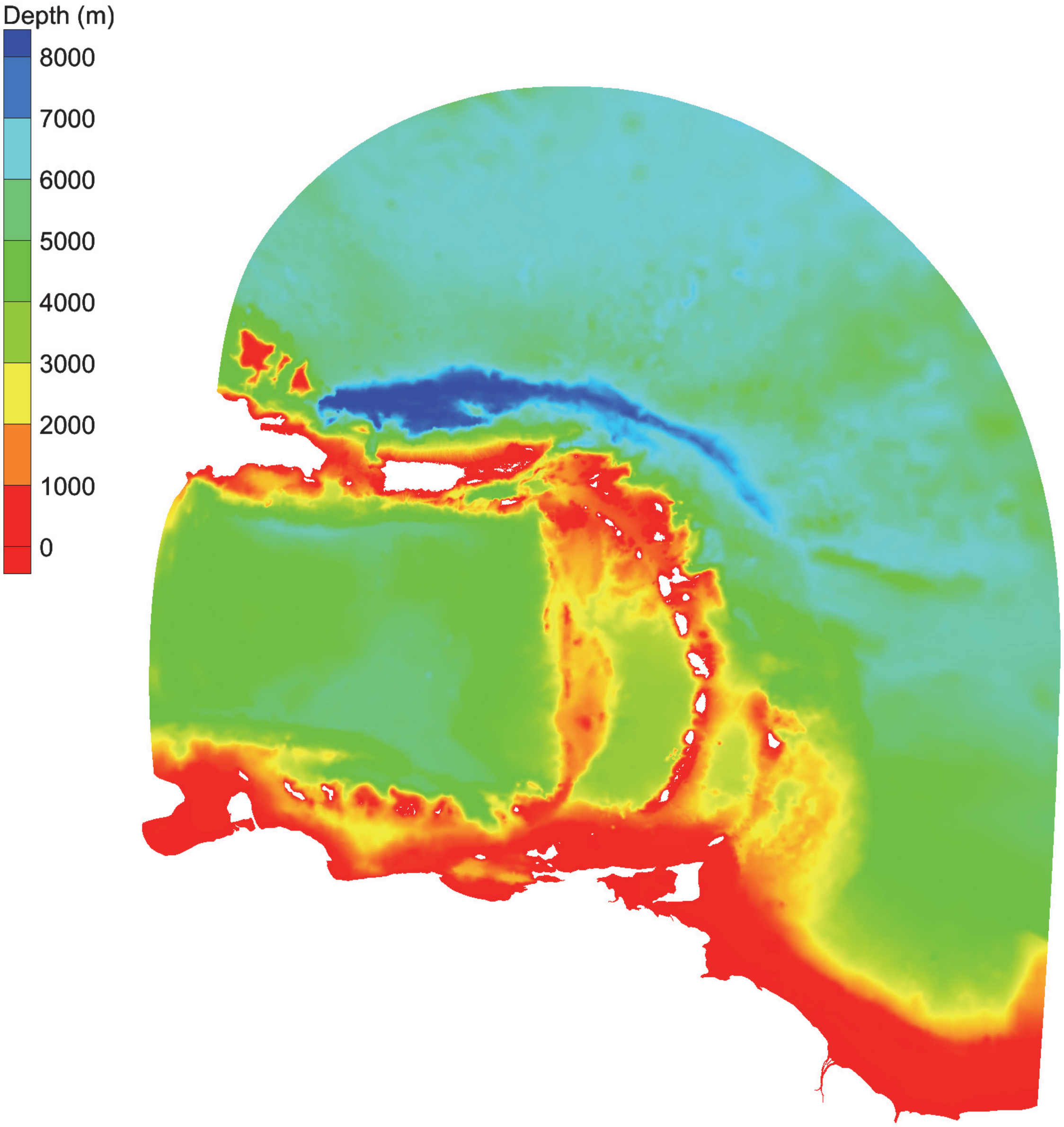


Figure 4. Model grid bathymetry relative to MSL.

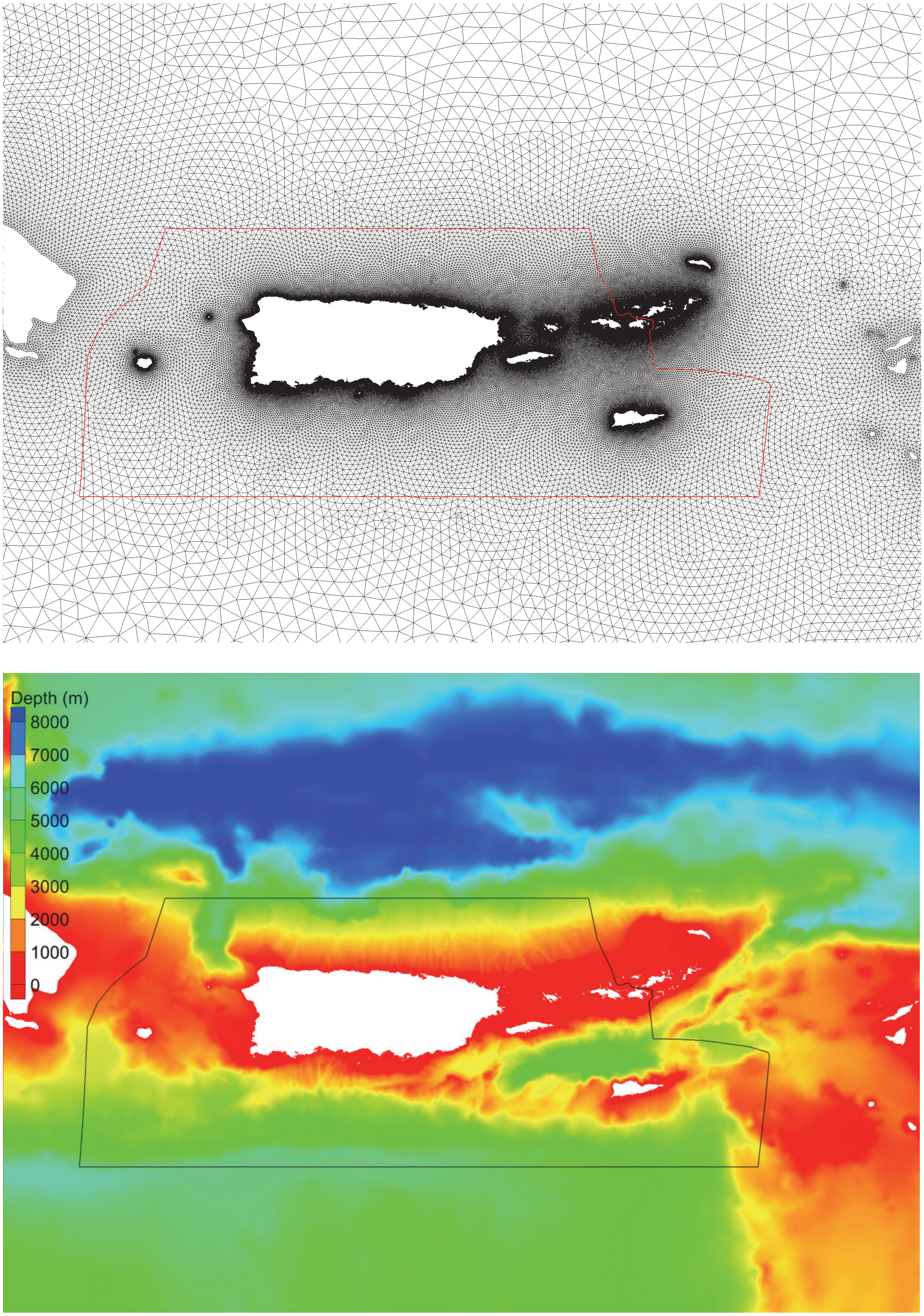


Figure 5. Close-up views of the model grid (top panel) and bathymetry (bottom panel) around Puerto Rico and the U.S. Virgin Islands.

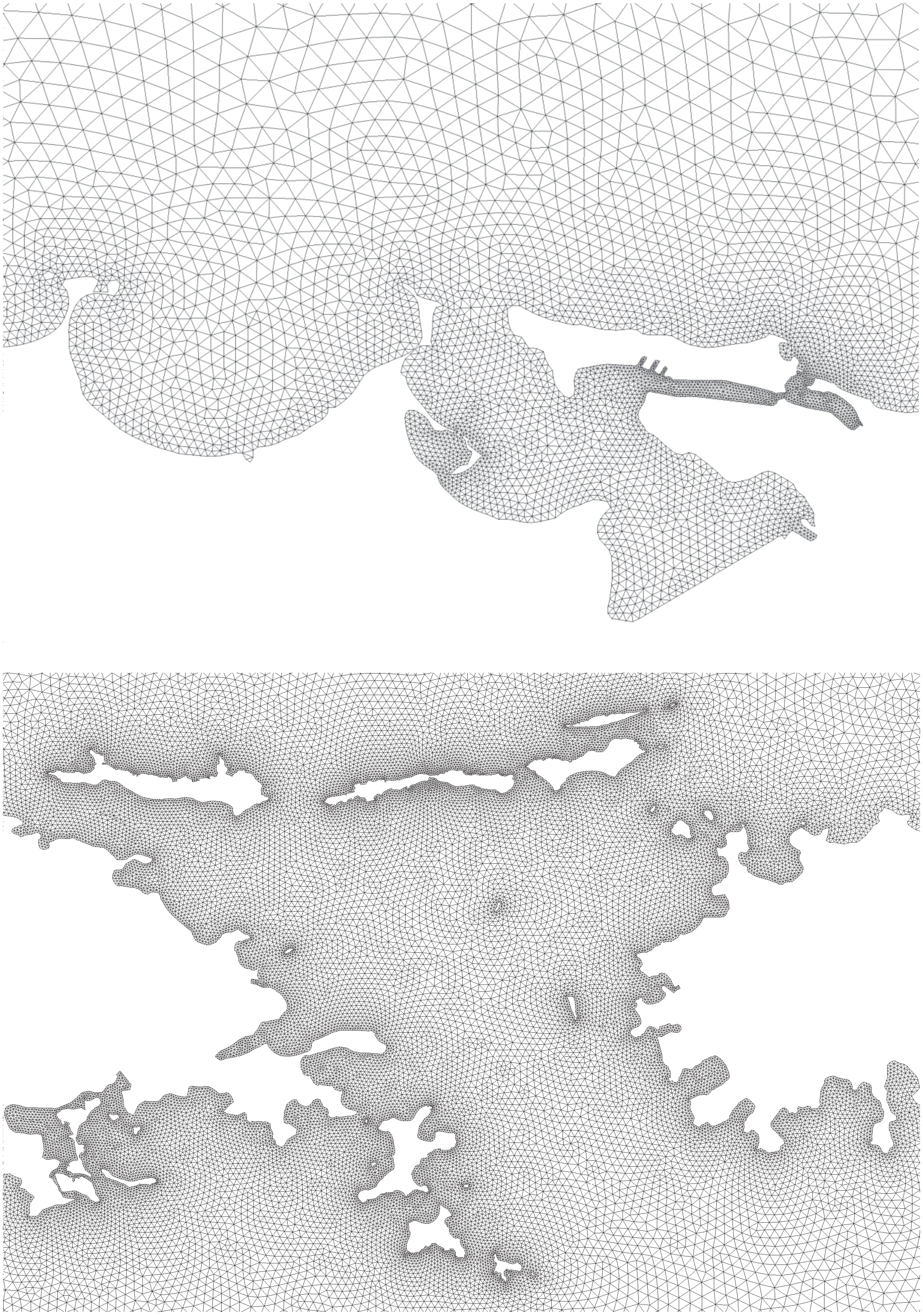


Figure 6. Close-up views of the model grid around San Juan, Puerto Rico (top panel) and in the channels and bays in between St. Thomas and St. John Islands, the U.S. Virgin Islands (bottom panel).

3.3. Model Setup

The ADCIRC Two-Dimensional Depth Integrated (2DDI) version was used in this study to solve the shallow water equations and simulate tidal water levels. The finite amplitude and convection terms were activated. The wetting and drying option was selected with the minimum water depth 0.02 m. The minimum depth of the grid nodes around Puerto Rico and the U.S. Virgin Islands was set to be 0.8 m. The grid nodes around PRVI retain wet for model runs due to the relatively small local tidal ranges. The Generalized Wave-Continuity Equation (GWCE) weighting factor TAU0 was set to be 0.05. The lateral viscosity was set as a constant, 5.0 m s^{-2}, throughout the model domain. The quadratic bottom friction scheme was used with a constant coefficient $C_d = 0.0025$. This value was selected based on the model performance of multiple test runs with different C_d values (e.g. 0.0015, 0.002, 0.0025, and 0.003).

The model was forced by a reconstructed tide at the ocean boundary using the harmonic constants of the nine most significant tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, and M_4). The harmonic constants were interpolated from the OSU/TPXO7.2 tidal database. In addition, principal tidal potential forces from M_2, S_2, N_2, K_2, K_1, O_1, P_1, and Q_1 were also included in the model simulations.

The time step was set to be 2 seconds based on numerical criteria involving the smallest element sizes in the grid. The model simulations were initiated from rest and covered a period of 40 days. The first 8 days were used for the tidal field to reach an equilibrium state. The 6-minute water level time series at each node from the last 32 days of the simulation were then used to derive various tidal datum fields.

The parallel run of ADCIRC model was conducted on 96-processors on the JET high performance computing system at NOAA's Earth System Research Laboratory. It took approximately 8 hours to complete the 40-day simulation.

3.4. Tidal Datum Computation and Validation

The 32-day time series of the simulated tidal water levels were analyzed to determine tidal datum fields. The MHW, MHHW, MLW, and MLLW datums at each model grid node were calculated by averaging the highs, higher highs, lows, and lower lows, respectively from the water level time series. These four tidal datums relative to MZ were further adjusted to be referenced to MSL, the mean values of the water level time series. In addition, the Mean Tide Level (MTL) was derived from averaging MHW and MLW, and the Diurnal Tide Level (DTL) was derived from averaging MHHW and MLLW.

Figures 7(a)-(d) display the model-derived MHHW, MHW, MLW, and MLLW datum fields for Puerto Rico and the U.S. Virgin Islands. The four fields exhibit a similar spatial pattern with higher absolute values on the north side of the PRVI waters and lower absolute values on the south side. There are significant gradients from the south toward the north in between the islands. The lower absolute datum values on the south side are mainly due to the existence of the semi-diurnal tidal amphidromic points, which lead to relatively small tidal amplitudes on the south side.

The modeled tidal datums were validated by comparing with data from 33 CO-OPS water level stations in the region (Appendix A). The comparisons for MHHW, MHW, MLW, and MLLW are shown in Figure 8(a)-(d), Table A.3 and Table 1. Generally the model results match closely with the observations. The RMSE for all the four datums was 1.2 cm.

Table 1. Statistics for all stations of observed MHHW, MHW, MLW, and MLLW datums (obs) and model-observation differences (Δ).

	MHHW (cm)	*MHW (cm)*	*MLW (cm)*	*MLLW (cm)*	*ALL (cm)*
Max(|obs|)	28.4	18.6	19.2	25.2	28.4
Mean(|obs|)	15.9	12.1	11.9	14.7	13.7
Max(|Δ|)	2.1	2.0	3.0	3.4	3.4
Mean(|Δ|)	0.8	0.8	1.3	1.0	1.0
Mean(Δ)	0.0	0.3	-0.8	-0.7	-0.3
Std(Δ)	1.1	1.0	1.2	1.1	1.2
RMSE	1.0	1.0	1.4	1.3	1.2

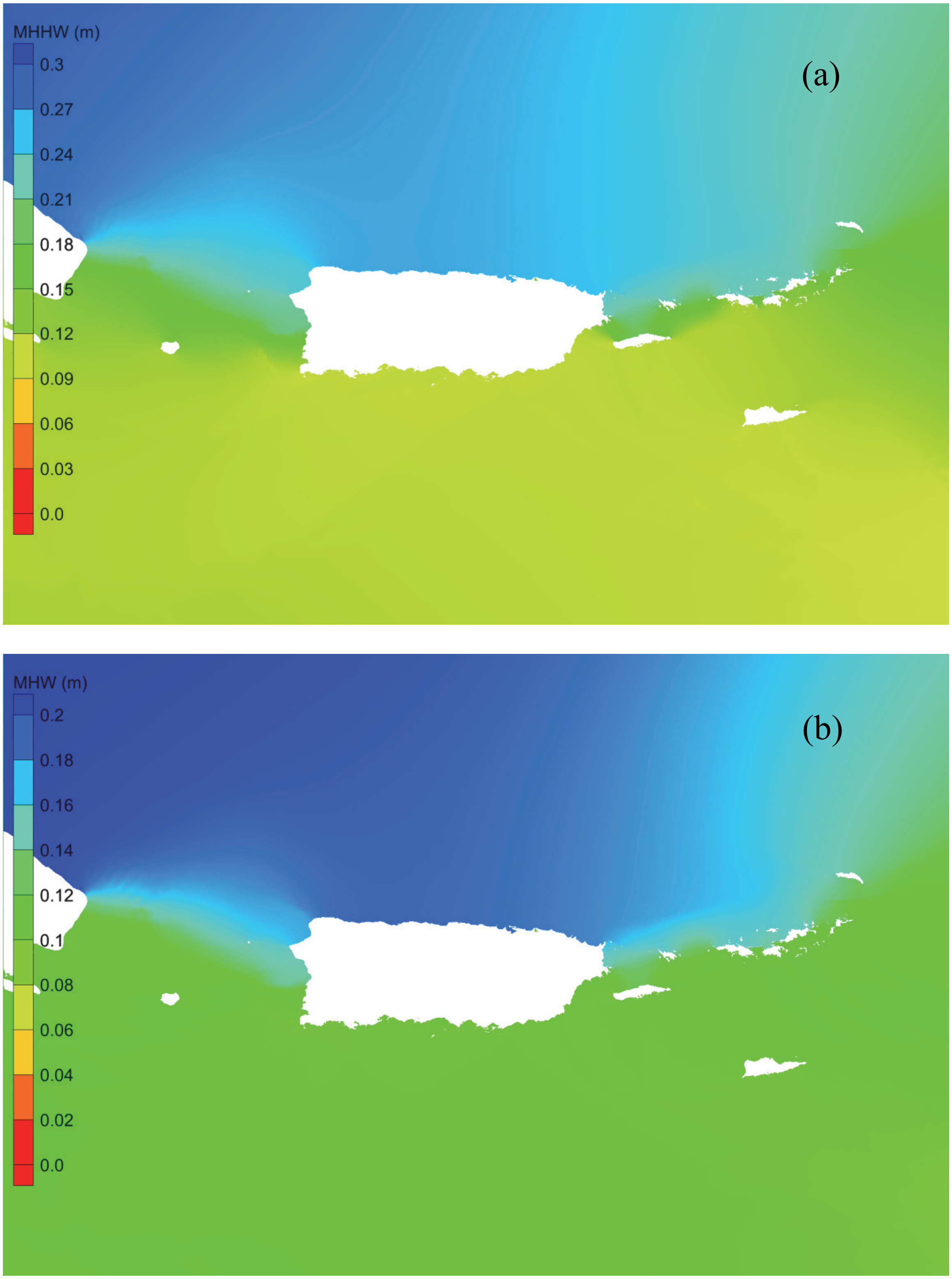


Figure 7. Modeled tidal datum fields: (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW around Puerto Rico and the U.S. Virgin Islands.

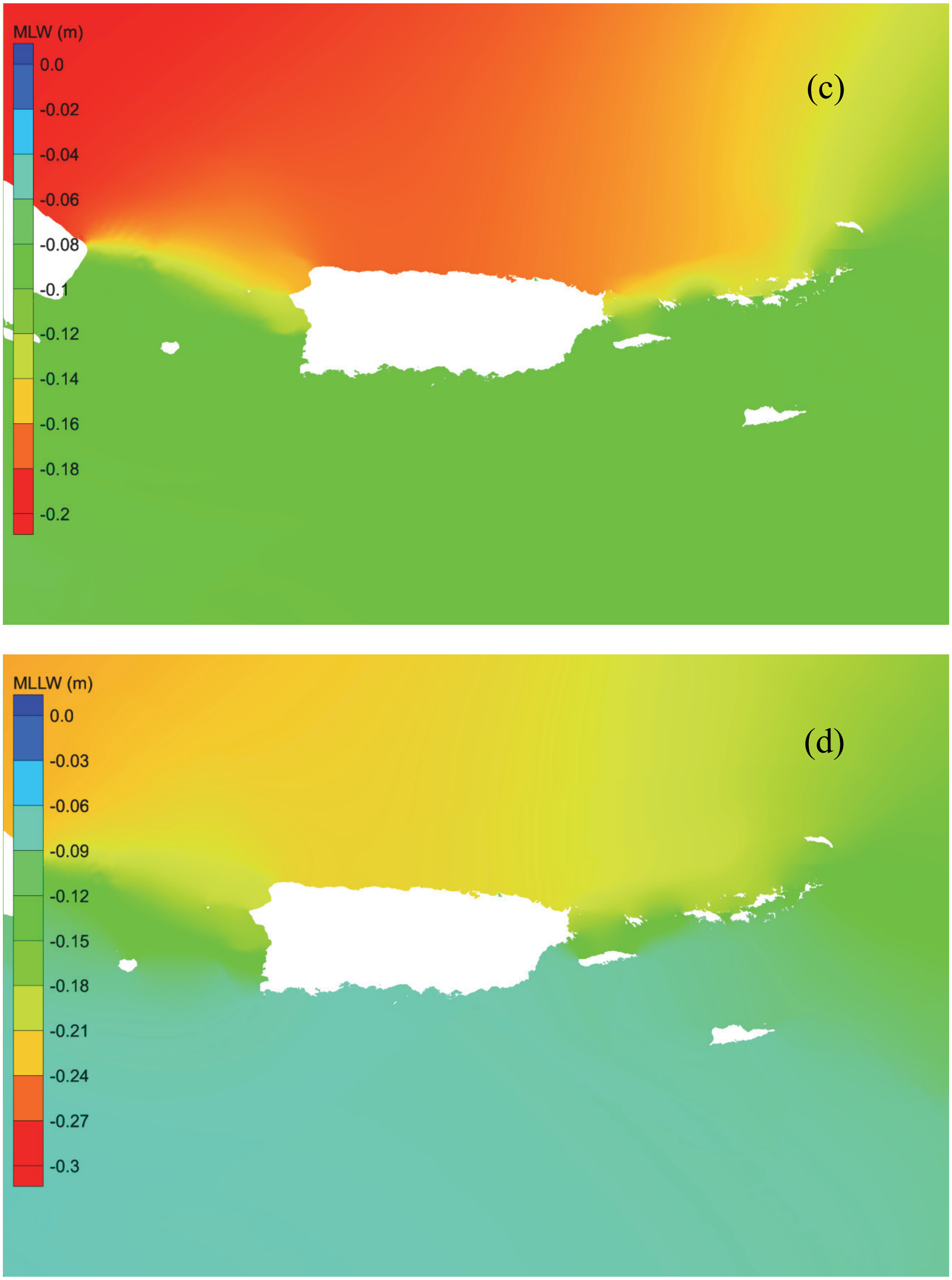


Figure 7. (Continued)

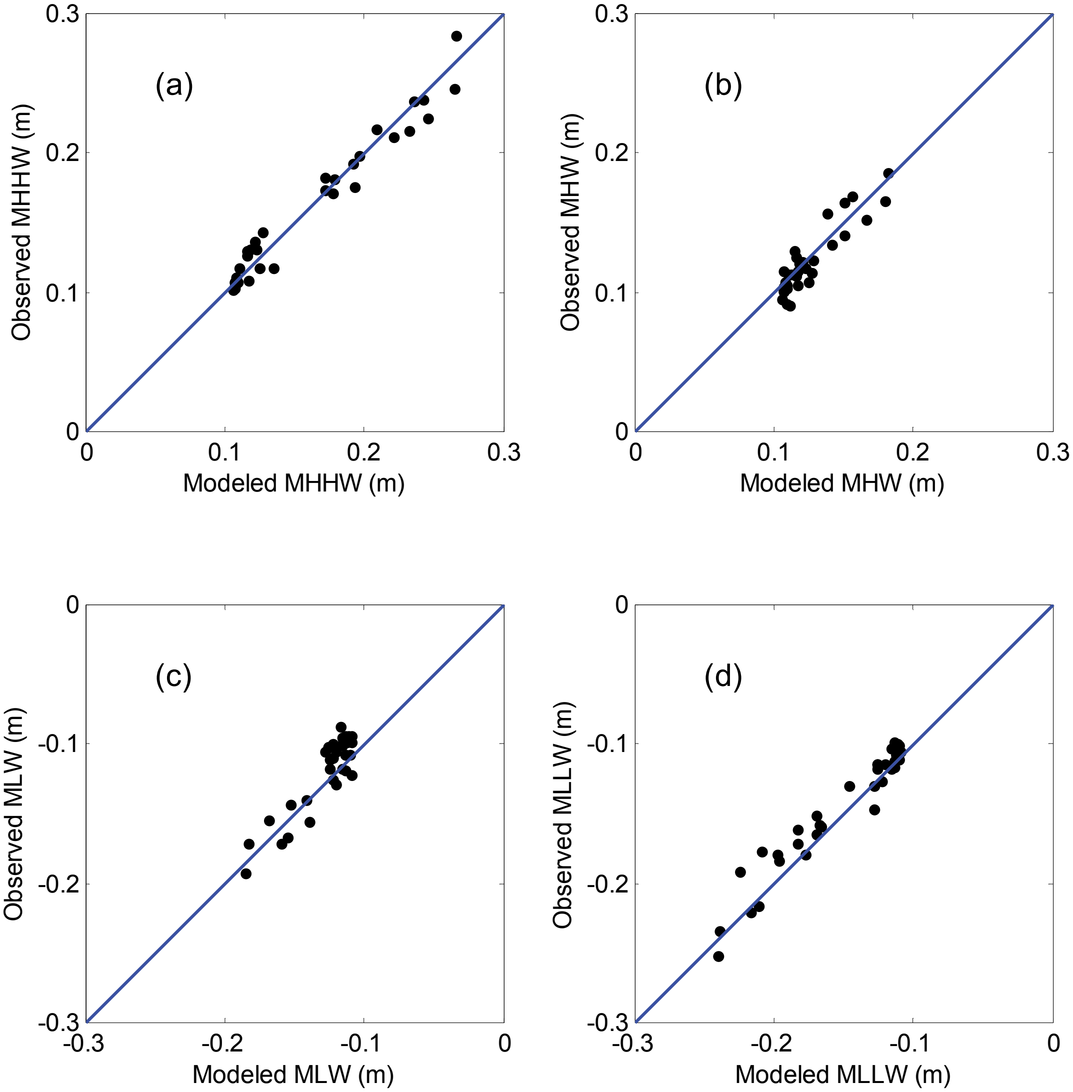


Figure 8. Comparisons between the modeled datums and the observations: (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW.

3.5. Corrections to the Modeled Tidal Datum Fields

In order to match exactly the modeled tidal datums with the observed datums at the water level gauge stations, the datum errors need to be added back to the modeled datum values. Similarly if the modeled datum fields need to be corrected throughout the domain, the spatially varying datum error fields are also required. These datum error fields can only be estimated from interpolation of the error values at the stations onto the model domain. This was achieved using TCARI method (Hess, 2002; Hess, 2003), a spatial interpolation method that solves Laplace's equation. TCARI has been designed for both structured and unstructured model grids. The latter version was employed in this study.

Figure 9 shows the interpolated error fields for MHW, MHHW, MLW, and MLLW, respectively. Generally the error fields have peak values in the vicinity of the water level stations and gradually decrease in magnitude farther away. Thus all the interpolated error values fall within a reasonable range confined by the maximum error values at the stations. As a result, the corrected datum fields match the observed datums at the stations and change within a reasonable range from the originally modeled datum fields for other regions.

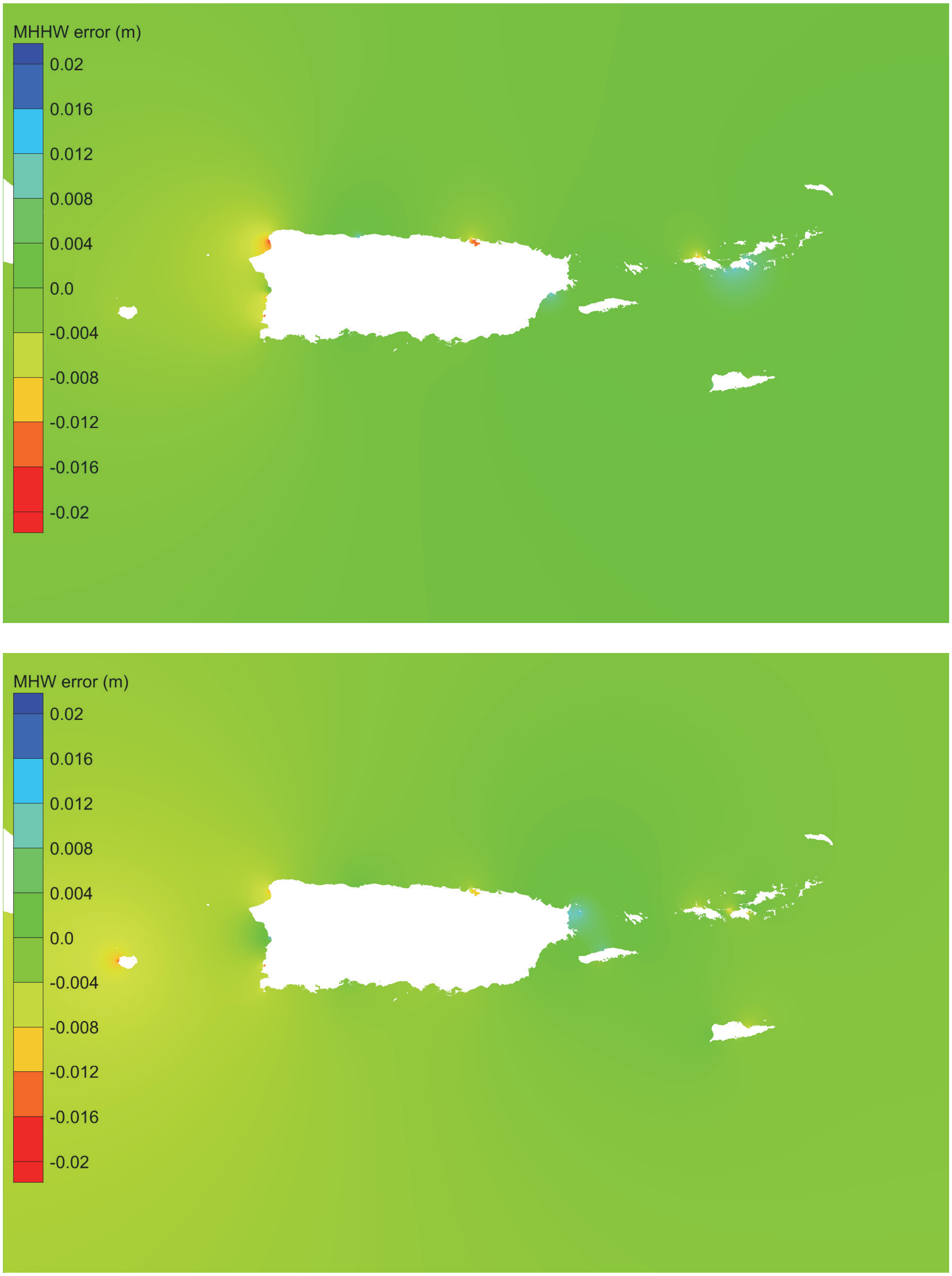


Figure 9. TCARI interpolated error fields: (a) MHHW, (b) MHW, (c) MLW, and (d) MLLW around Puerto Rico and the U.S. Virgin Islands.

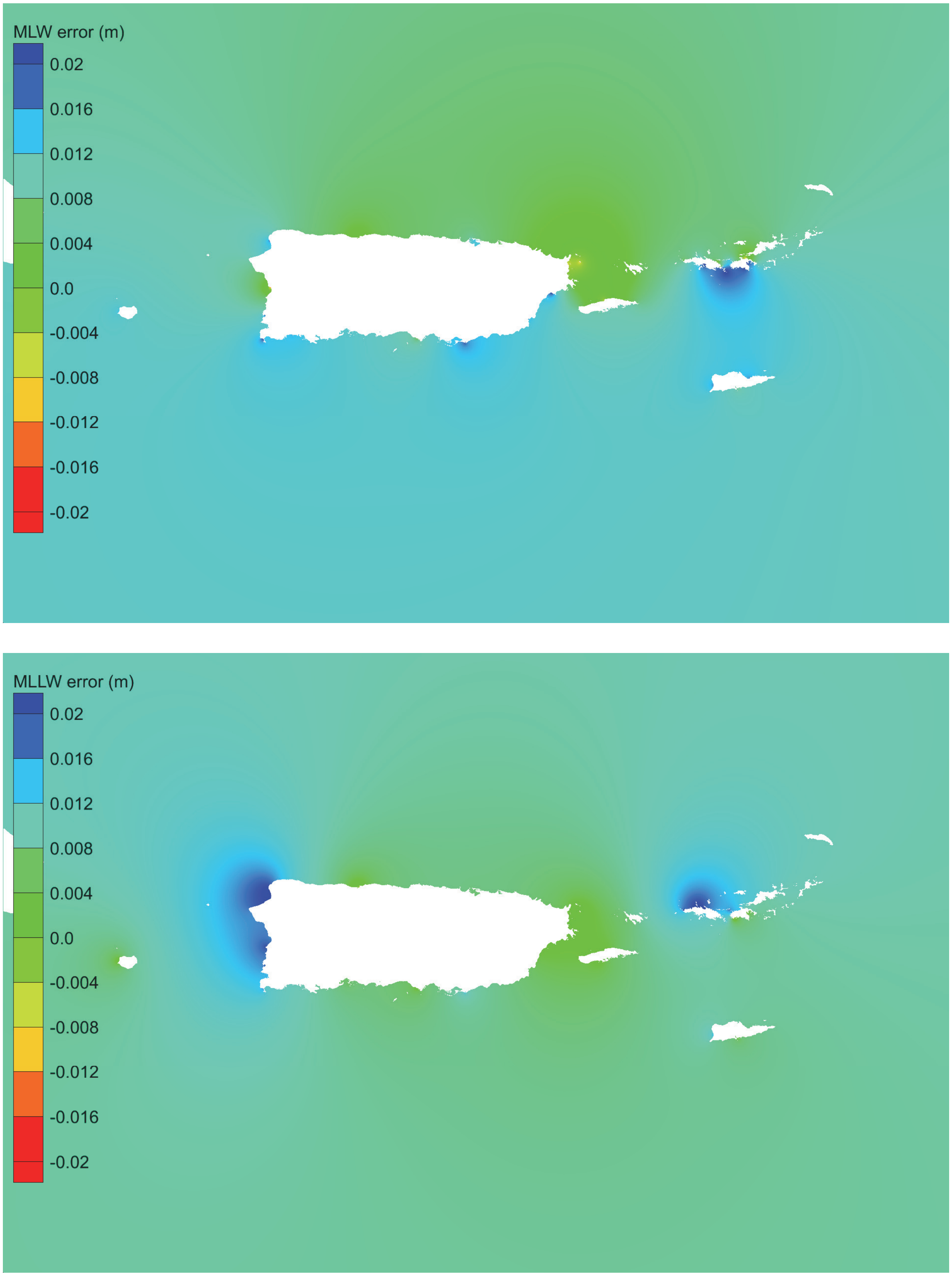


Figure 9. (Continued)

4. CREATION AND POPULATION OF THE MARINE GRID

4.1. Creation of VDatum Marine Grid

The VDatum software requires a rectangular marine grid which consists of points with uniform spacing in the longitudinal and latitudinal directions (Hess and White, 2004). The grid points are designated as either water points or land points according to their position relative to the coastline and bounding polygons. The water points are populated with tidal datum values interpolated from the corrected tidal datum fields over the unstructured model grid. The land points are given the null value, i.e. -88.8888.

A marine grid is built based on the geographic coordinates of the southwest point ($longitude_0, latitude_0$), the longitude and latitude spacing (del_lon, del_lat), and the total number of points in the eastward and northward directions (N_lon, N_lat). The position of all the points in the marine grid can be determined by:

$$longitude\_i = longitude_0 + (i-1)\times del\_lon,\ \ i=1,\ \ldots,\ N\_lon,$$
$$latitude\_j = latitude_0 + (j-1)\times del\_lat,\ j=1,\ \ldots,\ N\_lat,$$

where the indices i and j denote longitude and latitude, respectively. N_lon and N_lat can be determined if the position of the northeast most point ($longitude_1, latitude_1$) is designated:

$$N\_lon = 1 + (longitude_1 - longitude_0)/del\_lon$$
$$N\_lat = 1 + (latitude_1 - latitude_0)/del\_lat$$

In the present study, the entire region of Puerto Rico and the U.S. Virgin Islands is covered by a single marine grid. The parameters for this marine grid are listed in Table 2.

Table 2. Marine grid parameters.

Region Name	*$Longitude_0$ (degree)*	*$Latitude_0$ (degree)*	*del_lon (degree, $\times 10^{-4}$)*	*del_lat (degree, $\times 10^{-4}$)*	*N_lon*	*N_lat*
Puerto Rico and Virgin Islands	-68.32	17.22	5	5	8881	3482

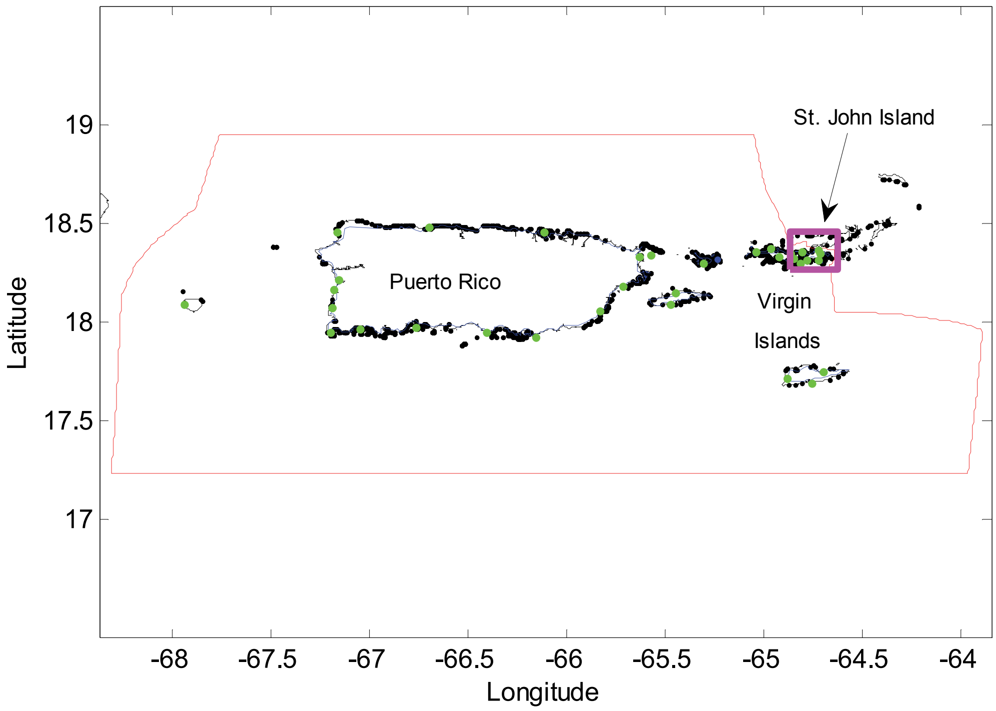
All the marine grid points were initially assigned to be either water points or land points using the guidance of the high-resolution MHW coastline (Section 2.1) and a series of bounding polygons (Figure 10). The outermost bounding polygon consists of the eastern and western international boundaries and the northern and southern latitude lines. The western boundary is between the Puerto Rican waters and the Dominican Republic's waters. The eastern boundary is between the U.S. and the British Virgin Islands. The northern line follows the latitude 18.96°, approximately 25 nautical miles away from the northernmost PRVI. The southern line follows the latitude 17.22°, approximately 25 nautical miles away from the southernmost PRVI. The inner bounding polygons within the islands were used to resolve the particular geographical features like some peninsular barriers and narrow islands. These geographical features usually separate the waters with distinct tidal ranges and thus datums.

All the grid points outside of the outermost bounding polygon were assigned to be land points with null values. The grid points in between the outermost and the inner bounding polygons or within up to one half of a cell size outside of (inland of) the coastline were delineated as water points. The grid points within the inner bounding polygons or those points more than one half of a cell size away from the coastline were marked as land points. Some initially designated water points were later manually changed back into land points in the vicinity of some peninsular barriers and narrow islands for fully separating the waters with distinct tidal datums.

4.2. Population of VDatum Grid with Tidal Datums

The marine grid was populated with the tidal datum values derived from the hydrodynamic model results and corrected to match the tide station data using TCARI (Section 3). Datum values at each water point are computed differently depending on whether a point is inside or outside of an ADCIRC model grid element consisting of three nodes. If the water point lies inside an element, datums are linearly interpolated from the values at the three nodes. If the water point lies outside all the elements, it is filled by the inverse distance weighted mean of the values at the closest two nodes. The top panels of Figures 11-16 display the populated tidal datums MHHW, MHW, MLW, MLLW, MTL, and DTL, respectively for the entire marine grid. The bottom panels of Figures 11-16 show the close-up views of datums in the vicinity of St. John Island.

As a quality control procedure, the tidal datum fields were further verified against those from the water level stations (Appendix A). The test gave a maximum absolute model-observation error less than 0.6 cm and a RMSE less than 0.1 cm for all four datums (MHHW, MHW, MLW, and MLLW).



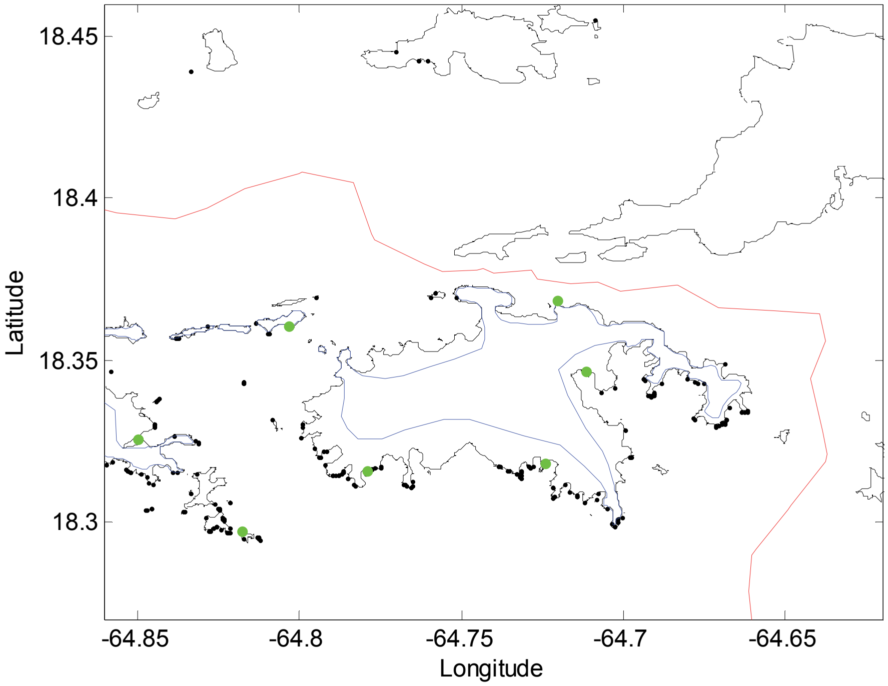


Figure 10. The bounding polygons for Puerto Rico and the U.S. Virgin Islands (top panel) and the close-up view for St. John Island (bottom panel). The black lines are the MHW coastline. The red lines are the outermost bounding polygon. The blue lines are the inner bounding polygons. The green dots are CO-OPS water level stations.

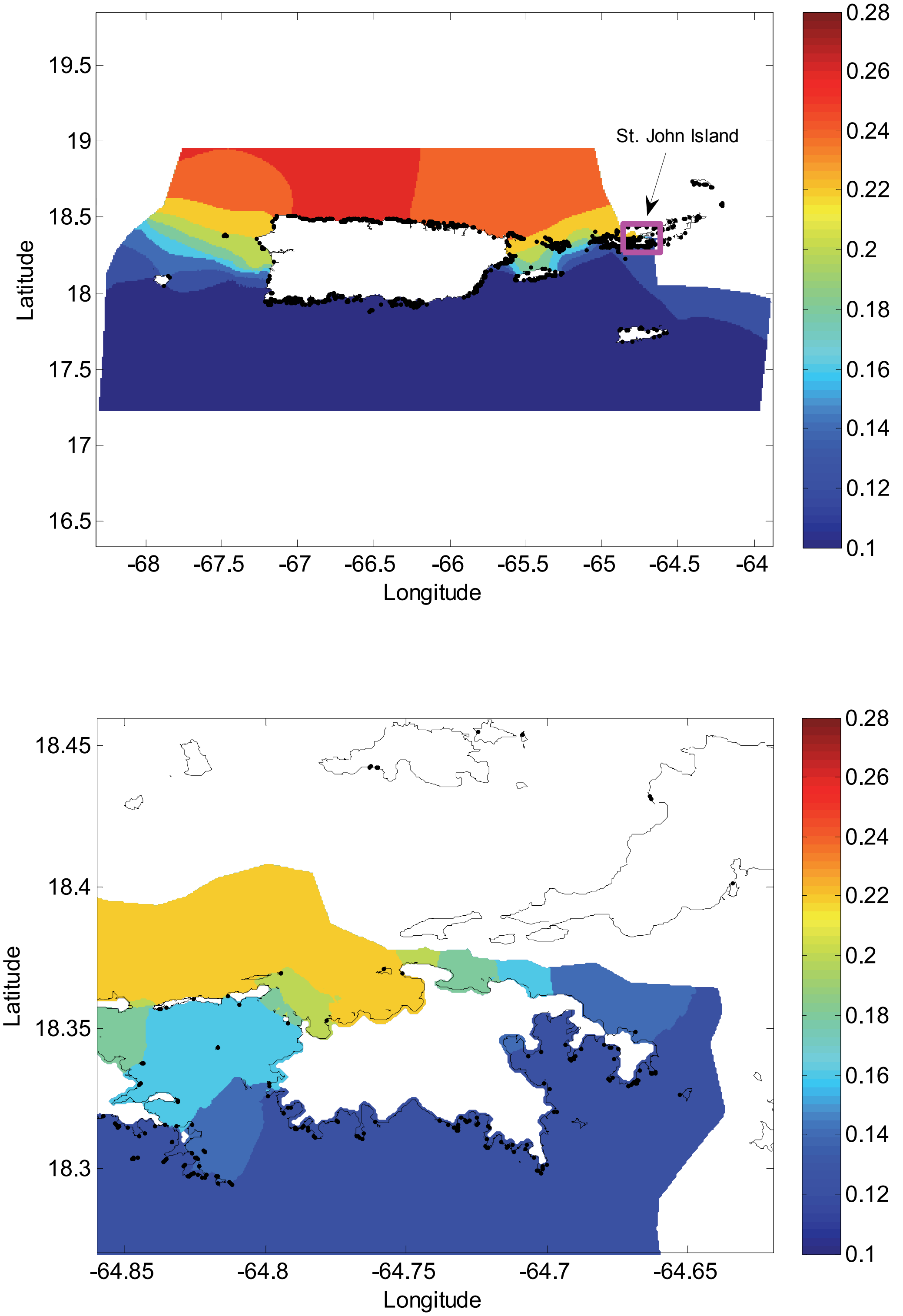


Figure 11. MHHW (in meters) referenced to MSL around Puerto Rico and the U.S. Virgin Islands (top panel) and the close-up view around St. John Island (bottom panel).

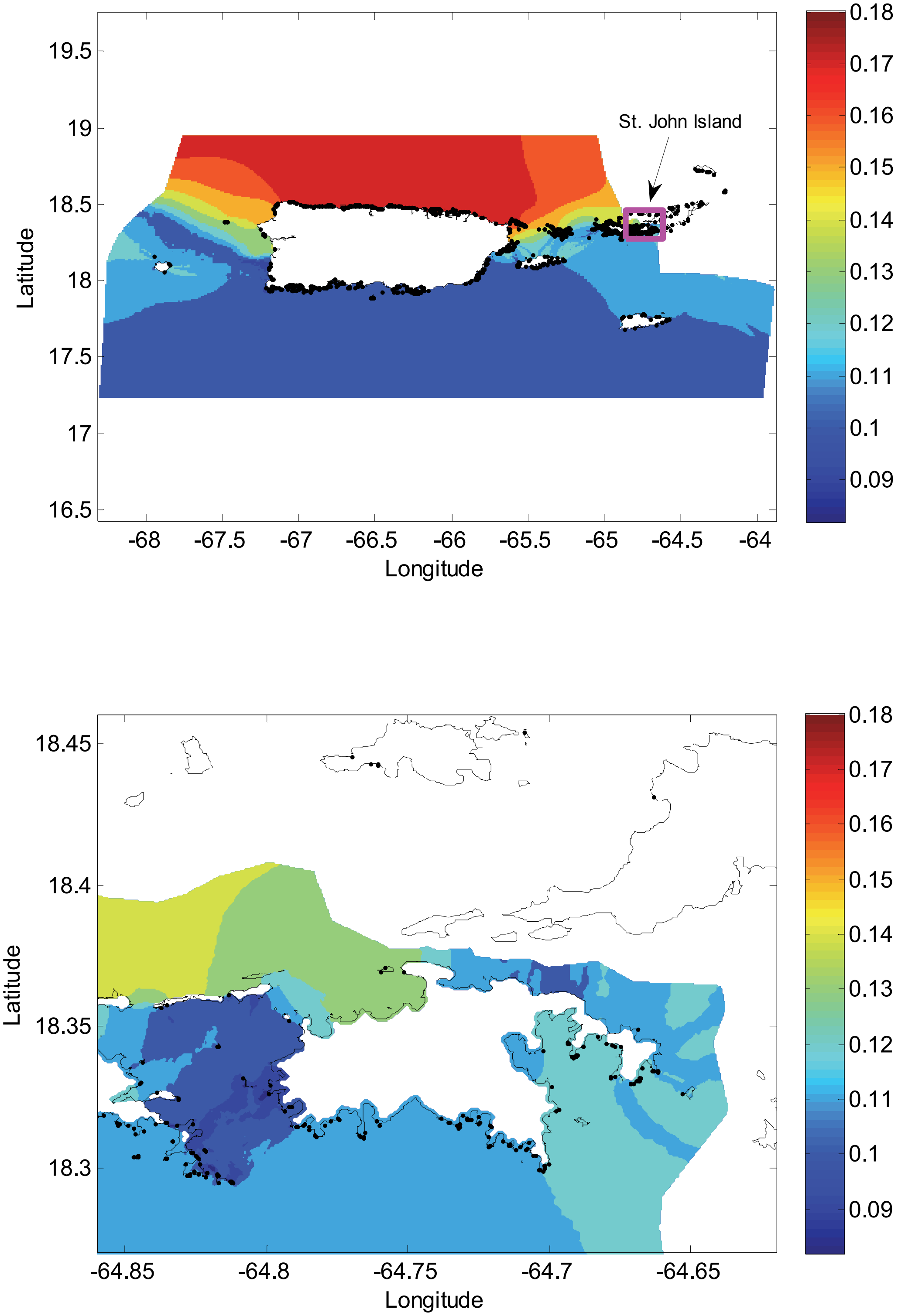


Figure 12. MHW (in meters) referenced to MSL around Puerto Rico and the U.S. Virgin Islands (top panel) and the close-up view around St. John Island (bottom panel).

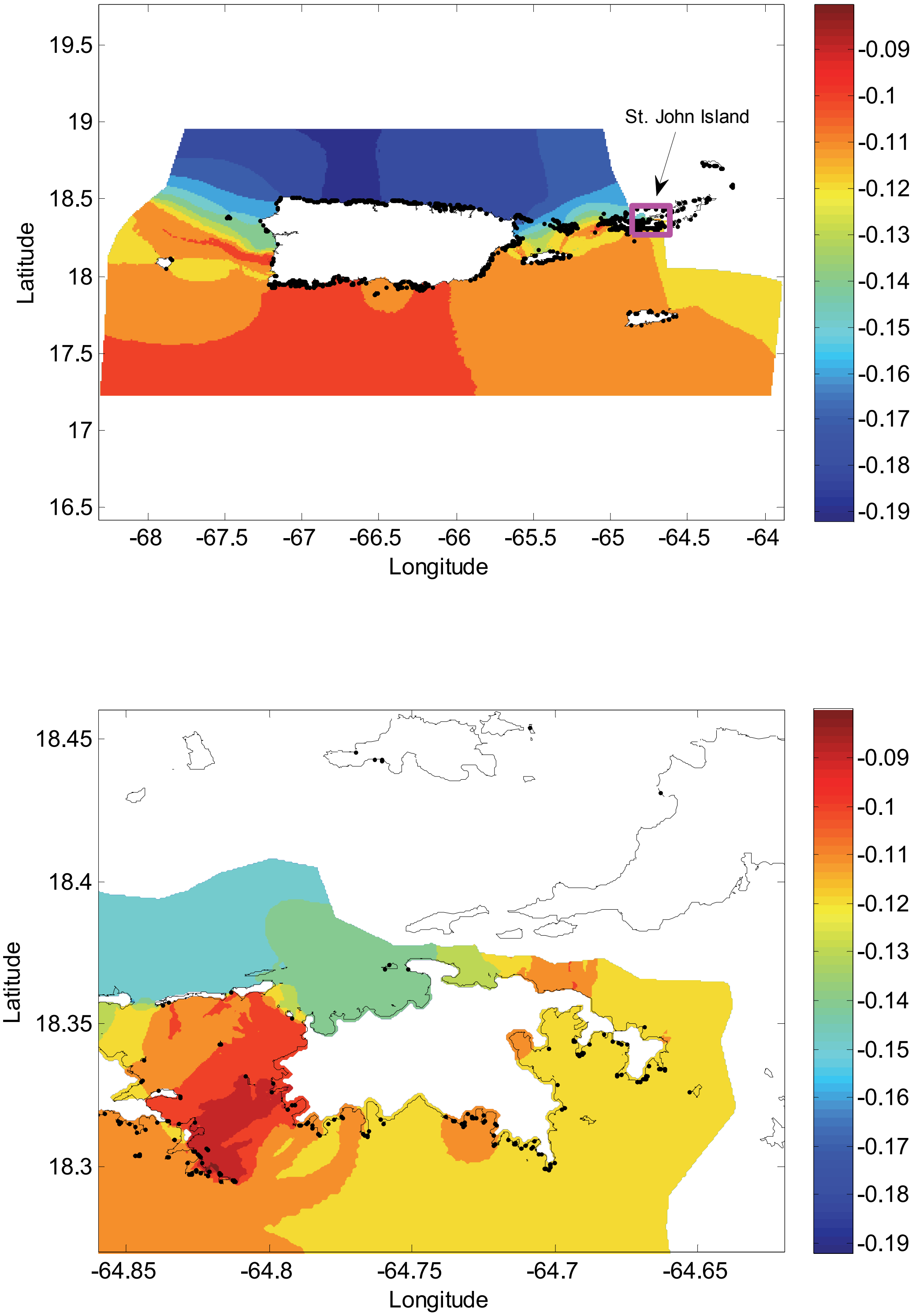


Figure 13. MLW (in meters) referenced to MSL around Puerto Rico and the U.S. Virgin Islands (top panel) and the close-up view around St. John Island (bottom panel).

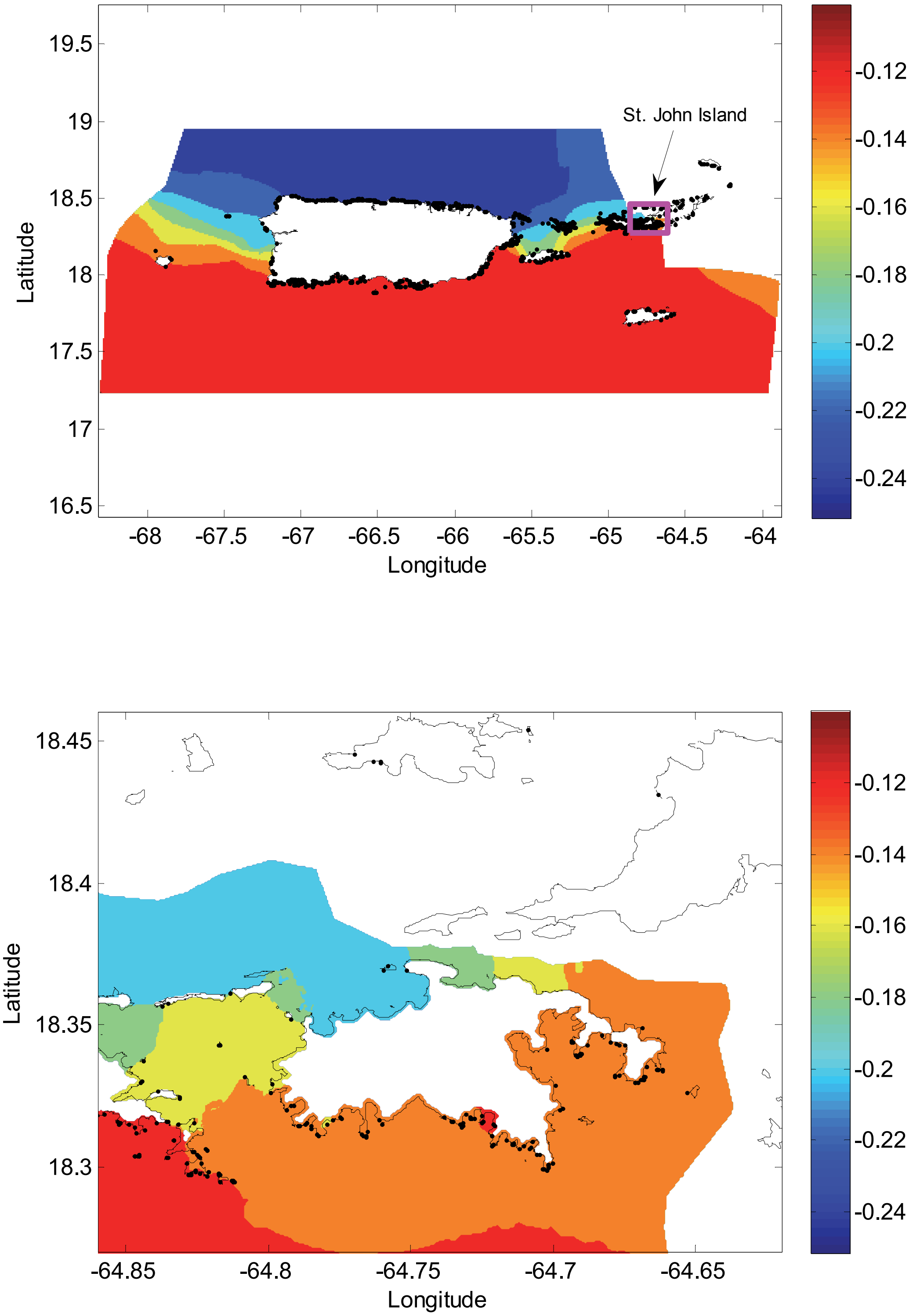


Figure 14. MLLW (in meters) referenced to MSL around Puerto Rico and the U.S. Virgin Islands (top panel) and the close-up view around St. John Island (bottom panel).

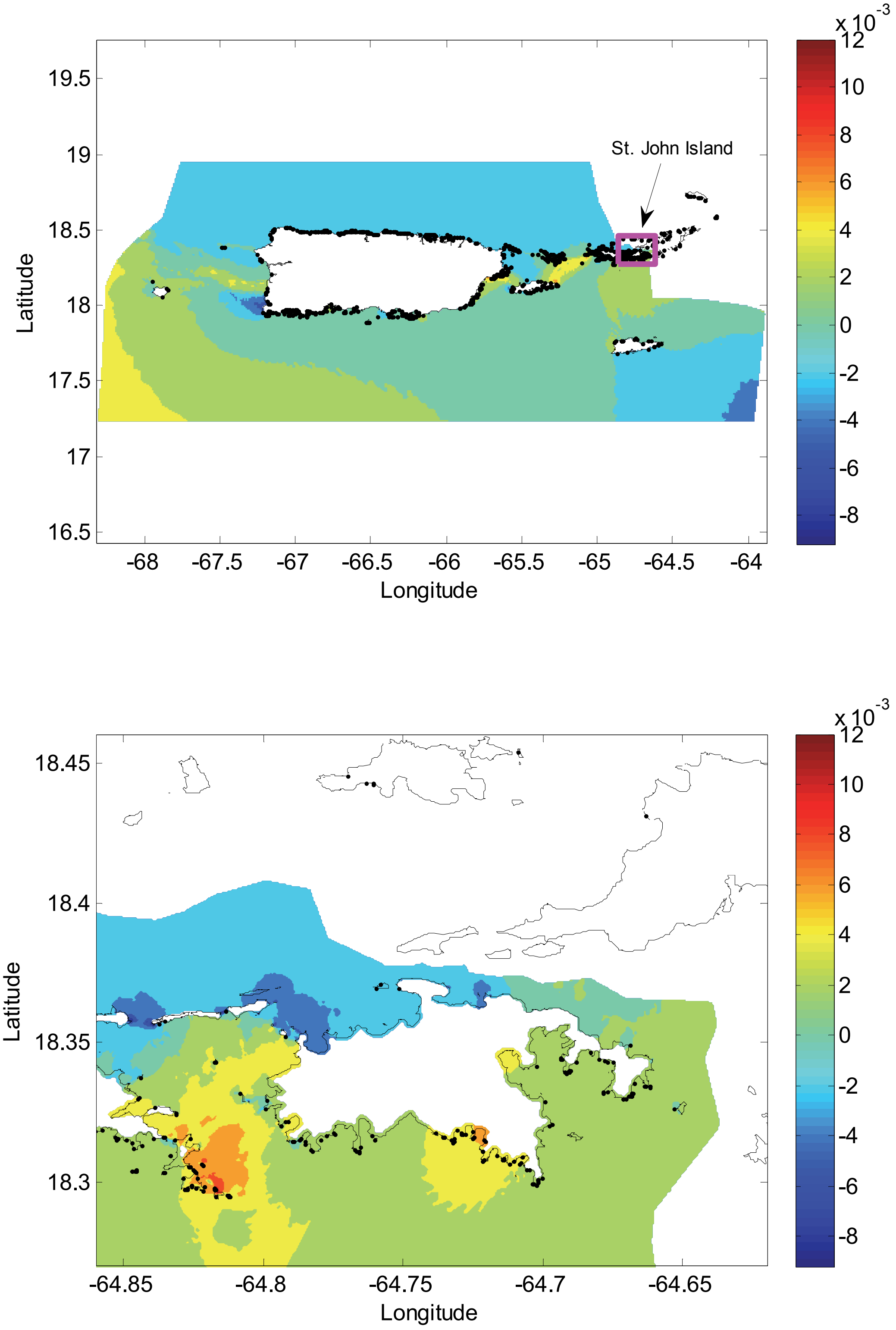


Figure 15. MTL (in meters) referenced to MSL around Puerto Rico and the U.S. Virgin Islands (top panel) and the close-up view around St. John Island (bottom panel).

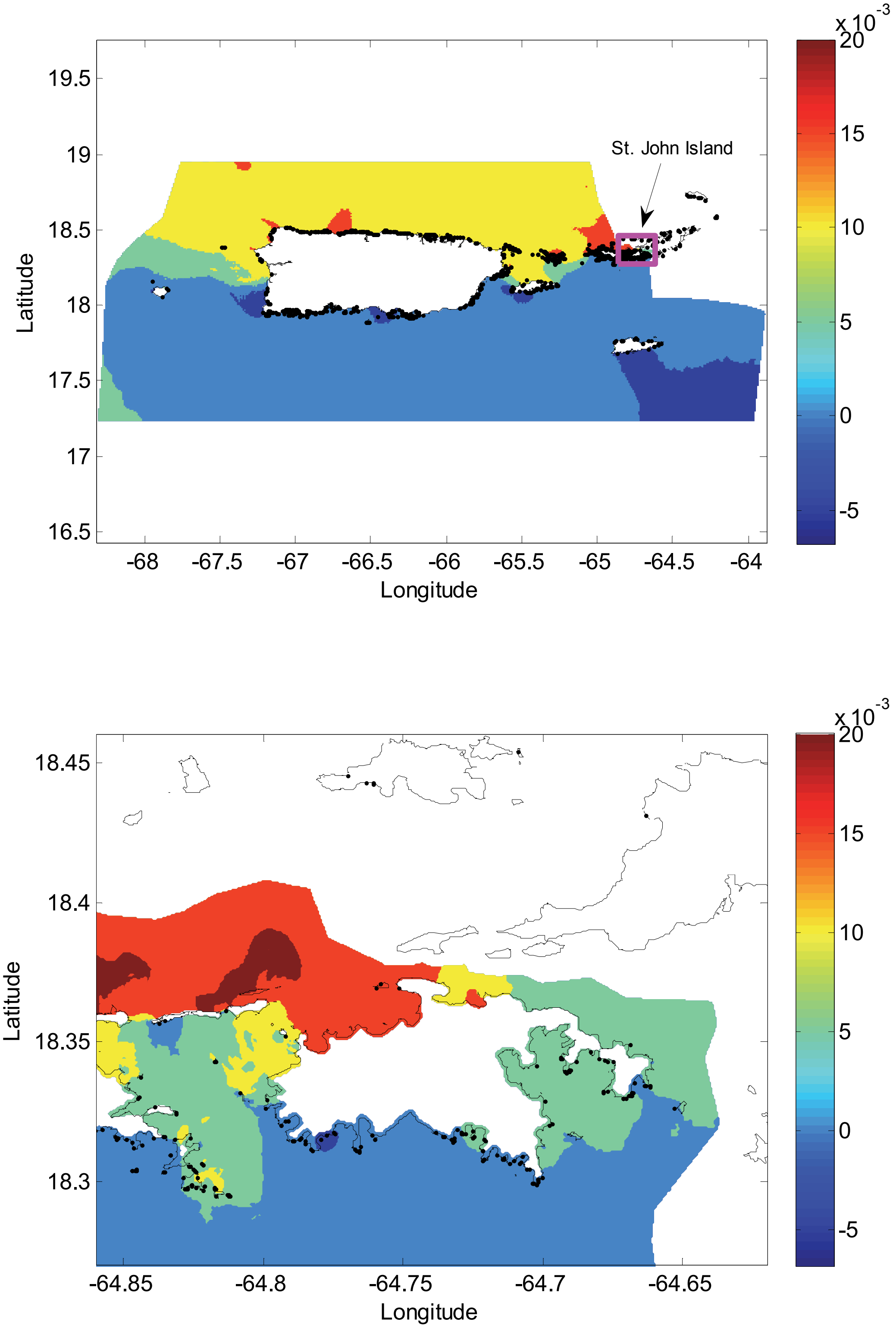


Figure 16. DTL (in meters) referenced to MSL around Puerto Rico and the U.S. Virgin Islands (top panel) and the close-up view around St. John Island (bottom panel).

5. TOPOGRAPHY OF THE SEA SURFACE

5.1. Generation of TSS field

The Topography of the Sea Surface (TSS) in this study is defined as the elevation of the Puerto Rico Vertical Datum of 2002 (PRVD02) and the Virgin Island Vertical Datum of 2009 (VIVD09) relative to mean sea level (MSL). This grid provides compensation for the local variations between a mean sea level surface and the PRVD02/VIVD09 geopotential surface over the Puerto Rico/U.S. Virgin Islands VDatum regions. A positive value specifies that the PRVD02/VIVD09 reference value is further from the center of the Earth than the mean sea level surface. All data are based on the most recent National Tidal Datum Epoch (1983-2001). The locations of tide gauges used for generation of the TSS are illustrated in Figure 17.

The PRVD02/VIVD09-to-MSL values are obtained through calculating orthometric-to-tidal datum relationships at NOAA tide gauges where elevation information has been compiled. Data for the direct method were supplied by CO-OPS and NGS.

Next, a continuous surface for each VDatum region was generated representing inverse sea-surface topography (Figure 18). A mesh covering the entire area of benchmarks and water level stations with a spatial resolution similar to that of the tidal marine grids was created. Breaklines were inserted to represent the influence of land. A sea surface topography field was then generated using the Surfer© software's minimum curvature algorithm to create a surface that honors the data as closely as possible. The maximum allowed departure value used was 0.0001 meters. To control the amount of bowing on the interior and at the edges of the grid, an internal and boundary tension of 0.3 was utilized. Once the gridded topography field was generated, null values were obtained from the marine tidal grids and inserted to denote the presence of land. Grid parameters are identical to those listed in Table 2.

5.2. Validation

The data used to compile TSS grids were compared against the TSS grid product, to generalize internal consistency. The mean delta between PRVD02/VIVD09 and MSL for each tide station utilized for creation of the TSS is depicted for the Puerto Rico/U.S. Virgin Islands VDatum in Appendix C, Table C.1. The overall mean and standard deviations for these delta values between PRVD02/VIVD09 to MSL relationships for the Puerto Rico/U.S. Virgin Islands regions were 0.00001 meters and 0.0007 meters respectively.

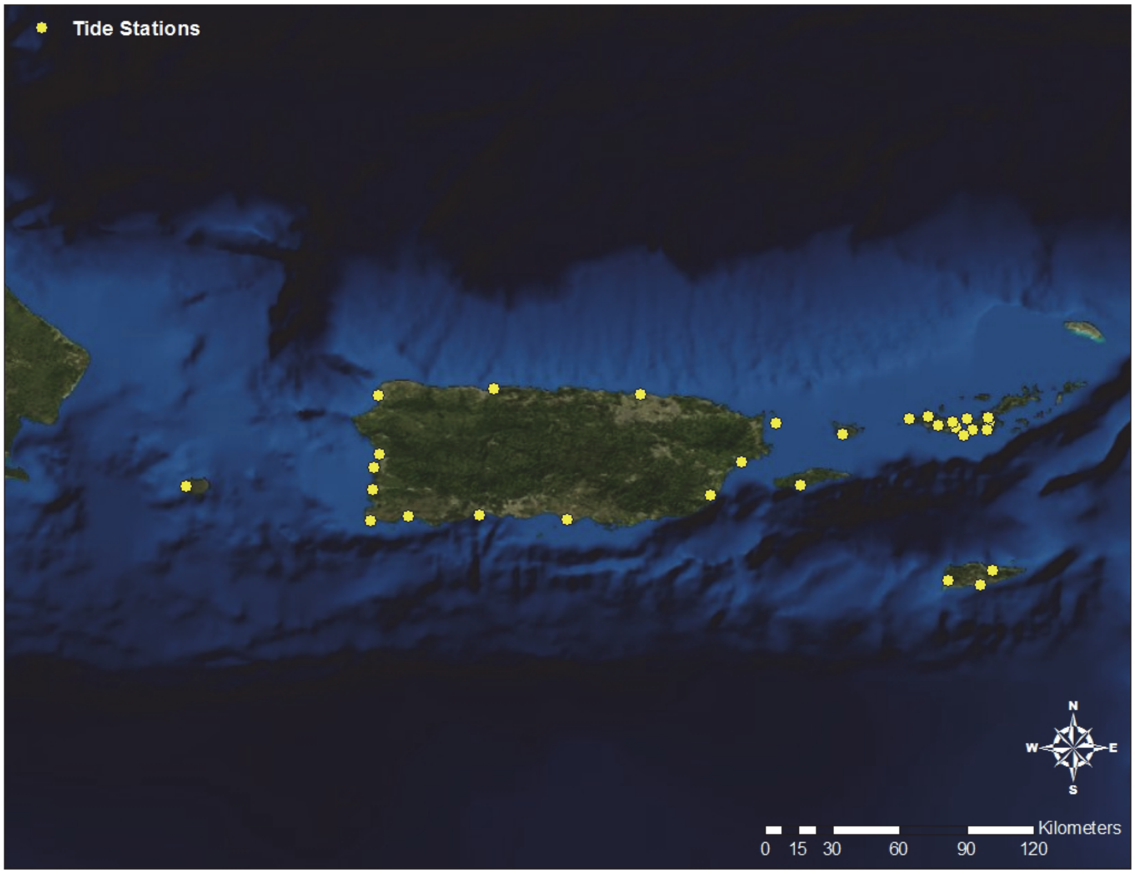


Figure 17. Locations of tide stations used to compute Puerto Rico and the U.S. Virgin Islands VDatum TSS grid.

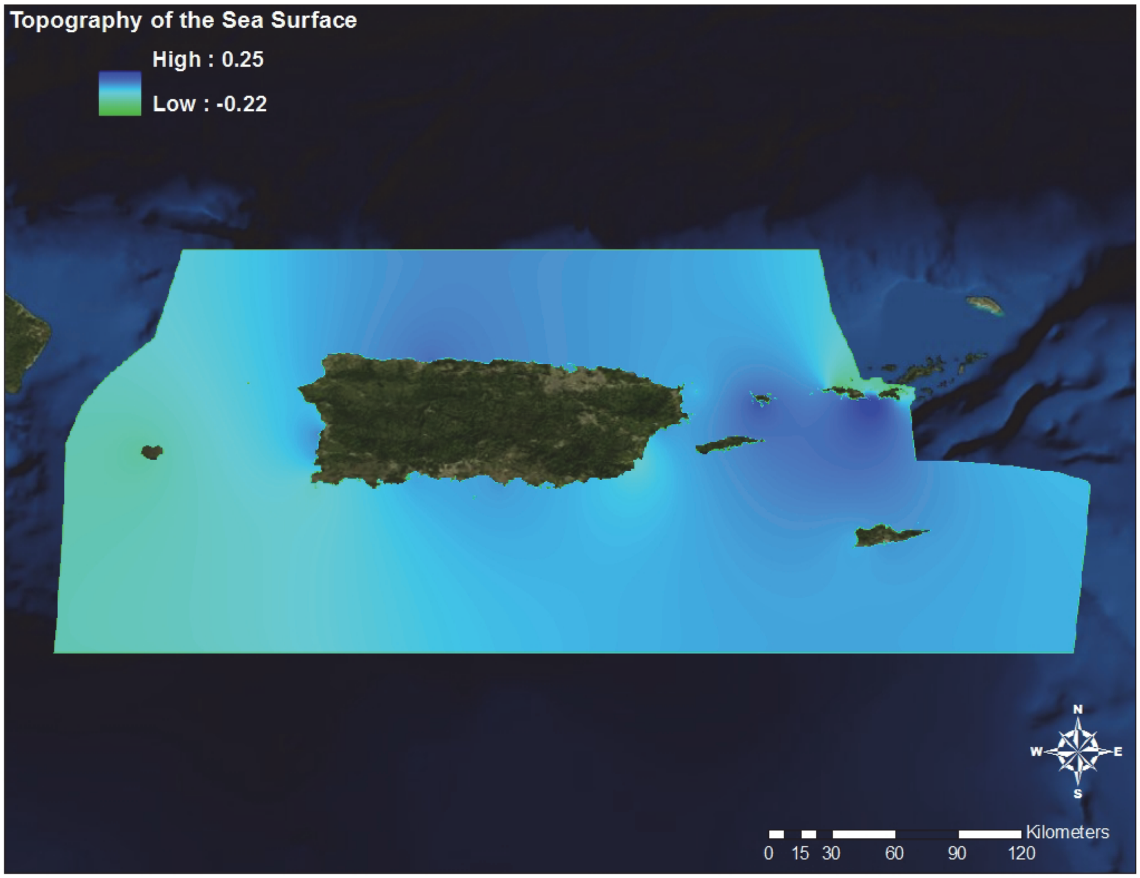


Figure 18. Topography of the Sea Surface (in meters) for Puerto Rico and the U.S. Virgin Islands.

6. UNCERTAINTY ANALYSIS

For the evaluation of uncertainties associated with VDatum transformations, the standard deviation is used to quantify the uncertainties in both the source vertical datums and of the transformations between them (http://vdatum.noaa.gov/docs/est_uncertainties.html). The source vertical datums for PRVI VDatum application include the ellipsoid-based reference systems (e.g. International Terrestrial Reference Frame, Version xx (ITRFxx)), the North American Datum of 1983 (NAD83), PRVD02/VIVD09, and tidal datums (MSL, MHHW, MHW, MLW, MLLW, MTL, and DTL). The uncertainty values are shown in Table 3 and Figure 19.

It is assumed that some uncertainties are constant throughout the U.S. For example, the uncertainties in the source data of NAD 83 and of the transformation between ITRFxx and NAD83 are both 2 cm. The source data of ITRFxx are assumed to have no uncertainty. Other uncertainties discussed below are unique for PRVI.

PRVD02/VIVD09 is realized in VDatum through the GEOID12A model (http://geodesy.noaa.gov/GEOID/GEOID12A/). According to NOAA's National Geodetic Survey (NGS), the source data uncertainty component drops down from 5 cm for NAVD88 to 2 cm for PRVD02/VIVD09 (personal communication with Tim Hanson of NGS). The uncertainty of the transformation between NAD83 and PRVD02/VIVD09, utilizing GEOID12A, is 3 cm (personal communication with Dan Roman of NGS), also lower than that between NAD83 and NAVD88.

The topography of the sea surface (TSS) field in PRVI is the transformation between PRVD02/VIVD09 and MSL and is constructed by spatial interpolation of the TSS values at the tide stations. The uncertainty in the TSS field is derived by combining an interpolation uncertainty and a height uncertainty. The interpolation uncertainty estimates the error due to the use of a limited set of tide stations in spatial interpolation. This uncertainty is 10.6 cm, calculated by analyzing the difference at each tide station between the interpolation results with and without that station (a jackknifing method). The height uncertainty is estimated by analyzing the difference between the observed TSS value at each tide station and the value interpolated using VDatum software at the same location. This uncertainty is 0.1 cm. Thus the total uncertainty in the TSS field is 10.6 cm, the square root of the sum of two squared uncertainties.

The observed tidal datums are computed from time series of observed water levels at tide stations. The source data uncertainty for tidal datums is derived from estimates of the error due to water level data collection and processing. The average error of tidal datums at PRVI tide stations is 1.5 cm (NOAA CO-OPS, 2010).

The uncertainty in the tidal datum transformations is estimated by comparing the observed tidal datum to the modeled value. While spatially varying correction factors are applied such that the final tidal datum transformations match the CO-OPS data, these original model-data errors are used as an estimate of what uncertainty may still be present in the corrected field at locations away from the tide stations. Thus the modeled tidal datum uncertainty value is calculated by analyzing the water level time series produced by the hydrodynamic model and does not include the correction by adding the interpolated error field. The uncertainty of the transformation between MSL and each individual tidal datum is derived from the standard deviation of the errors at all tide stations for that tidal datum.

The maximum cumulative uncertainty (MCU) is the square root of the sum of the squared uncertainties from ITRFxx through to a tidal datum, following the tidal transformation with the maximum uncertainty (here MSL to MLW). The MCU for the PRVI VDatum is 11.8 cm, the square root of the sum of the squared uncertainties of the ITRFxx-to-NAD83 (2.0 cm), the source NAD83 (2.0 cm), the NAD83-to-PRVD02/VIVD09 (3.0 cm), the source PRVD02/VIVD09 (2.0 cm), the PRVD02/VIVD09-to-MSL (10.6 cm), the source MSL (1.5 cm), the MSL-to-MLW (1.2 cm), and the source MLW (1.5 cm).

Table 3. Uncertainty (standard deviation) for transformation and source data (cm) for Puerto Rico and the U.S. Virgin Islands.

TRANSFORMATION							SOURCE	MCU
PRVD02/ VIVD09 to MSL	MSL to MHHW	MSL to MHW	MSL to MTL	MSL to DTL	MSL to MLW	MSL to MLLW	All Tidal Datums	
10.6	1.1	1.0	0.4	0.5	1.2	1.1	1.5	11.8

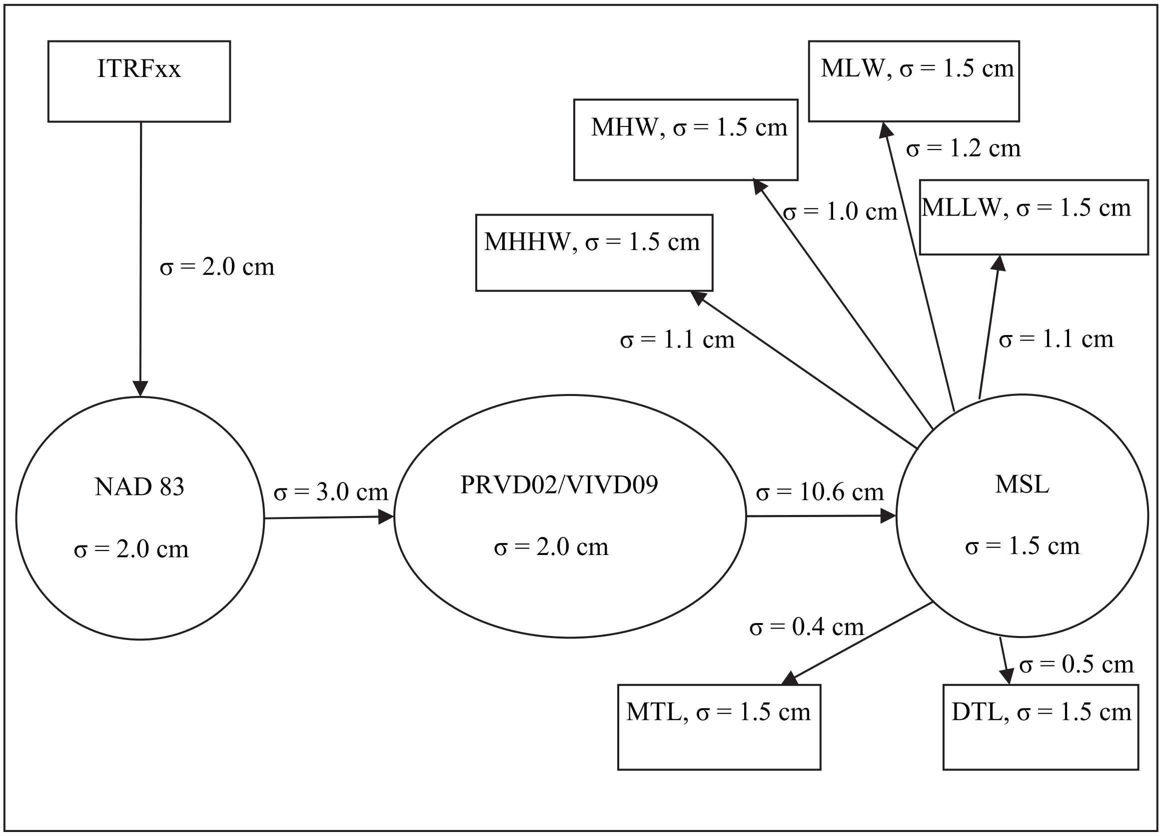


Figure 19. The uncertainties in the source vertical datums and of the transformations between them, for the PRVI VDatum application, expressed as the standard deviation σ. Uncertainties associated with the data that go into defining each vertical datum are shown inside the rectangular boxes, circles, and ovals, while uncertainties associated with transformations between vertical datums are shown alongside the arrows.

7. SUMMARY

In support of the VDatum program, tidal datum and TSS fields for the coastal waters of Puerto Rico and the U.S. Virgin Islands were developed in this study. Tidal datums were derived from tidal simulations using the ADCIRC hydrodynamic model over a triangular finite-element grid consisting of 274,885 nodes and 522,334 cells. The model was forced with nine tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, and M_4) at the open ocean boundary and generated 40-day water level time series at each grid node. The last 32 days of water level time series were used to derive various tidal datum values, including mean lower low water (MLLW), mean low water (MLW), mean high water (MHW), and mean higher high water (MHHW). Modeled tidal datums were validated by comparing with the observations at 33 water level stations maintained by NOAA's CO-OPS. To match the values at these stations, the model datum fields were corrected by adding the spatially interpolated error fields using TCARI. The corrected tidal datums were then interpolated from the unstructured triangular grid onto a regularly structured marine grid to be used by the VDatum software.

The TSS field was derived by interpolating orthometric-to-MSL relationships at NOAA tide gauges. The final TSS on the marine grid was then incorporated into the VDatum tool.

The uncertainties associated with VDatum transformations are evaluated and quantified using the standard deviation. The uncertainties in both the source vertical datums and of the transformations between them are provided in this report and the VDatum website.

ACKNOWLEDGMENTS

Digital coastline and bathymetric data sets were provided by OCS' Julia Skory and Cuong Hoang, respectively. OCS' Dr. Kurt Hess developed the software for the VDatum marine grid generation and tidal datum population. Juan Gonzalez and Aurelio Mercado in University of Puerto Rico shared with us very useful experience and information about coastal ocean modeling around Puerto Rico and the Virgin Islands. The authors would like to express genuine gratitude for their time and effort.

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APPENDIX A. WATER LEVEL STATION DATA

Table A.1. CO-OPS water level station numbers, positions, and names.

No.	Station ID	Latitude	Longitude	Station Name
1	9751309	18.367611	-64.720722	Leinster Point, Leinster Bay, St. John, VI
2	9751364	17.747781	-64.698487	Christiansted Harbor, St. Croix, VI
3	9751373	18.346491	-64.711763	Coral Harbor, St. John, VI
4	9751381	18.318186	-64.724111	Lameshur Bay, St. John, VI
5	9751401	17.694446	-64.753831	Lime Tree Bay, St. Croix, VI
6	9751456	18.315961	-64.779264	Hart Bay, St. John, VI
7	9751467	18.360666	-64.803528	Lovango Cay, St. John, VI
8	9751494	18.297139	-64.817830	Dog Island, St. Thomas, VI
9	9751540	18.325850	-64.850000	Redhook Bay, St. Thomas, VI
10	9751583	18.348944	-64.864167	Water Bay, St. Thomas, VI
11	9751584	17.713300	-64.884100	Fredericksted, St. Croix, VI
12	9751639	18.335000	-64.921000	Charlotte Amalie, St. Thomas, VI
13	9751768	18.371250	-64.963472	Dorothea Bay, St. Thomas, VI
14	9751774	18.355300	-65.035000	Botany Bay, St. Thomas, VI
15	9752235	18.301000	-65.302700	Culebra, PR
16	9752619	18.152585	-65.443816	Isabel Segunda, Vieques Island, PR
17	9752695	18.093794	-65.471355	Esperanza, Vieques Island, PR
18	9752962	18.344972	-65.569600	Isla Palominos, PR
19	9753216	18.335500	-65.631200	Fajardo, PR
20	9753641	18.187060	-65.711390	Naguabo, PR
21	9754228	18.055000	-65.833333	Yabucoa Harbor, PR
22	9755371	18.458888	-66.116411	San Juan, PR
23	9755679	17.928331	-66.159818	Las Mareas, PR
24	9756639	17.954000	-66.408600	Santa Isabel, PR
25	9757809	18.479700	-66.701600	Arecibo, PR
26	9758053	17.973333	-66.761667	Penuelas (Punta Guayanilla), PR
27	9759110	17.970000	-67.046667	Magueyes Island, PR
28	9759189	18.074540	-67.188780	Puerto Real, PR
29	9759197	17.951220	-67.196690	Bahia Salinas, PR
30	9759394	18.217505	-67.158886	Mayaguez, PR
31	9759412	18.456647	-67.164731	Aguadilla, PR
32	9759421	18.166258	-67.184438	Punta Guanajabo, Mayagues, PR
33	9759938	18.088825	-67.938599	Mona Island, PR

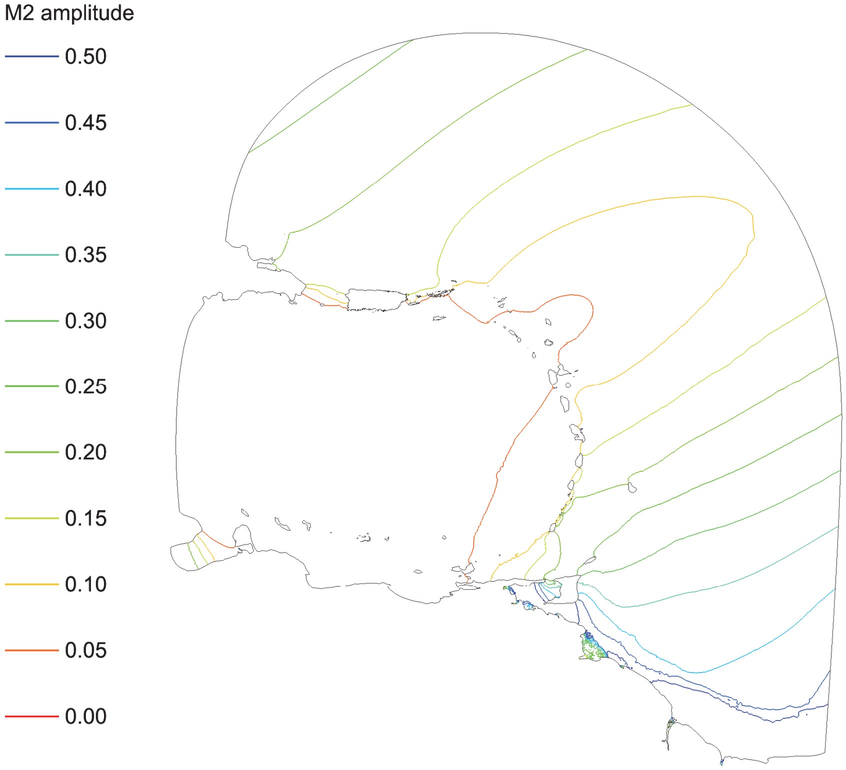
Table A.2. Tidal datums (in meters) relative to mean sea level. The ‘N/A’ in the table denotes a missing value.

No.	Station ID	Longitude (degree)	Latitude (degree)	MHHW (m)	MHW (m)	MLW (m)	MLLW (m)	PRVI02/ VIVD09 (m)
1	9751309	-64.720722	18.367611	0.183	0.115	-0.122	-0.159	-0.199
2	9751364	-64.698487	17.747781	0.109	0.105	-0.105	-0.114	0.001
3	9751373	-64.711763	18.346491	0.143	0.114	-0.105	-0.13	-0.217
4	9751381	-64.724111	18.318186	0.131	0.118	-0.102	-0.118	-0.002
5	9751401	-64.753831	17.694446	0.104	0.102	-0.108	-0.112	0
6	9751456	-64.779264	18.315961	0.137	0.115	-0.111	-0.147	0.074
7	9751467	-64.803528	18.360666	0.171	0.091	-0.094	-0.151	-0.146
8	9751494	-64.817830	18.297139	0.131	0.105	-0.087	-0.114	0.258
9	9751540	-64.850000	18.325850	0.174	0.13	-0.119	-0.158	0.082
10	9751583	-64.864167	18.348944	0.193	0.122	-0.125	-0.171	-0.126
11	9751584	-64.884100	17.713300	0.117	0.113	-0.101	-0.103	-0.032
12	9751639	-64.921000	18.335000	0.126	0.113	-0.1	-0.114	-0.142
13	9751768	-64.963472	18.371250	0.216	0.141	-0.143	-0.177	-0.205
14	9751774	-65.035000	18.355300	0.212	0.134	-0.14	-0.179	-0.009
15	9752235	-65.302700	18.301000	0.181	0.121	-0.118	-0.165	0.109
16	9752619	-65.443816	18.152585	0.198	0.125	-0.129	-0.179	N/A
17	9752695	-65.471355	18.093794	0.107	0.103	-0.107	-0.116	0.003
18	9752962	-65.569600	18.344972	0.237	0.165	-0.167	-0.216	-0.038
19	9753216	-65.631200	18.335500	0.238	0.169	-0.171	-0.221	N/A
20	9753641	-65.711390	18.187060	0.13	0.112	-0.095	-0.118	-0.002
21	9754228	-65.833333	18.055000	0.111	0.107	-0.098	-0.107	-0.109
22	9755371	-66.116411	18.458888	0.246	0.166	-0.171	-0.234	0
23	9755679	-66.159818	17.928331	0.103	0.101	-0.094	-0.1	N/A
24	9756639	-66.408600	17.954000	0.104	0.101	-0.108	-0.111	-0.003
25	9757809	-66.701600	18.479700	0.284	0.186	-0.192	-0.252	0.043
26	9758053	-66.761667	17.973333	0.107	0.104	-0.099	-0.105	-0.018
27	9759110	-67.046667	17.970000	0.103	0.101	-0.097	-0.101	-0.068
28	9759189	-67.188780	18.074540	0.117	0.092	-0.1	-0.13	-0.008
29	9759197	-67.196690	17.951220	0.102	0.095	-0.094	-0.098	-0.111
30	9759394	-67.158886	18.217505	0.217	0.157	-0.156	-0.184	-0.047
31	9759412	-67.164731	18.456647	0.225	0.152	-0.154	-0.191	-0.015
32	9759421	-67.184438	18.166258	0.176	0.123	-0.118	-0.161	0.018
33	9759938	-67.938599	18.088825	0.118	0.107	-0.11	-0.126	-0.155

Table A.3. Tidal datums errors (model value minus observed value, in meters).

No.	Station ID	ΔMHHW (m)	ΔMHW (m)	ΔMLW (m)	ΔMLLW (m)
1	9751309	-0.011	-0.008	0.013	-0.007
2	9751364	0.008	0.012	-0.015	-0.006
3	9751373	-0.016	0.013	-0.023	0.002
4	9751381	-0.009	0.004	-0.024	-0.008
5	9751401	0.003	0.005	-0.006	-0.002
6	9751456	-0.016	0.003	-0.014	0.018
7	9751467	0.006	0.02	-0.015	-0.018
8	9751494	-0.013	0.004	-0.03	-0.012
9	9751540	-0.002	-0.015	0.006	-0.009
10	9751583	-0.001	-0.001	0.002	-0.012
11	9751584	-0.007	-0.003	-0.015	-0.013
12	9751639	-0.01	-0.001	-0.022	-0.012
13	9751768	0.016	0.009	-0.01	-0.032
14	9751774	0.009	0.007	-0.002	-0.019
15	9752235	-0.002	-0.003	0.002	-0.005
16	9752619	-0.002	-0.009	0.009	0.001
17	9752695	0.002	0.006	-0.007	0.002
18	9752962	-0.002	-0.014	0.013	0.005
19	9753216	0.004	-0.013	0.011	0.004
20	9753641	-0.014	0.004	-0.021	0.002
21	9754228	-0.003	0.001	-0.014	-0.005
22	9755371	0.018	0.013	-0.012	-0.005
23	9755679	0.004	0.006	-0.017	-0.011
24	9756639	0.003	0.006	-0.002	0.001
25	9757809	-0.018	-0.004	0.007	0.011
26	9758053	0	0.003	-0.01	-0.004
27	9759110	0.004	0.006	-0.013	-0.009
28	9759189	0.018	0.017	-0.015	-0.016
29	9759197	0.004	0.011	-0.02	-0.015
30	9759394	-0.008	-0.019	0.017	-0.013
31	9759412	0.021	0.014	-0.015	-0.034
32	9759421	0.017	0.005	-0.006	-0.022
33	9759938	0.007	0.018	-0.012	0.004

APPENDIX B. AMPLITUDE AND PHASE OF SELECTED TIDAL CONSTITUENTS



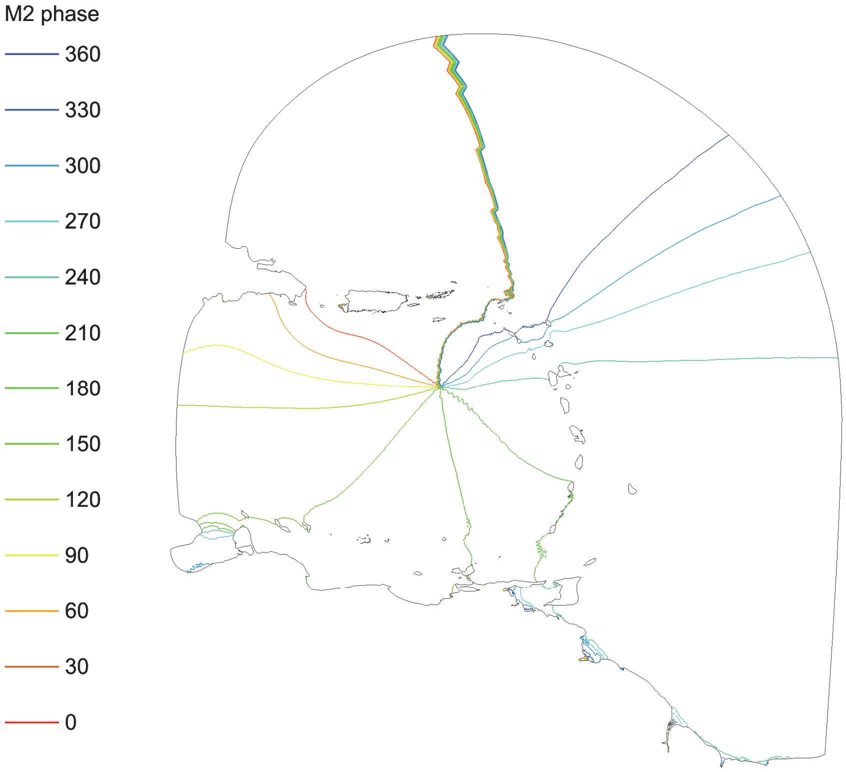


Figure B.1. M_2 amplitude (in meters) and phase (in degrees).

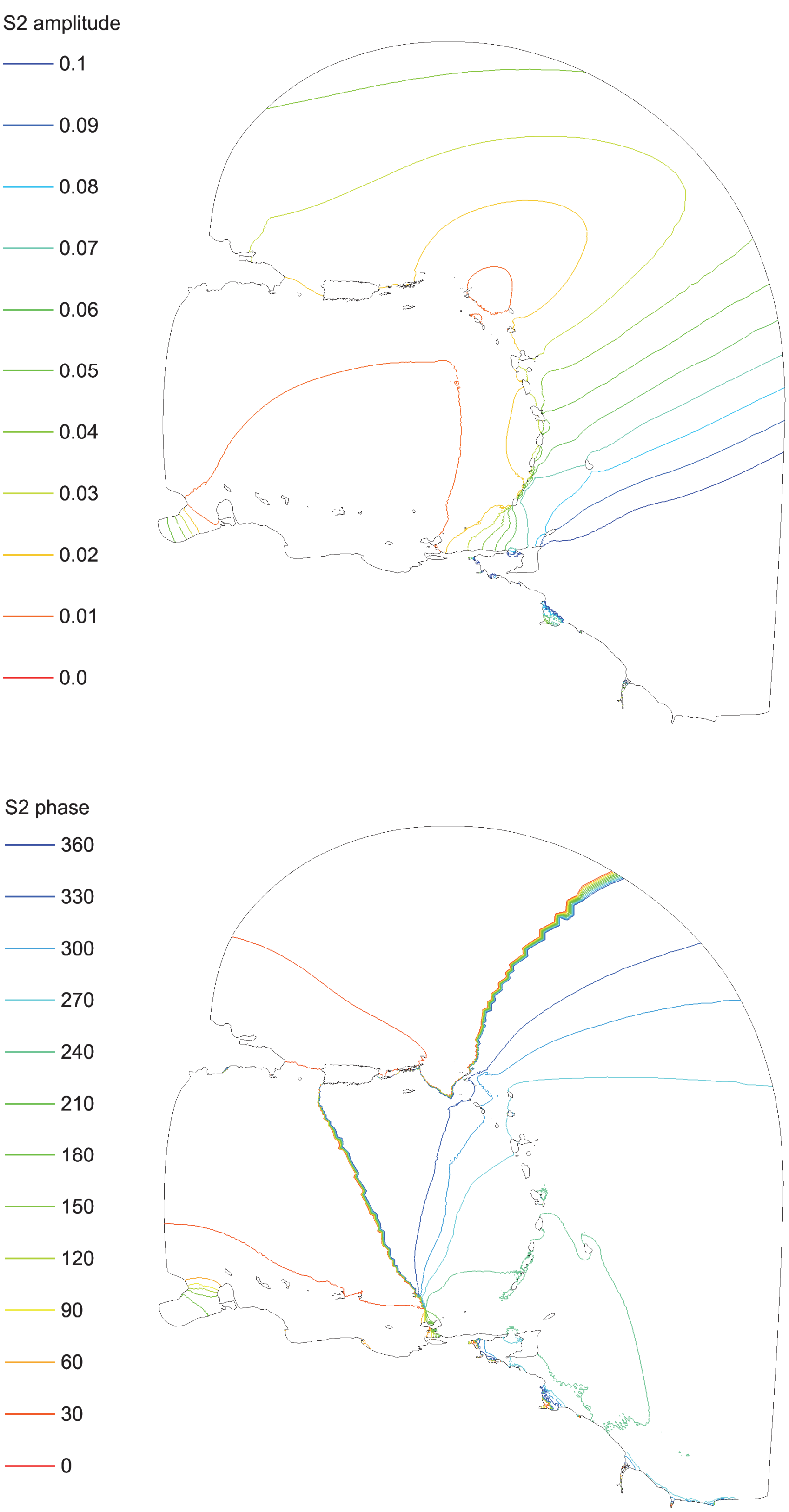


Figure B.2. S_2 amplitude (in meters) and phase (in degrees).

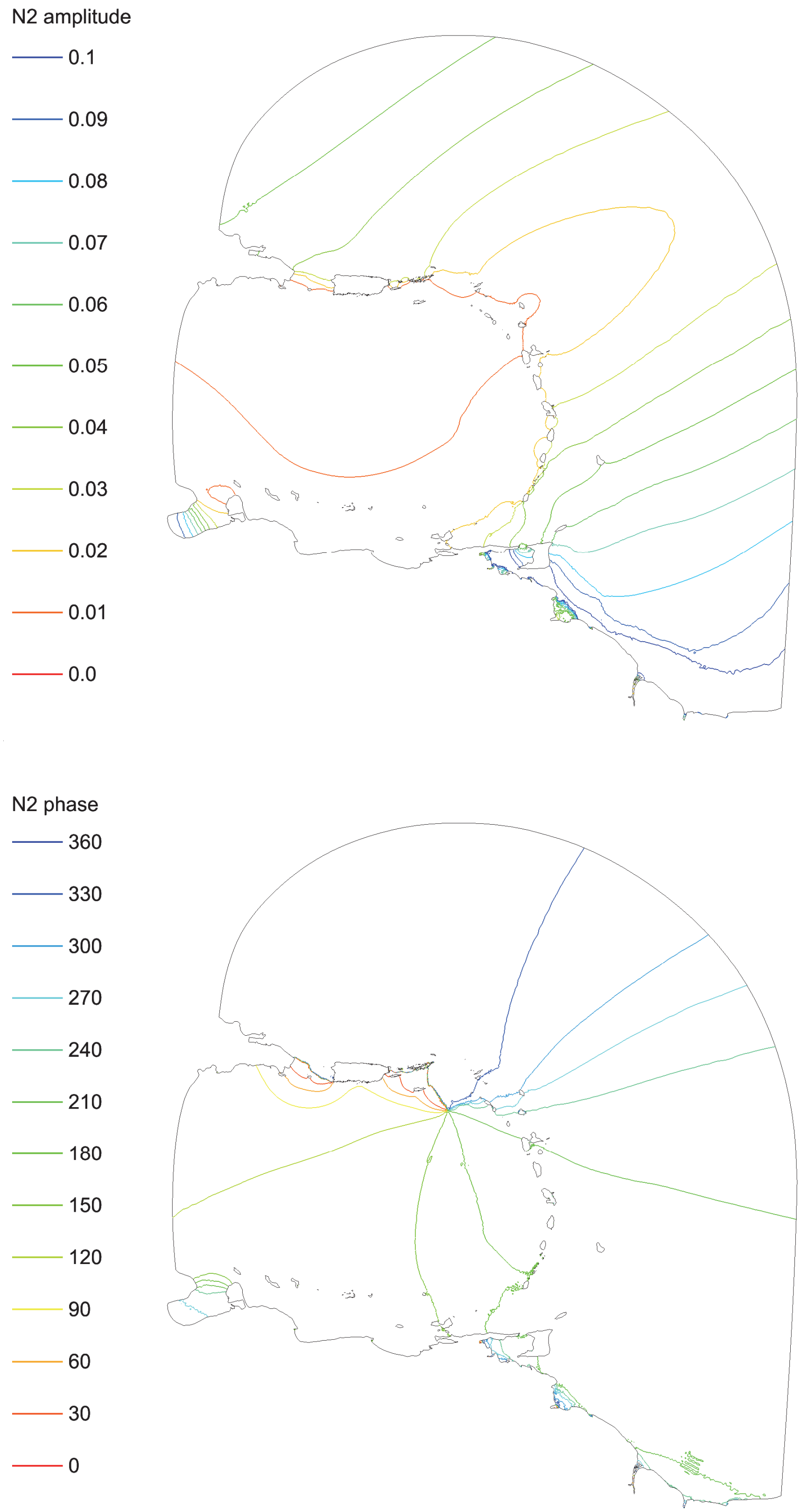


Figure B.3. N_2 amplitude (in meters) and phase (in degrees).

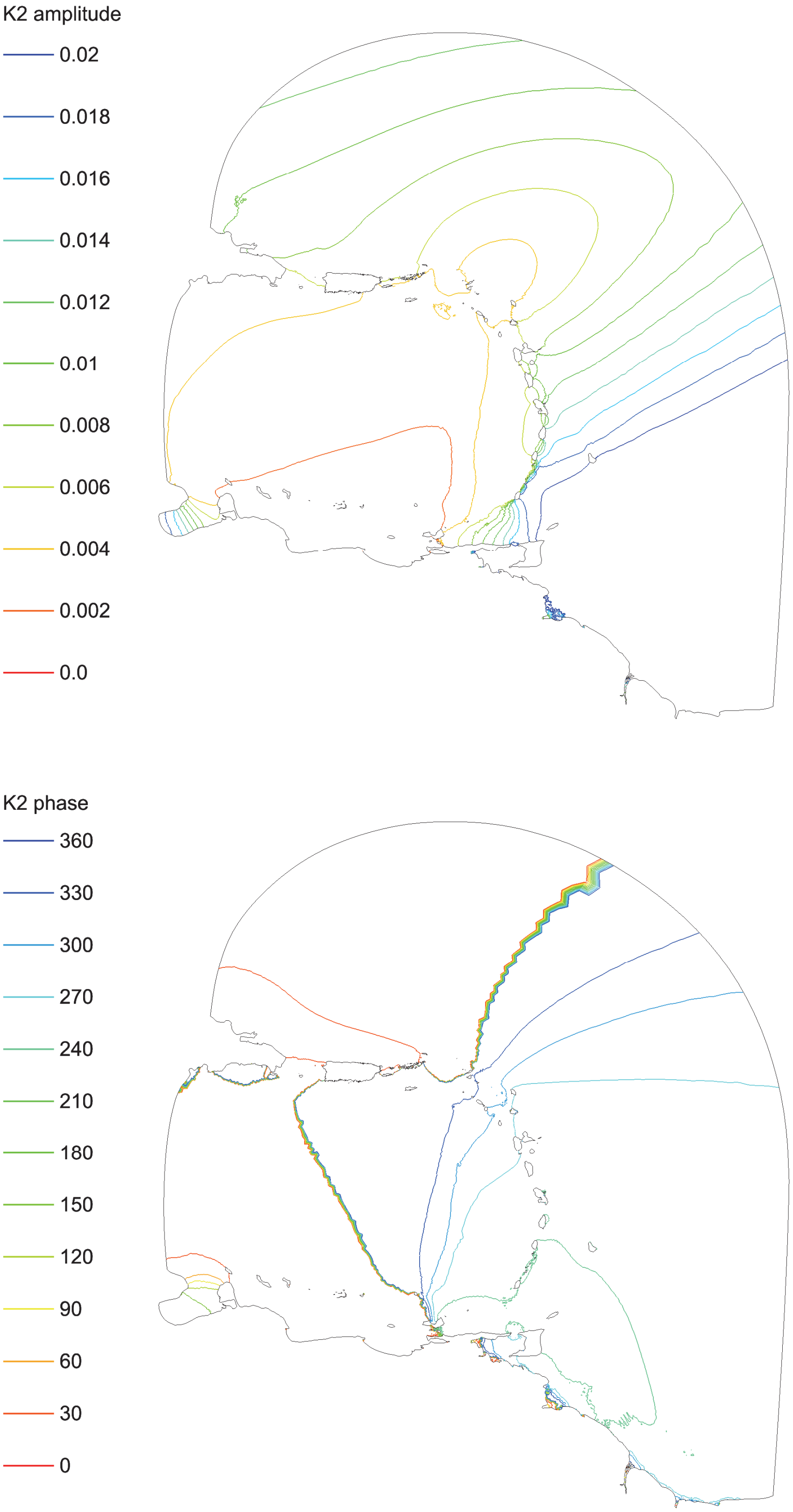
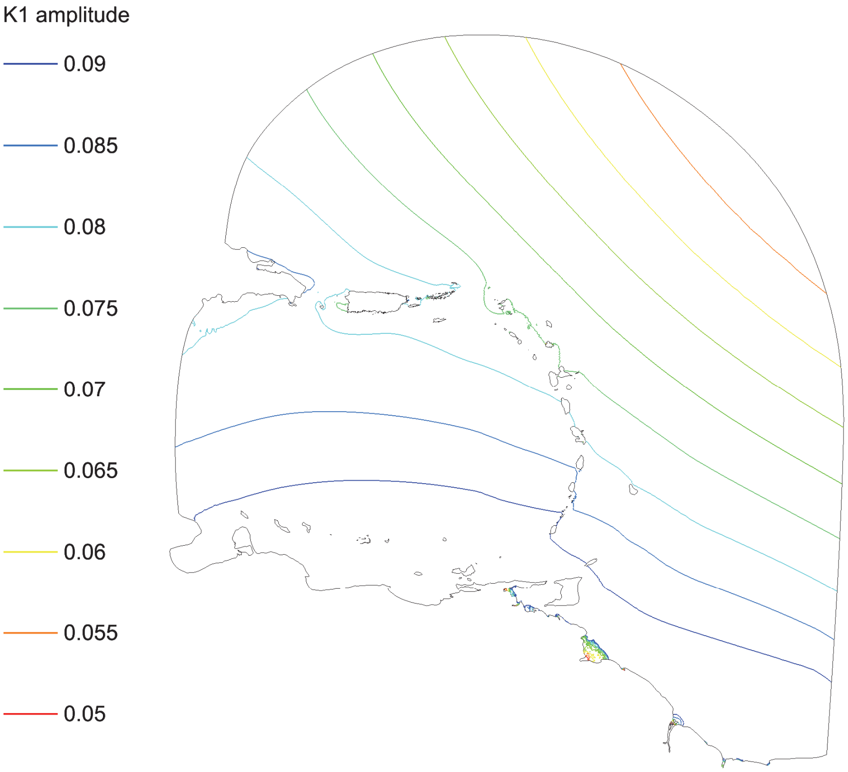


Figure B.4. K_2 amplitude (in meters) and phase (in degrees).



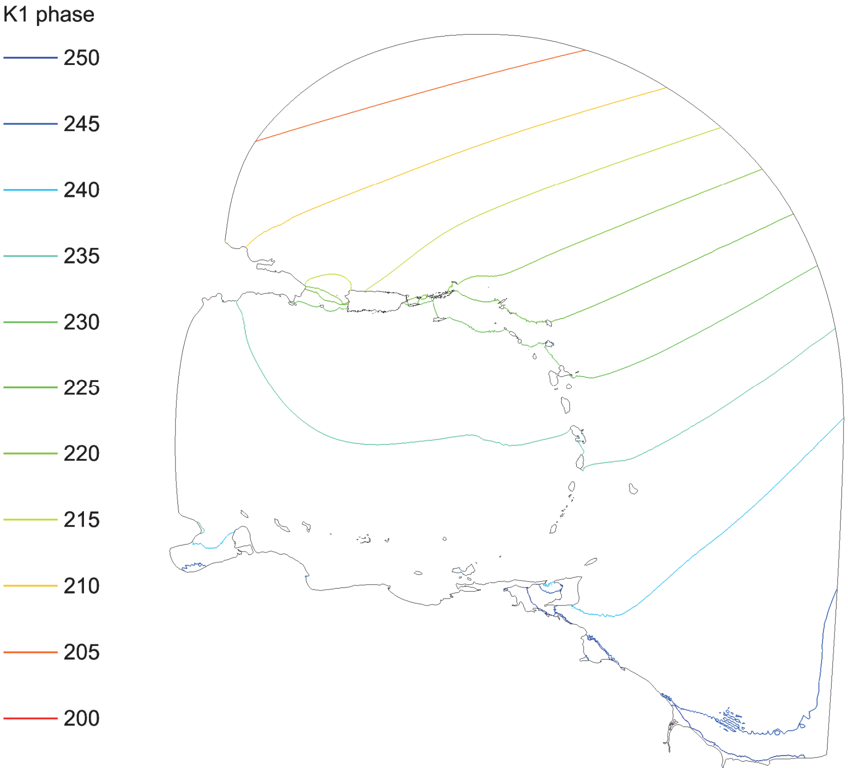


Figure B.5. K_1 amplitude (in meters) and phase (in degrees).

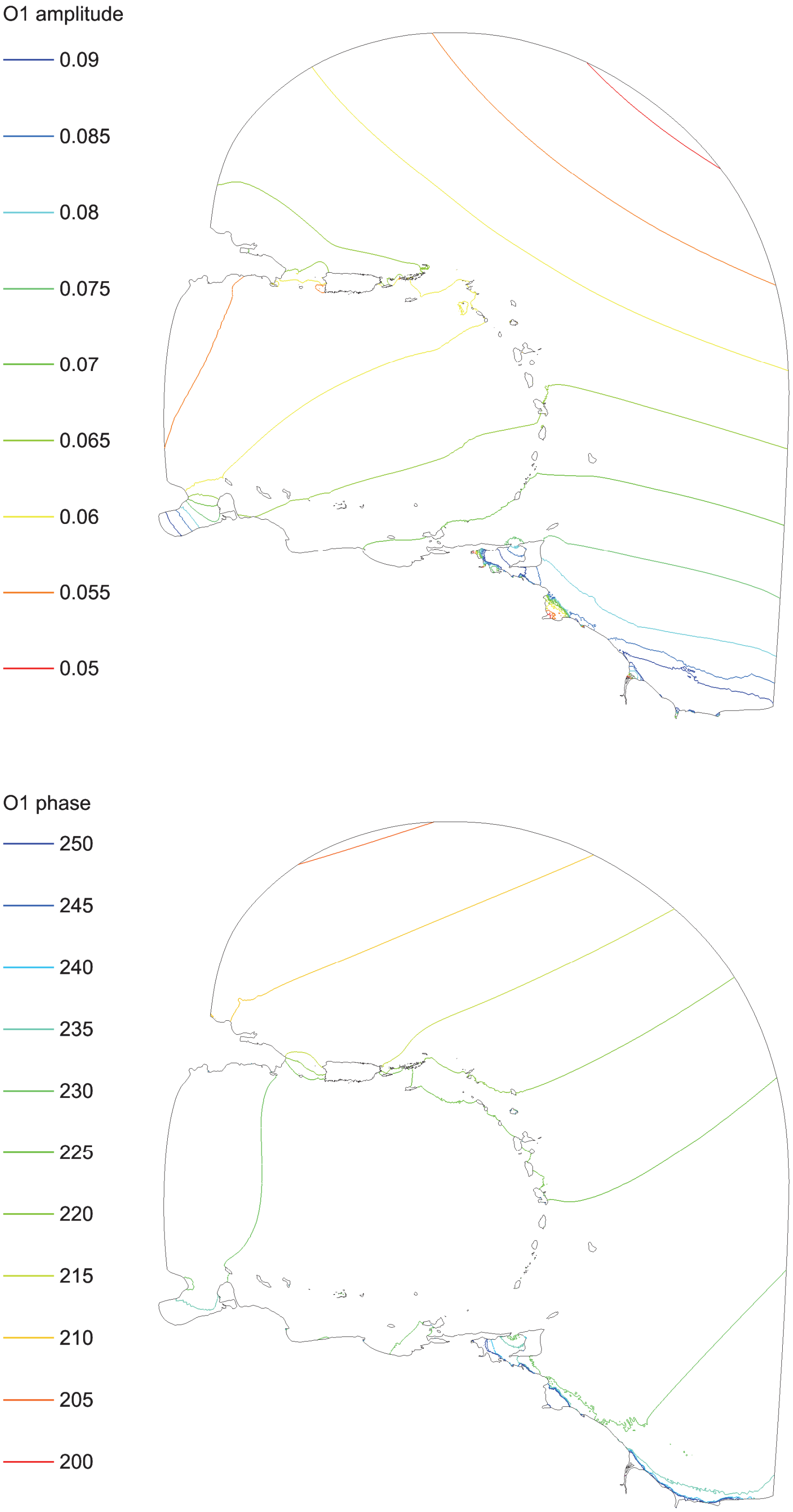


Figure B.6. O_1 amplitude (in meters) and phase (in degrees).

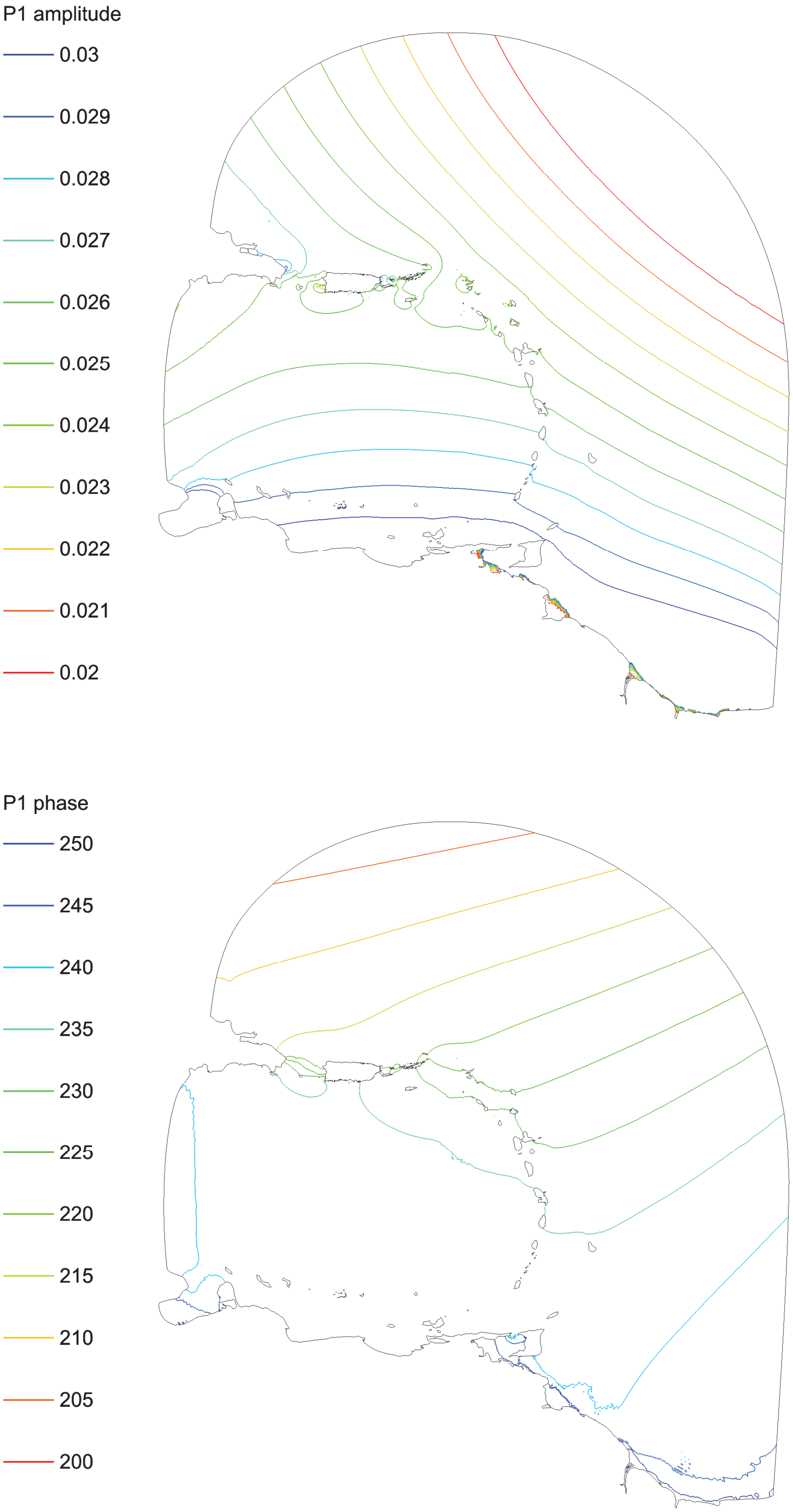


Figure B.7. P_1 amplitude (in meters) and phase (in degrees).

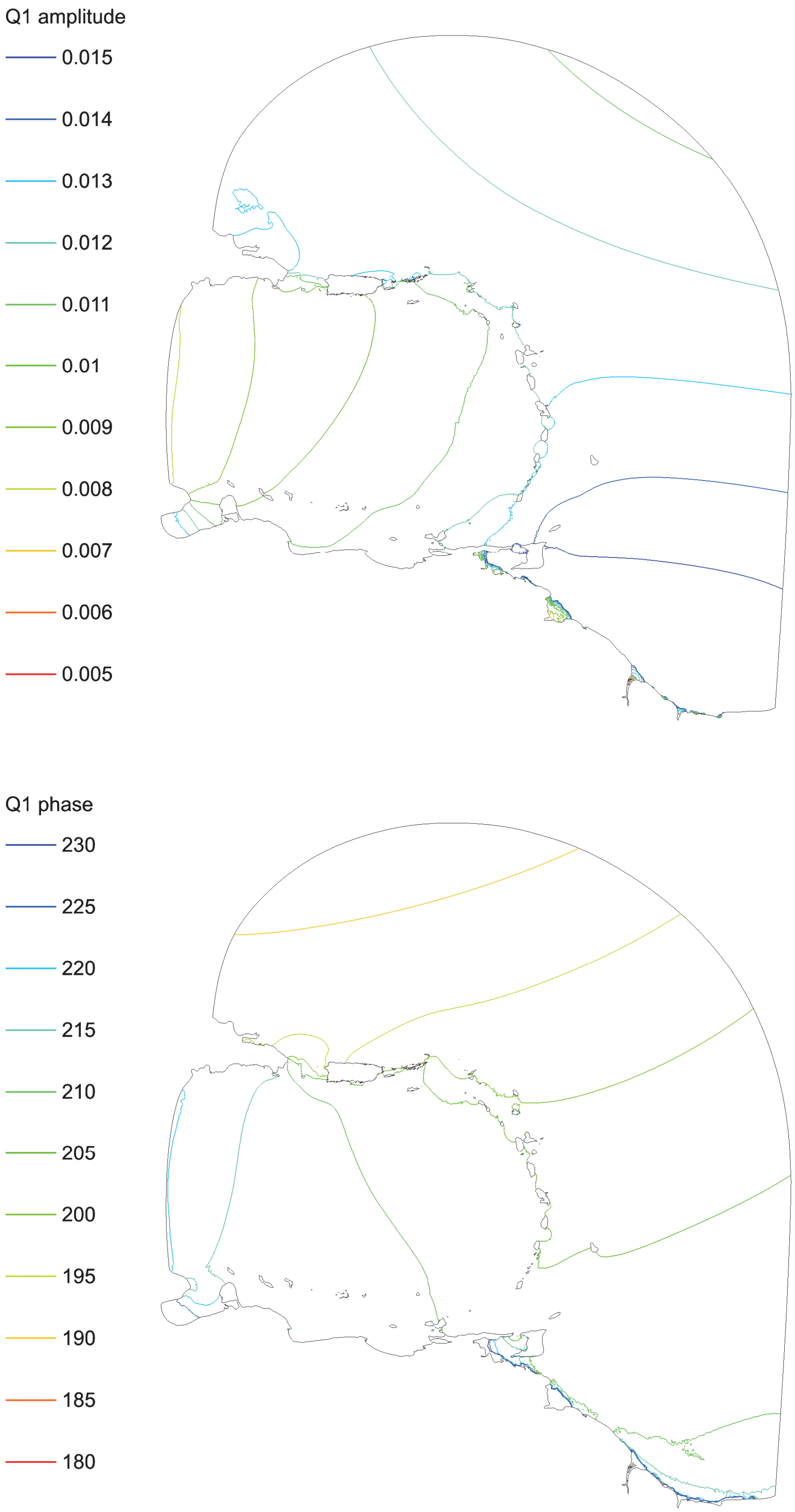


Figure B.8. Q_1 amplitude (in meters) and phase (in degrees).

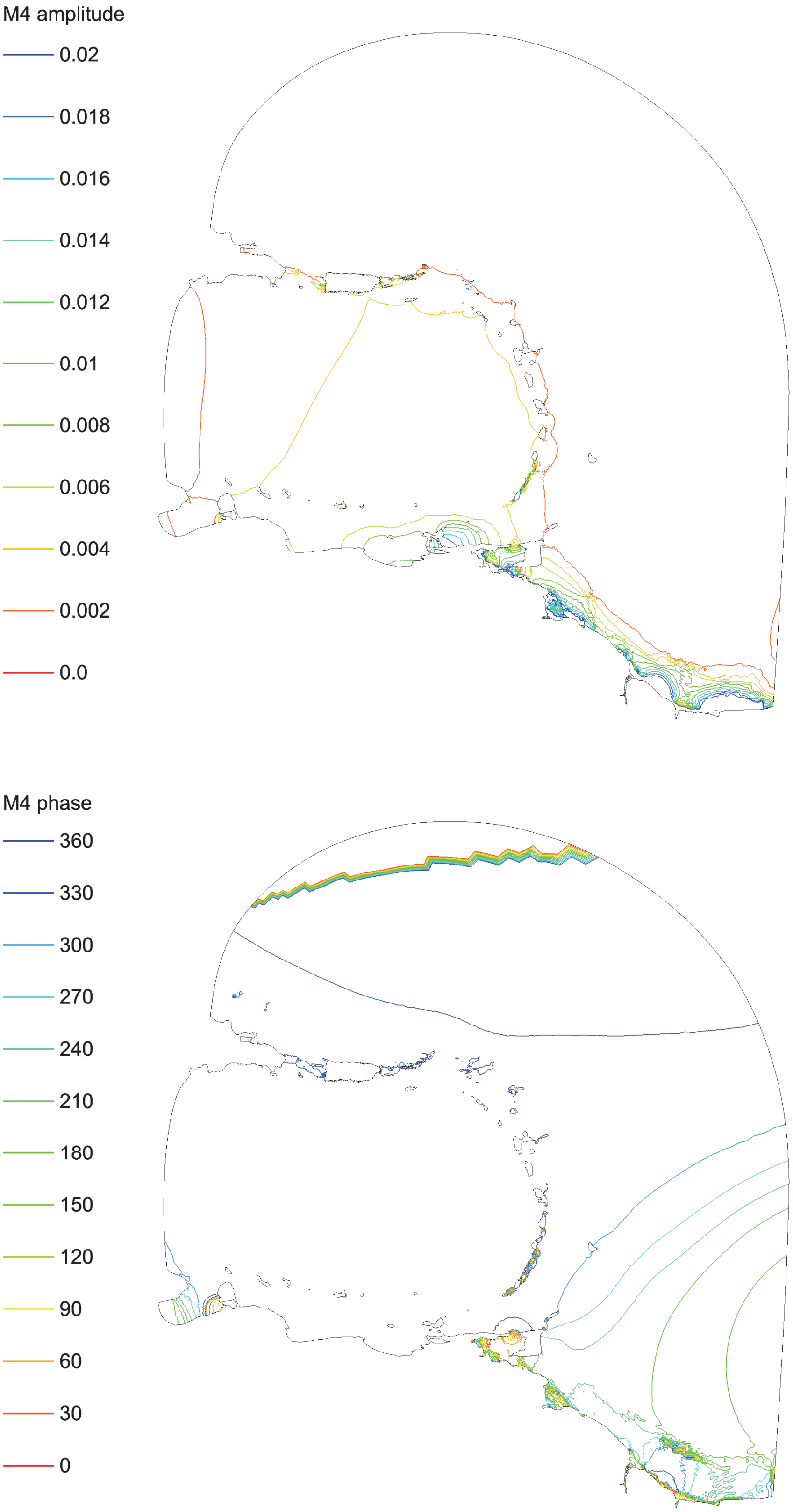


Figure B.9. M_4 amplitude (in meters) and phase (in degrees).

APPENDIX C. CREATION AND VALIDATION OF MODELED TSS FIELD

Table C.1. Puerto Rico/U.S. Virgin Islands tide station data utilized for TSS creation and also deltas computed against the TSS grid. The 'N/A' indicates that the transformation is not available in the VDatum software.

ID	Latitude (deg)	Longitude (deg)	PRVD02/VIVD09 to MSL (m)	TSS Derived Value (m)	Delta (m)
9751309	18.36761	-64.72072	-0.199	-0.199	-0.0005
9751364	17.75000	-64.70500	0.001	0.001	0.0000
9751373	18.34830	-64.71670	-0.217	N/A	N/A
9751381	18.31825	-64.72422	-0.002	-0.002	-0.0004
9751401	17.69472	-64.75381	0.000	0.000	0.0000
9751456	18.31670	-64.78170	0.074	N/A	N/A
9751467	18.36067	-64.80353	-0.146	-0.146	-0.0002
9751494	18.29714	-64.81775	0.258	0.256	0.0025
9751540	18.32670	-64.85170	0.082	0.081	0.0014
9751583	18.34894	-64.86417	-0.126	-0.125	-0.0004
9751584	17.71330	-64.88330	-0.032	-0.032	-0.0002
9751639	18.33583	-64.92000	-0.142	-0.140	-0.0019
9751768	18.37125	-64.96347	-0.205	-0.205	-0.0005
9751774	18.36330	-65.03500	-0.009	-0.009	-0.0001
9752235	18.30086	-65.30247	0.109	0.109	0.0003
9752695	18.09386	-65.47136	0.003	0.003	0.0000
9752962	18.34497	-65.56950	-0.038	-0.038	0.0000
9753641	18.18706	-65.71139	-0.002	-0.002	0.0001
9754228	18.05508	-65.83300	-0.109	-0.109	-0.0001
9755371	18.45894	-66.11642	0.000	0.000	0.0000
9756639	17.95500	-66.40670	-0.003	-0.003	0.0001
9757809	18.48053	-66.70236	0.043	0.042	0.0001
9758053	17.97253	-66.76178	-0.018	-0.018	0.0001
9759110	17.97008	-67.04642	-0.068	-0.068	0.0000
9759189	18.07481	-67.18878	-0.008	-0.008	0.0002
9759197	17.95144	-67.19658	-0.111	-0.111	-0.0001
9759394	18.22000	-67.16000	-0.047	N/A	N/A
9759412	18.45664	-67.16458	-0.015	-0.015	0.0000
9759421	18.16500	-67.18170	0.018	N/A	N/A
9759938	18.08992	-67.93850	-0.155	-0.154	-0.0001