NOAA Technical Report NOS CS 21

VDATUM FOR CENTRAL COASTAL NORTH CAROLINA: TIDAL DATUMS, MARINE GRIDS, AND SEA SURFACE TOPOGRAPHY

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noaa National Oceanic and Atmospheric Administration

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

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NOTICE

TABLE OF CONTENTS

LIST OF FIGURES v

LIST OF TABLES vi

ABSTRACT vii

1. INTRODUCTION 1

2. BATHYMETRIC, TIDAL, AND COASTLINE DATA 3

  2.1. Bathymetric Data 3
  2.2. Tidal Data 5
  2.3. Digitized Coastline 9

3. TIDAL AND HYDRODYNAMIC MODELING 11

  3.1. The Hydrodynamic Model 11
  3.2. Model Grid Development 12
  3.3. Population of the Model Grid with Bathymetric Data 13
  3.4. Ocean Boundary Forcing 14
  3.5. Results of Model Water Level Simulations 15
  3.6. Corrections to the Modeled Tidal Datum Fields 18

4. THE TIDAL MARINE GRIDS 21

  4.1. Grid Point Location 21
  4.2. Population of the Marine Grids 22
  4.3. Illustration of Problems at Barrier Islands 23
  4.4. The Bounding Polygons 25
  4.5. Assessment of Errors in the Marine Grid 28

5. SEA SURFACE TOPOGRAPHY 31

6. SUMMARY AND CONCLUSIONS 33

ACKNOWLEDGEMENTS 34

REFERENCES 35

APPENDIX A. BATHYMETRIC DATA SOURCES 37

APPENDIX B. WATER LEVEL STATION DATA 39

APPENDIX C. HYDRODYNAMIC MODEL PARAMETERS 41

APPENDIX D. SUMMARY OF HYDRODYNAMIC MODEL ERRORS 43

APPENDIX E. SUMMARY OF VDATUM ERRORS 45

LIST OF FIGURES

Figure 1. The area of North Carolina around Pamlico Sound for which VDatum was developed. 2

Figure 2. Dates of NOS surveys. 4

Figure 3. Location of NOS soundings. 4

Figure 4. Locations of water level stations (red squares) in the study area. Only the last four digits of the station numbers are shown; the first three digits are 865 for all stations except for the northernmost, where they are 863. See Appendix B for further information. 7

Figure 5. Locations of water level stations (red squares) around Oregon inlet. Only the last four digits of the station numbers are shown; the first three digits are 865. See Appendix B for further information. 8

Figure 6. Locations of water level stations (red squares) around Beaufort Inlet. Only the last four digits of the station numbers are shown; the first three digits are 865. See Appendix B for further information. 8

Figure 7. Sample of extracted vector shoreline for MHW (black) and MLLW (green). 9

Figure 8. Finite element grid for the regional model. 12

Figure 9. Model finite element grid with DEM boundary (dark black box) and MHW coastline (blue line). 13

Figure 10. Time series of water levels over 21 days with extrema noted. 15

Figure 11. Time series of water levels for 40 hours at a grid node with a depth of 0.22 m above model zero elevation. When total water depth falls to 10 cm or less, the cell becomes inactive. 16

Figure 12. Comparison of (a) the MHHW and MLLW datums (m) and (b) MHW and MLW datums obtained from observations (horizontal axis) and from the hydrodynamic model (vertical axis). RMS error for all datums is 5.2 cm. 17

Figure 13. Mean sea level, as computed by the hydrodynamic model. MSL is relative to the model's zero elevation. 17

Figure 14. Diurnal tide range (the difference between MHHW and MLLW) as computed by the hydrodynamic model. 18

Figure 15. Error (modeled value minus observed value) in the MHHW datum field as interpolated by the TCARI method. 19

Figure 16. Sample region with marine grid points (solid squares) and their numerical datum values (cm), hydrodynamic model grids (large triangles) with datum values at their vertices (cm), narrow barrier island (gray area), and test points A and B. 24

Figure 17. Sample region with marine grid points (solid squares) and their datum values (cm), hydrodynamic model grids (large triangles) with their MHHW to MSL datum values (cm) at the vertices, a narrow barrier island (curved lines), and the bounding polygon (solid line inside barrier island). 24

Figure 18. The bounding polygons for the Coastal North area (purple line), Coastal Central area (green line), and Pamlico Sound area (blue line). Also shown are shoreline (gray) line, the hydrodynamic model's offshore boundary (dashed black line) and the 25 nmi limit (dotted black line). 26

Figure 19. Area around Oregon Inlet showing the locations of the tidal marine grid points for the Pamlico Sound grid (blue squares) and the Coastal North grid (purple squares). The plus signs represent null points for each grid. The value (cm) of the tidal datum (here the difference between MHHW and MSL) is shown next to the non-null points. Points along a track crossing the bounding polygon are shown as black squares. 27

Figure 20. Datum values along a 10-point track from northeast to southwest (see Figure 19) from (a) both grids having equal spacing of approximately 0.24 nmi (open squares), and (b) a Pamlico grid with spacing of 0.24 nmi and a coastal grid with spacing of 0.48 nmi (plus signs). Notice the discontinuity of 0.11 m at an along-track distance of 0.25 nmi. 27

Figure 21. The computed sea surface topography (TSS). Elevations are in meters. 32

LIST OF TABLES

Table 1. Diurnal range values at stations where data from the 1960-1978 epoch and the 1983-2001 epoch are both available. Ranges and differences are in meters. 6

Table 2. Sample of tidal constituents and their harmonic constants at a boundary node in the regional grid. 15

Table 3. Parameters for the North Carolina tidal marine grids. Latitude is positive northward, and longitude is positive eastward. 22

Table 4. Observed values of NAVD 88 relative to LMSL. The data are based on the most recent National Tidal Datum Epoch (1983-2001) unless noted, and a positive value means that the NAVD 88 elevation lies above the LMSL surface. 31

Table 5. Parameters for the initial North Carolina sea surface topography (TSS) grid. Latitude is positive North, longitude is positive East. 32

ABSTRACT

VDatum, a software tool for vertical datum transformation, has been developed for a portion of the North Carolina coastal area. To support VDatum, gridded fields representing the conversion between various tidal datums and mean sea level, and between mean sea level and the North American Vertical Datum of 1988, were created. Initial fields of tidal datum transformations (such as the difference between mean higher high water and mean sea level) were generated by the two-dimensional, barotropic, finite-element numerical tidal model, ADCIRC. The model grid covers the central portion of the North Carolina coast including Currituck, Albemarle, Pamlico, Core, Back, and Bogue Sounds, as well as their offshore areas. Digitized coastline was available from the Extracted Vector Shoreline project, and depths were taken from historical Coast Survey hydrographic surveys. The hydrodynamic model was forced by a reconstructed tide at the ocean boundary, using harmonic constants from a basin-scale tidal model. After a 37-day model run, the 6-minute water level time series at each model node for the last 30 days was analyzed for high and low waters, then averaging produced the initial tidal datum fields. When the model's tidal datums were compared to values at 45 historical tide stations, the RMS error for all datums was 5.2 cm. To reduce this error, a two-dimensional correction field was constructed by spatial interpolation of the error values at each tide station using the TCARI method. When the correction fields were added to the hydrodynamic model's tidal datum fields to get the final datum fields, the datum values closely matched the historical values at the tide stations. The final corrected datum field values were then transferred to a set of three regular marine grids. These grids have a uniform spacing in latitude and longitude. Three grids were needed to accurately represent the effect of the barrier islands and to keep file sizes small. The datum values from the marine grids match the observed datums to within 1.1 cm RMS. The sea surface topography (TSS), or difference between local mean sea level and the NAVD 88 geopotential surface, was generated by a minimum curvature algorithm using data at 18 historical tide stations with benchmark data. The TSS field values were then transferred to the same three regular marine grids.

Key Words: tides, tidal datums, North Carolina, Pamlico Sound, North American Vertical Datum of 1988, mean sea level, spatial interpolation, coast line.

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 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. For example, using VDatum, ellipsoidal elevations can be converted, by parametric equations, to elevations relative to the North American Datum of 1983 (NAD 83); NAD 83 elevations can be converted to elevations relative to the North American Vertical Datum of 1988 (NAVD 88) using a gridded geoid model such as Geoid99; NAVD 88 elevations can be converted to elevations relative to Local Mean Sea Level (LMSL) using a gridded field called the sea surface topography; and LMSL elevations can be converted to elevations relative to other tidal datums, such as MLLW, by using gridded tidal datum fields.

Because the tides and the sea surface topography vary widely throughout the coastal region, each geographic area of VDatum application requires a unique set of gridded data. To date, tidal datum and sea surface topography fields for VDatum have been produced by NOS for Tampa Bay (Hess, 2001), coastal southern Louisiana (Hess et al., 2004), the New York Bight (Hess, 2001), central coastal California (Myers, 2001), Delaware Bay (Hess et al., 2003), Puget Sound (Hess and Gill, 2003; Hess and White, 2004), and Lake Calcasieu (Spargo and Woolard, 2005). VDatum for Tampa Bay was employed to integrate elevation data from a variety of sources into a bathymetric-topographic Digital Elevation Model for use in coastal GIS applications (Parker et al., 2003; Gesch and Wilson, 2001). VDatum was also used for testing a method of processing the hydrographic data from a kinematic-GPS hydrographic survey in Delaware Bay (Hess et al., 2003).

NOS routinely collects water level observations at shore-based stations along U.S. coasts and analyzes them to produce tidal datums. As described above, there is an important need to obtain two-dimensional tidal datum fields that cover the coastal waters between the water level stations. This paper discusses the process of obtaining (1) tidal datum fields in coastal North Carolina by the combined use of a hydrodynamic model and spatial interpolation of errors, and (2) the sea surface topography by spatial interpolation.

VDatum in North Carolina grew from a study of the impacts of long-term sea level rise on the coastal ecosystems in the sounds and nearby estuaries of North Carolina (Hess et al., 2004). The study is being led by the Center for Sponsored Coastal Ocean Research/Coastal Ocean Program (CSCOR/COP) of NOS' National Centers for Coastal Ocean Science. Technical support is provided by NOS' Office of Coast Survey (OCS), National Geodetic Survey (NGS), and the Center for Operational Oceanographic Products and Services (CO-OPS), which are cooperating to develop data sets, modeling tools, and maps that will be useful to coastal managers. Based on project resources, the area of VDatum was selected to focus on Currituck, Albemarle, Pamlico, Core, Back, and Bogue Sounds (Figure 1).

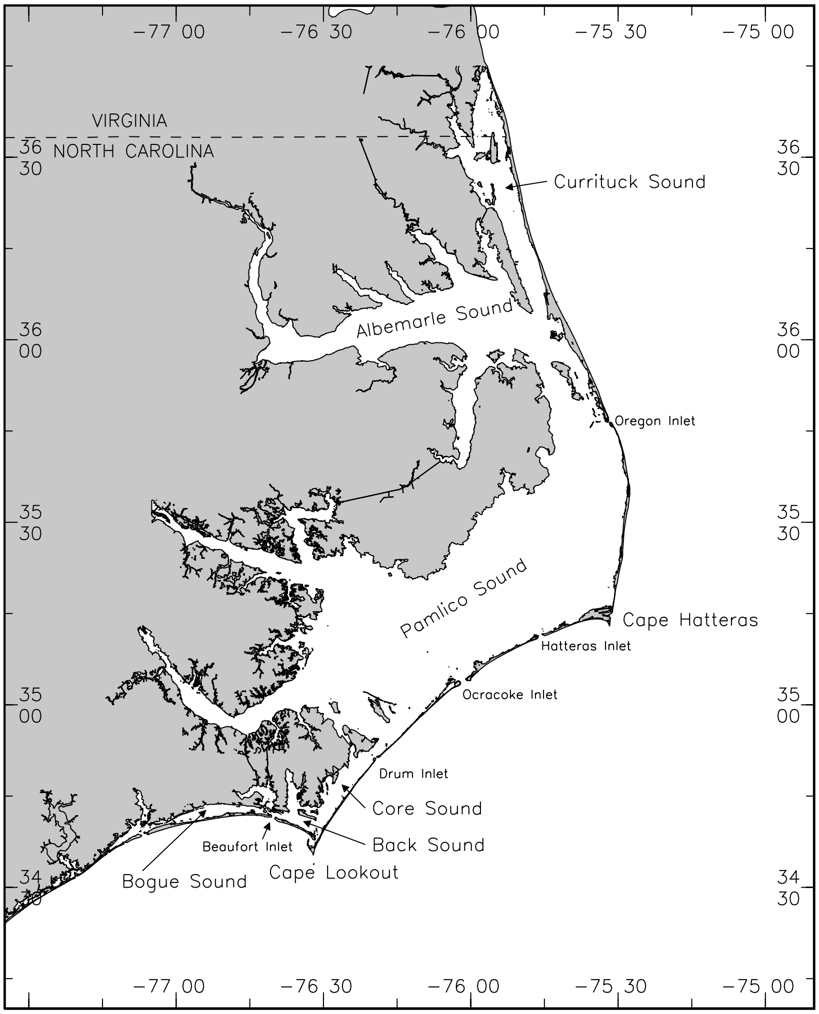


Figure 1. The area of North Carolina around Pamlico Sound for which VDatum was developed.

The following sections describe the technical approach and the accomplishments in the major components of the study:

- Access of historical NOS bathymetric, coastline, and tidal data,
- Development of the hydrodynamic grid and model,
- Creation of the tidal marine grid, and
- Generation of the sea surface topography.

The appendices include a discussion of the bathymetric data and the locations and names of the water level stations and their tidal datum values.

2. BATHYMETRIC, TIDAL, AND COASTLINE DATA

Water level model development for the Pamlico Sound region requires three types of data: bathymetry, tidal data, and coastline data. Historical bathymetric, or sounding, data are available from NOS and other sources. Model validation depends on comparisons to datums based on observed water levels. Updated tidal datums were therefore derived for several local tide stations, and a new tide station was installed in Core Sound. Historical water levels were re-analyzed to determine updated estimates of long-term sea level rise. A digital coastline was accessed and used to delineate land and water areas.

2.1. Bathymetric Data

Several sources of bathymetric data for the North Carolina coast were evaluated and processed for the development of the water level model. Sounding values were initially selected from the NOS Office of Coast Survey (OCS) hydrographic database maintained at the National Geophysical Data Center (NGDC), which developed the interactive GEOphysical DAta System (GEODAS) to assimilate, store and manage geophysical data. The NOS OCS bathymetric database contains soundings digitized from smooth sheets of hydrographic surveys completed between the years 1851 and 1965, as well as digital soundings acquired by survey ships since 1965. Lead line measurements are assumed for surveys before 1940. Water depths are recorded by digital echo sounders from 1940 onward. For some regions of the coastal United States, the NOS OCS bathymetric database includes high-density multibeam sonar depth measurements processed from hydrographic surveys since 1980.

Accuracies reported for survey data apply the rigorous standards specified by the International Hydrographic Office (IHO) since the 1800s. The horizontal accuracy of the NOS sounding datasets ranges from 2 to 15 m nearshore and from 20 to 75 m offshore, with improved accuracy of recent surveys that employ a differential global position system (DGPS). NGDC's GEODAS Hydrographic Survey Database System archives the original depth units (feet, fathoms or meters) as tenths of meters. To establish a common horizontal reference, the original horizontal datum of each survey was transformed to North American Datum 1983(1986) [NAD 83(86)] using the North American Datum Conversion utility (NADCON) developed at NOS. For surveys before 1927, horizontal coordinates were transformed using a single pair of datum latitude/longitude shift values for the entire survey to approximate North American Datum 1927 (NAD 27), which NADCON further transformed to NAD 83(86).

The NOS sounding data are referenced to one of several vertical datums; each sounding has associated metadata that lists whether the depth value is referenced to Mean Low Water (MLW), MLLW, or the low water datum (LWD), which is defined for North Carolina as 0.5 feet (0.15 meters) below the local Mean Water Level (MWL). MWL is the average water level over the available record. Analysis of tidal data included in NOAA hydrographic reports reveals that LWD is usually used for surveys within Pamlico Sound at locations far from inlets. The vertical accuracy of NOS soundings conform to IHO standards: 0.3 m in 0 to 20 m of water, 1.0 m in 20 to 100 m of water, and 1% of the water depth in waters deeper than 100 m.

More than 200 NOS hydrographic surveys were conducted within the North Carolina project area between 1851 and 2002. Approximately 1,980,120 soundings from 158 surveys were accessible and processed from GEODAS. NOS soundings were sorted, and then merged by year and by original vertical (tidal) datum. Soundings in each survey were checked against adjacent and overlapping surveys to ensure continuous coverage. Thirty-four separate spatial-temporal filters, consisting of raster layers resolved by date and sounding density, were generated to compile the best historical bathymetry retrievable from the NOS hydrographic survey database. The map below shows the dates, location, and density distribution of sounding data compiled from NOAA ENCs and historical NOS surveys (Figures 2 and 3). Appendix A contains further information on the sounding data.

🟦 **ENC soundings**

NOS Hydrographic Surveys

- 🟦 **1998-2001**
- 🟫 **1974-1981**
- 🟪 **1970-1971**
- 🟦 **1962-1965**
- 🟥 **1953-1955**
- 🟫 **1942-1943**
- 🟪 **1932-1936**
- 🟪 **1920-1927**
- 🟩 **1913-1917**
- 🟧 **1869-1877**

Figure 2. Dates of NOS surveys.

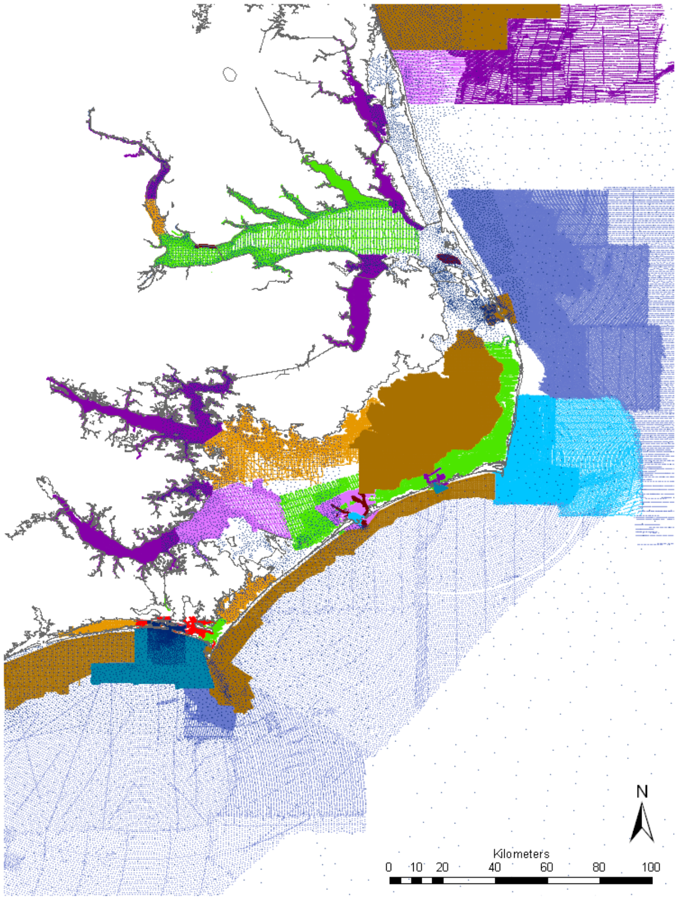


Figure 3. Location of NOS soundings.

Multibeam sonar data from surveys conducted in 2002 and later and sounding data from at least 40 older surveys (the majority in the 1800s) were unavailable for distribution via GEODAS. Because these data had been processed and validated for publication by OCS, sounding values were collected from the 2004 editions of NOAA ENCs at map scales up to 1:50:000 or larger. Originally digitized from NOAA raster nautical charts, ENCs comprise the official charting database provided in IHO native S-57 vector format, which is the data standard developed by the IHO to be used for the exchange of digital hydrographic data.

Historical NOS bathymetry data are also available in an interpolated, gridded format as part of NOAA's Coastal Relief Model (CRM) at NGDC. CRM gridded bathymetry are available at a horizontal spacing of 3 arc-seconds, or approximately 90 m, while seafloor elevations are resolved to 0.1 m. However, CRM depths have not been corrected from their original horizontal datum or vertical datum (MLW, MLLW, or LWD).

Recent bathymetry data from the U.S. Army Corps of Engineers (USACE) originate from 54 inlet and channel surveys conducted between 1997 and 2003. Sounding data provided by the USACE are regularly published in the latest editions of NOAA nautical charts. Survey data were processed to 61,573 soundings whose horizontal coordinates were converted from NC State Plane (feet) to NAD 83 with Geodetic Reference System 1980 ellipsoid (decimal degree), which closely corresponds to World Geodetic System 1984. The vertical datum for USACE surveys were recorded as local MLW. Soundings in feet were converted to depth in meters. Where applicable, USACE channel soundings blend with or supersede the historical NOS bathymetry (see Section 3.3).

2.2. Tidal Data

The NOS bathymetric data to be used by the hydrodynamic model is referenced to a tidal datum, so they must be adjusted to mean sea level. Tidal datum values at NOS water level stations are routinely computed and are available to the public in the form of the station benchmark sheets. Tidal datums at water level stations are elevation values that are determined from a time series of observations. For stations located along the coasts of the U.S. (except for the Great Lakes), the analysis starts with the identification of all the tidal extrema (highs and lows) in the record, and continues with the selection (within a 25-hour time period) of the higher of the two highs and the lower of the two lows. If only one high water is present in the time period, it is categorized as a higher high. Thus, for high water (for example), each day has either a lower high and a higher high, or a single higher high. The average of all the lower highs and the higher highs is the MHW, and the average of just the higher highs is the MHHW. The process for producing Mean Low Water (MLW) and MLLW from the low waters is similar. The average of the MHW and the MLW is called the Mean Tide Level (MTL) and the average of the MHHW and the MLLW is called the Diurnal Tidal Level (DTL). Mean Sea Level (MSL) is the average of the hourly water levels. Where MSL is not computed, the MTL or DTL can be used as approximations. For further information on tidal datums, see Gill and Schultz (2001).

Tidal datums derived from observations made in a limited time period are adjusted to represent equivalent values for a 19-year National Tidal Datum Epoch (NTDE). The present NTDE of 1983-2001 was implemented in April 2003 and replaced the previous 1960-1978 NTDE period. This recent epoch will give more accurate datums for locations where apparent sea levels are changing rapidly due to local land subsidence caused by mineral and ground water extraction, isostatic rebound following the last ice age, or tectonic motion. Although tidal data throughout the U.S. are in the process of being updated to the new epoch, not all stations will be included in the update. Nevertheless, datums from older epochs may be useful in developing the hydrodynamic model and the datum fields. The data in Table 1 shows values at stations where data from the 1960-1978 epoch and the 1983-2001 epoch are both available for comparison. For these stations, the mean range for the newer epoch is 0.90 m, the ratio of the mean tide range for the new epoch to the range for the older epoch is 1.014, the mean difference is 2.4 cm, and the mean of the percentage differences is 3.9% (the percentage difference at each station is 100 times the absolute value of the difference divided by the average range). Therefore, because the differences are relatively small, it was decided to use datums from the previous epoch if only they, and not the newer datums, were available.

Table 1. Diurnal range values at stations where data from the 1960-1978 epoch and the 1983-2001 epoch are both available. Ranges and differences are in meters.

No.	Station	Epoch	Range	Epoch	Range	Ratio	Diff	%Diff
1	8651370	1960	1.143	1983	1.124	0.983	-0.019	1.676
2	8652587	1960	0.350	1983	0.356	1.017	0.006	1.700
3	8652678	1960	0.675	1983	0.687	1.018	0.012	1.762
4	8653215	1960	0.241	1983	0.299	1.242	0.058	21.567
5	8654400	1960	1.076	1983	1.056	0.981	-0.020	1.871
6	8656306	1960	1.042	1983	1.065	1.022	0.023	2.183
7	8656394	1960	0.195	1983	0.203	1.041	0.008	3.983
8	8656483	1960	1.061	1983	1.079	1.017	0.018	1.710
9	8656502	1960	1.043	1983	1.065	1.021	0.022	2.087
10	8656518	1960	0.963	1983	0.979	1.017	0.016	1.648
11	8656539	1960	0.812	1983	0.830	1.022	0.018	2.192
12	8656590	1960	1.305	1983	1.264	0.969	-0.041	3.157
13	8656841	1960	1.353	1983	1.391	1.028	0.038	2.747
14	8656937	1960	1.170	1983	1.201	1.026	0.031	2.578
Means:			0.888		0.900	1.014	0.024	3.633

The locations of the tidal stations used in this study are shown in Figures 4, 5, and 6. Station locations and tidal datum values are given in Appendix B.

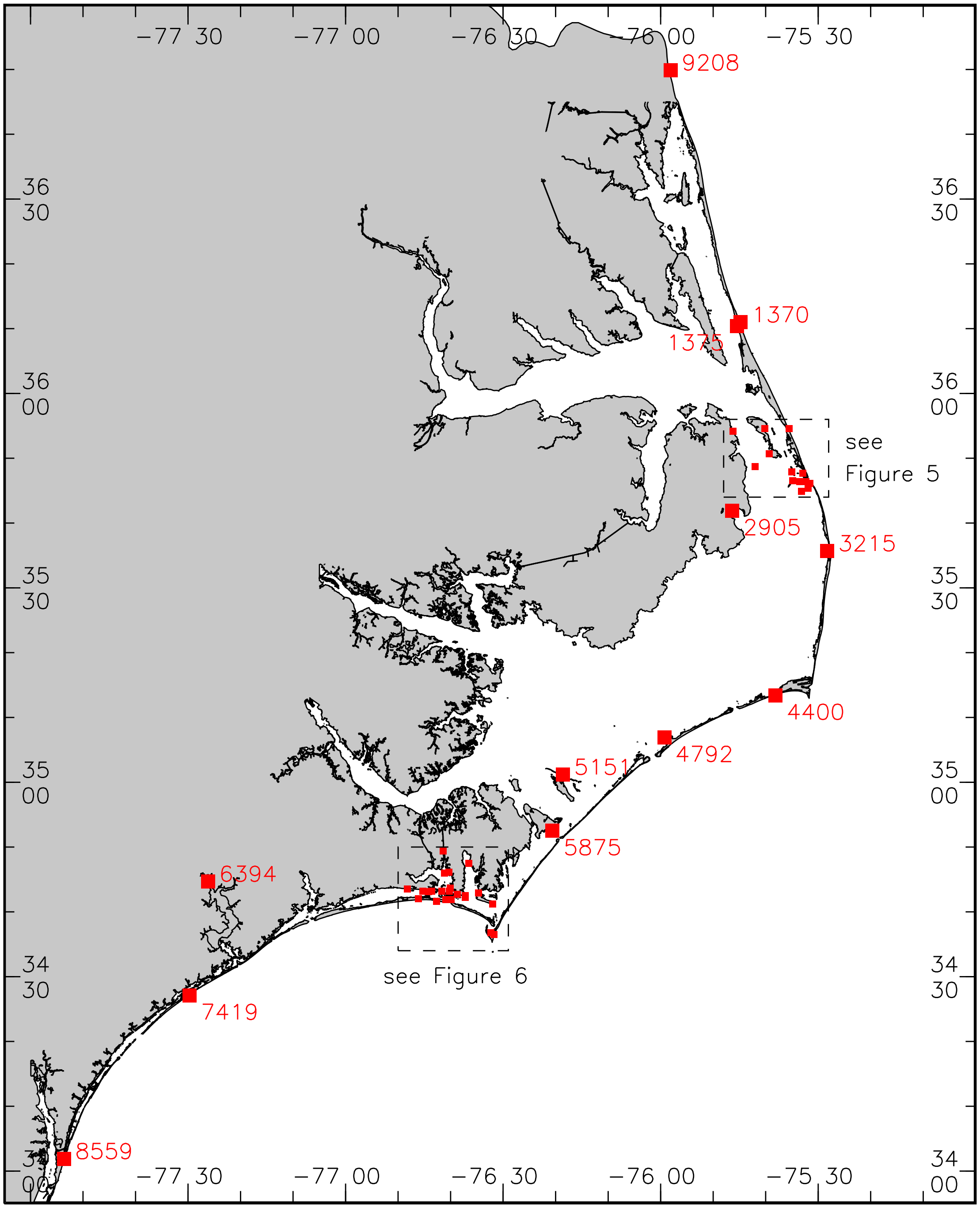


Figure 4. Locations of water level stations (red squares) in the study area. Only the last four digits of the station numbers are shown; the first three digits are 865 for all stations except for the northernmost, where they are 863. See Appendix B for further information.

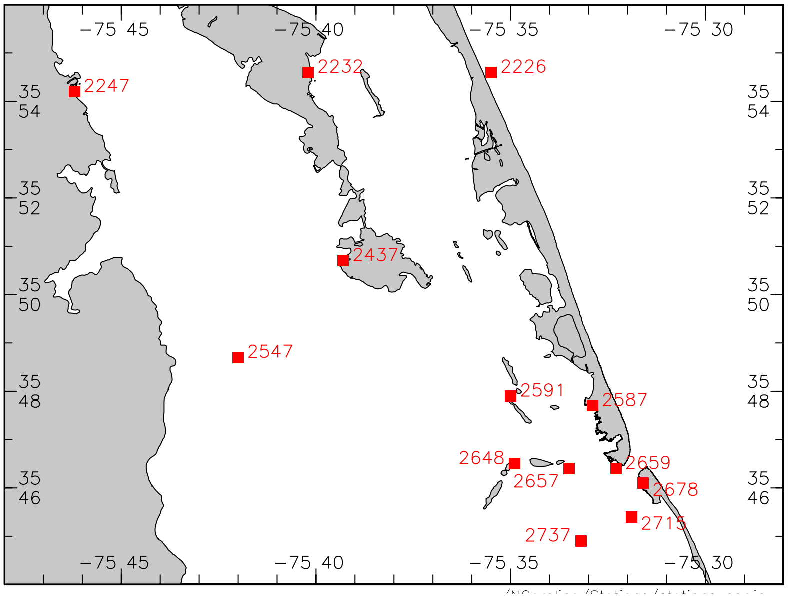


Figure 5. Locations of water level stations (red squares) around Oregon inlet. Only the last four digits of the station numbers are shown; the first three digits are 865. See Appendix B for further information.

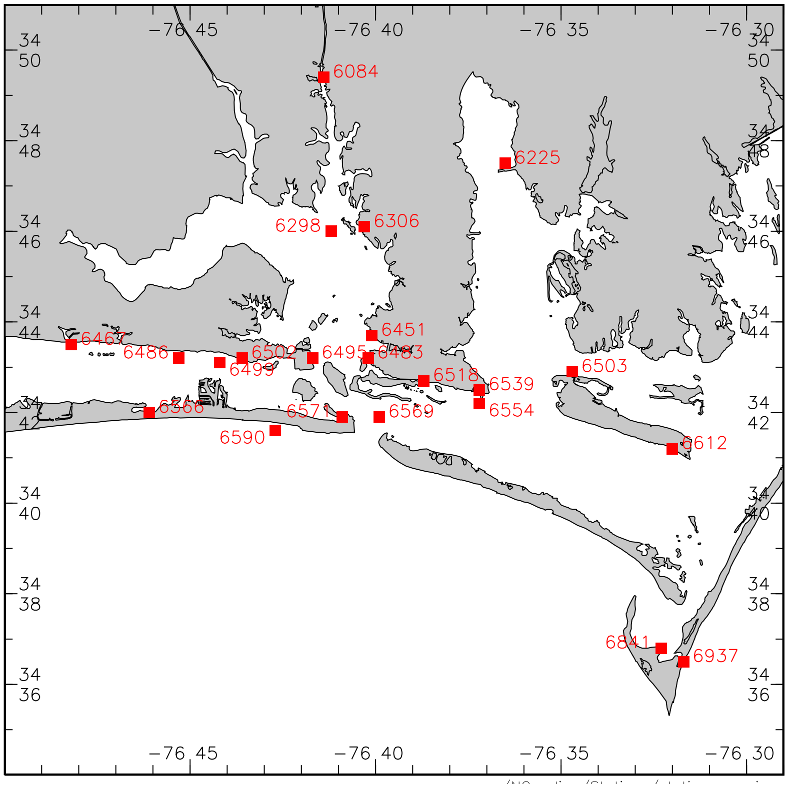


Figure 6. Locations of water level stations (red squares) around Beaufort Inlet. Only the last four digits of the station numbers are shown; the first three digits are 865. See Appendix B for further information.

2.3. Digitized Coastline

Digital files containing the MHW and the MLLW lines were obtained from the Coast Survey's Extracted Vector Shoreline (EVS) project. The digital files contain points defining the coastline that were extracted from digital images of NOS' nautical charts, and were used for identifying the land-water boundary. A sample is shown in Figure 7.

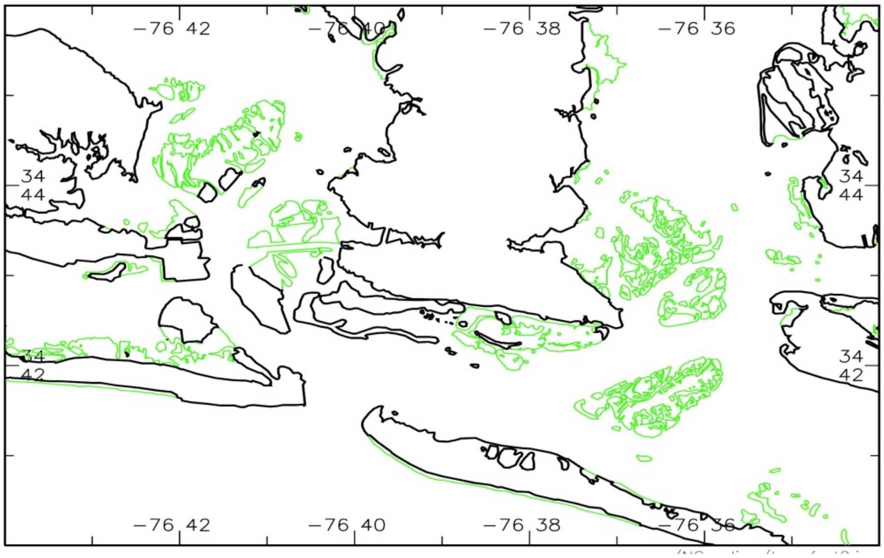


Figure 7. Sample of extracted vector shoreline for MHW (black) and MLLW (green).

3. TIDAL AND HYDRODYNAMIC MODELING

As part of the tidal model development, a high-resolution finite element hydrodynamic model was created for the study area, and historical bathymetry from NOS and other sources was used to populate the grid with depths. The model was run numerous times to simulate astronomical tides, and further revised and calibrated until it produced relatively accurate tidal datum information. Tidal datum fields have been produced, and bathymetry was re-referenced to MSL.

3.1. The Hydrodynamic Model

Hydrodynamic water level modeling was accomplished using ADCIRC, the ADvanced CIRCulation model for oceanic, coastal and estuarine waters. The model runs in two-dimensional (i.e., barotropic) mode on an unstructured grid composed of triangular elements; this type of grid is ideally suitable for representing complex coastlines to any desired resolution, and can be easily modified to add spatial resolution in any geographic area with little effort. The grid must then be populated by bathymetry to represent the region, and boundary forcing must be added to simulate tides and other types of water level variability.

The ADCIRC model was developed by Rick Luettich at the University of North Carolina at Chapel Hill, Institute of Marine Sciences, and Joannes Westerink at the University of Notre Dame, Department of Civil Engineering and Geologic Sciences (Luettich, et al., 1992; Luettich and Westerink, 2004). This model is a system of computer programs that solves time-dependent, free surface circulation and transport problems in two and three dimensions. The ADCIRC Two-Dimensional Depth Integrated (2DDI) version, used for the North Carolina area studies, is the barotropic version of the model. ADCIRC utilizes the finite element method in space, taking advantage of highly flexible, irregularly spaced grids. Numerous studies have shown this model to be robust throughout the Eastern North Atlantic and Gulf of Mexico regions (Luettich and Westerink, 1995; Mukai, et al., 2000) and the West Coast (Spargo, 2003).

ADCIRC has a wetting and drying algorithm that works as follows. When the water level at any node drops to less that a user-specified depth (here 10 cm), that node becomes temporarily inactive. When surrounding water levels are sufficiently high to push water into the nodal area to make the water level rise above the 10 cm value, the node is reactivated. During the model runs, some nodes become ‘ponded’ when their depths are at or near 10 cm, because the surrounding nodes were inactive and there was not a sufficient gradient for the water to flow out of them.

The modeling of bottom friction and other parameters are discussed in detail in Appendix C.

3.2. Model Grid Development

The modeling strategy was to create a regional grid (Figure 8) by taking a portion of a larger scale grid, in this case, the western North Atlantic grid (Luettich and Westerink, 1995). Then, grid elements covering Pamlico and Albemarle Sounds and Beaufort Inlet developed by Luettich et al. (1999) were incorporated. Finally, additional elements were added by NOS to parts of the region within the DEM area where more resolution was needed, including the Intracoastal Waterway. A portion of the high-resolution part of the grid around Beaufort is shown in Figure 9. The grid contains 36,409 nodes, and the smallest elements in that area have a node spacing on the order of 13 m. At the request of the U.S. Army Corps of Engineers in Wilmington, North Carolina, the Intracoastal Waterway was explicitly included in the grid wherever possible.

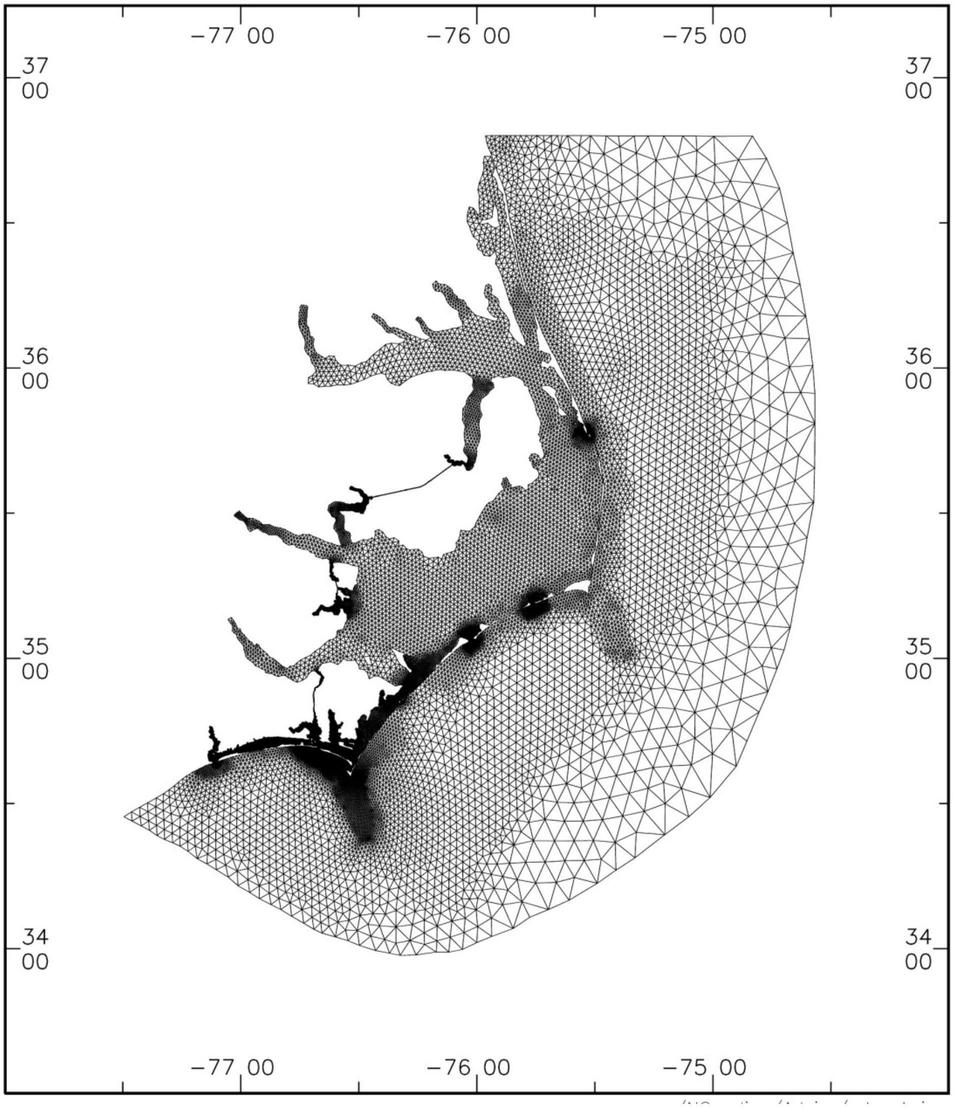


Figure 8. Finite element grid for the regional model.

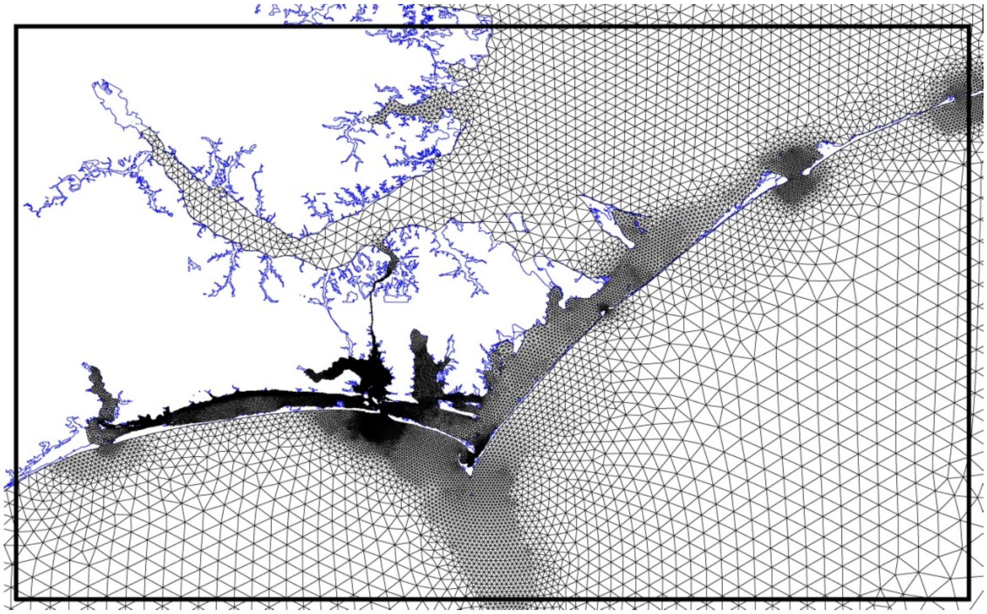


Figure 9. Model finite element grid with DEM boundary (dark black box) and MHW coastline (blue line).

3.3. Population of the Model Grid with Bathymetric Data

The bathymetric data used to populate the model grid came from five different sources. These data are: (1) Post-Hurricane Isabel (September 18, 2003) U.S. Army Corps of Engineers (USACE) sounding data, (2) Pre-Hurricane Isabel USACE sounding data, (3) NOS historical sounding data, (4) CRM depth data, and (5) manually digitized values appearing on NOAA paper nautical charts. The Post-Hurricane Isabel sounding data, henceforth, POST-ISA, is referenced to MLW. The Pre-Hurricane Isabel sounding data, henceforth referred to as PRE-ISA, is referenced to MLLW. The NOS sounding data is referenced to one of several datums; each sounding has associated metadata that lists whether the point is referenced to MLW, MLLW, or a low water datum (LWD). The CRM data is referenced to MLW. The NOAA paper nautical chart data, digitized 15 years ago at the University of North Carolina, are referenced to MLW; these data points were incorporated into the finite element grid.

The grid was filled with depth data from these sources, and at some locations, data were available from several sources. Priority was given first to the POST-ISA data, then to PRE-ISA data, then to NOS soundings, then to CRM data, and finally to the digitized NOAA chart data. At the start of the fill, all POST-ISA points within the DEM region were used. The nodal depth value was taken as the average depth of all points that fell within the triangular elements adjacent to the node. For filling from the remaining sources, a tolerance distance of 0.0004° (44.4 m) was set. Then, the data with the next highest priority (the PRE-ISA data) were examined and any points that fell within the tolerance distance from any previously–filled data point were eliminated; points that were beyond the tolerance distance were retained and used to fill nodal values. The process was repeated for the remaining data sources. Additionally, CRM data with 0.0 or

-99999.0 depth values were eliminated, since these two values were only used in the CRM as “placeholders”.

The depths were adjusted to MSL by an iterative process. Initially, a MSL-to-LWD difference of 15 cm in the portions of Pamlico Sound where LWD was used, and estimated MSL-to-MLW and MSL-to-MLLW differences of 50 cm were applied elsewhere to the bathymetric depths. After the first and each subsequent 30-day tide simulation, the computed MSL-to-MLW, MSL-to-MLLW, and MSL-to-LWD differences were averaged for each triangular element and applied to the bathymetric depths from the original sources within that element. Depth adjustments at most locations converged to within 1 cm of their final values after three to five simulations. Note that the modeled MSL, determined by averaging hourly values at each node, differs from the model’s zero elevation in Pamlico Sound by approximately 5 cm.

Inter-tidal areas often did not have depth values, since neither NOS nor USGS measures depths there and Lidar data is usually not collected when the water level is at or below MLLW. Therefore, depths in the inter-tidal areas, which in the Sounds are usually vegetated, were assumed to be everywhere 10 cm below MSL.

3.4. Ocean Boundary Forcing

The outer coastal boundary of the regional grid (Figure 8) is forced with periodic water level variations to astronomical tides. The water level, relative to the model’s zero elevation, at the outer boundary is

$$H = h_o + \sum f_n A_n \cos(\omega_n t + [Vo + u]_n - \kappa_n)$$

where H is the total water level (m), h_o represents a constant offset (here taken to be zero), and the remaining term represents the astronomical tide. A_n is the constituent amplitude (m), ω_n is the constituent speed (degrees/hr), t is the time relative to some reference time, $[Vo + u]_n$ is the equilibrium angle (degrees), and κ_n is the phase relative to Greenwich time (degrees). There is a unique set of harmonic constants at each grid node along the coastal boundary; a sample is shown in Table 2.

For the simulation of water levels that are to be used to generate tidal datums, as opposed to simulating the tide for a specific date, the day and year of the simulation is not important. Therefore, for the following model runs the lunar node factor, f_n, was set to 1.0 and the equilibrium angle $[Vo + u]_n$ was set to 0.0.

Table 2. Sample of tidal constituents and their harmonic constants at a boundary node in the regional grid.

Constituent	Amplitude (m) A_n	Phase (deg) κ_n
K_1	0.091433	177.978
O_1	0.068979	191.636
Q_1	0.012528	177.459
M_2	0.408000	351.313
S_2	0.074515	10.154
N_2	0.096141	336.247
K_2	0.017007	16.020

3.5. Results of Model Water Level Simulations

The model was run to simulate astronomical tides by forcing with the elevation equation discussed in the previous section, and the time series of water levels were saved at 6-min intervals at all grid nodes. The water level amplitudes were linearly increased from zero to their full values over the first 5 days, and the total simulation period was 37 days.

The time series were analyzed to determine tidal datums. The datums at each node in the grid were found by extracting the high and low waters from the last 30 days of the 37-day simulation, categorizing them as highs, higher highs, lows, or lower lows, then averaging. Figure 10 shows a sample time series with the tidal extrema denoted.

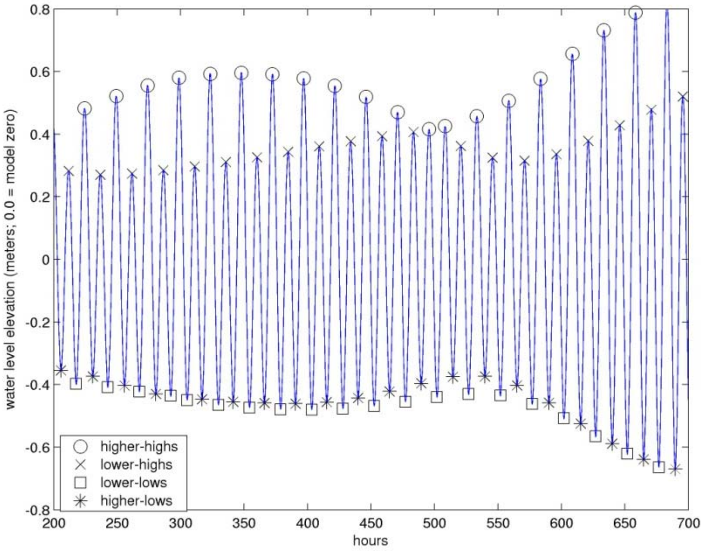


Figure 10. Time series of water levels over 21 days with extrema noted.

For nodes that have gone dry (Figure 11) or have ‘ponded’ (i.e., have a non-zero depth but are within an area encircled by dry nodes), low water in the time series does not accurately reflect a tidal datum. Therefore, for these points, the tidal datums from the closest non-drying nodes were used.

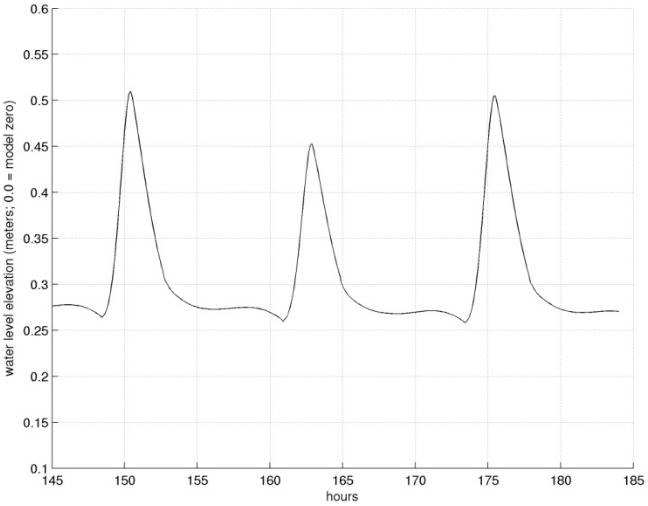
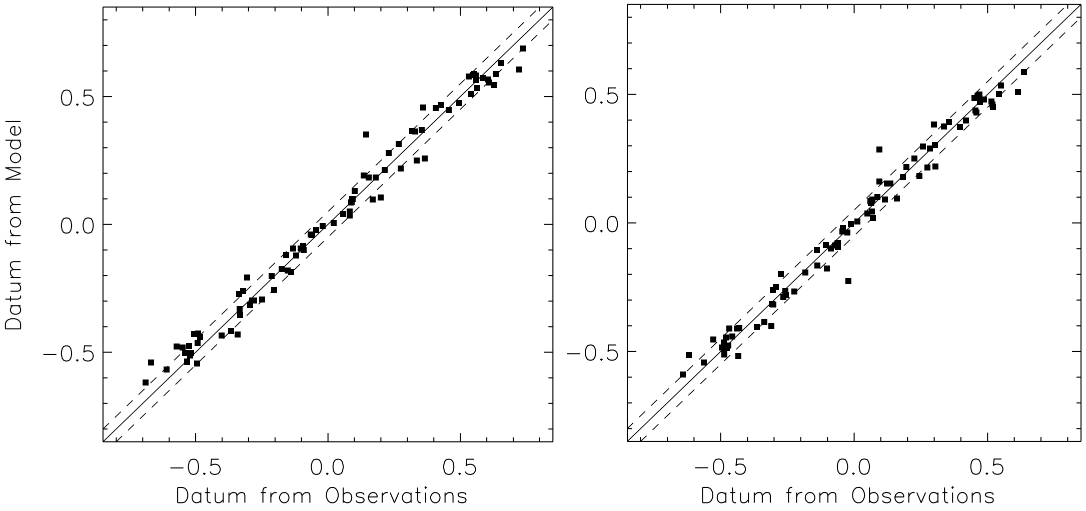


Figure 11. Time series of water levels for 40 hours at a grid node with a depth of 0.22 m above model zero elevation. When total water depth falls to 10 cm or less, the cell becomes inactive.

After each run, the computed datum fields were used to adjust the water depths from the original sounding datum (MLLW, MLW, or LWD) to the model zero elevation. After three runs, the datum adjustments converged to repeating values.

Then the computed datums were compared to those derived from observations. Several sets of runs were completed to make the tides more realistic; these involved alterations in the grid to better represent geographic features or modifications in the method used in assigning bathymetric values to grid nodes. For the final run, the root mean square (RMS) difference between the modeled and observed MHHW, MHW, MLW, and MLLW datum values, relative to MSL, was 5.2 cm (Appendix D). A plot of the MHHW and MLLW comparisons is shown in Figure 12. The modeled fields for MSL and diurnal range are shown in Figures 13 and 14, respectively.

River flows for the Pamlico, Neuse, and Tar Rivers were added to the water level model to assess their influence on mean levels. The differences between the tide-only and the tide-plus-rivers computed water levels were negligible, except in the upper reaches on the rivers, where differences on the order of less than 1 cm were found.



(a) (b)

Figure 12. Comparison of (a) the MHHW and MLLW datums (m) and (b) MHW and MLW datums obtained from observations (horizontal axis) and from the hydrodynamic model (vertical axis). RMS error for all datums is 5.2 cm.

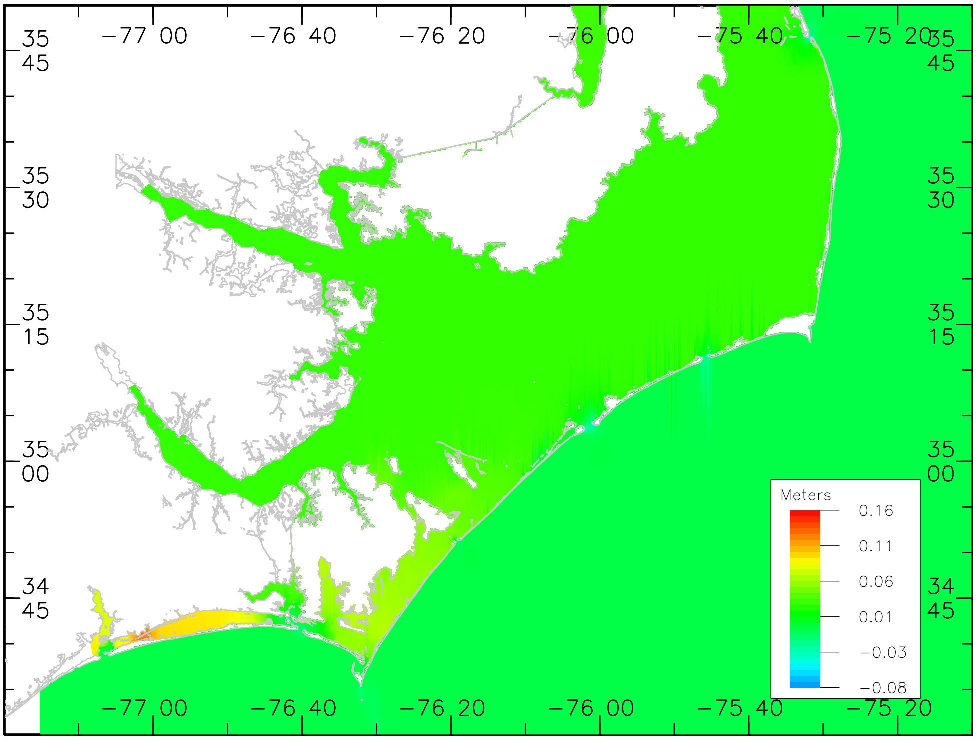


Figure 13. Mean sea level, as computed by the hydrodynamic model. MSL is relative to the model's zero elevation.

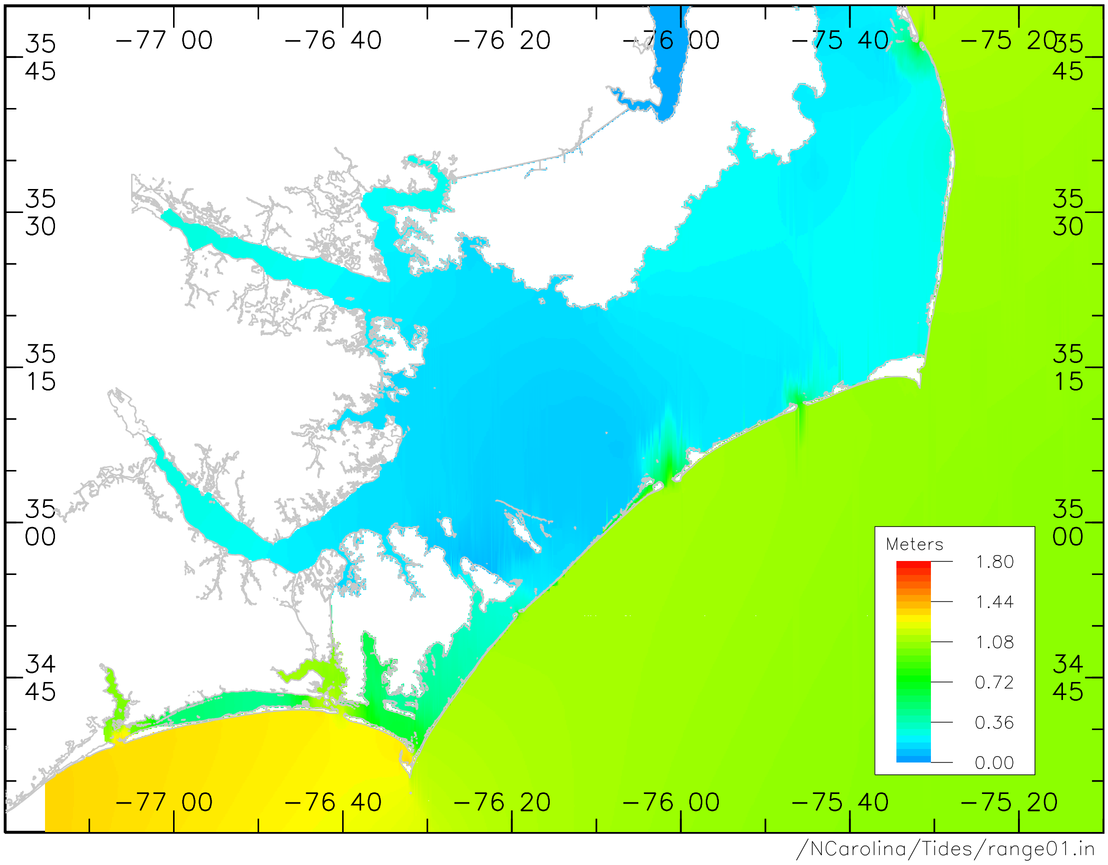


Figure 14. Diurnal tide range (the difference between MHHW and MLLW) as computed by the hydrodynamic model.

3.6. Corrections to the Modeled Tidal Datum Fields

The tidal datum fields as computed by the hydrodynamic model match closely, but not exactly, to the datums at the stations based on observed water levels. The RMS error for the four tidal datum fields (MHHW, MHW, MLW, and MLLW) was 5.2 cm. Plots of the errors for MHHW and MLLW, and for MHW and MLW, are shown in Figure 12. Therefore, the four datum fields were ‘corrected’ by subtracting the interpolated error field. The interpolated error field was generated by taking the error at each individual water level station, and creating an interpolated field using the Tidal Constituent And Residual Interpolation (TCARI) model (Hess, 2002; Hess, 2003). A sample error field is shown in Figure 15. The corrected fields closely match the observed datums at the water level stations.

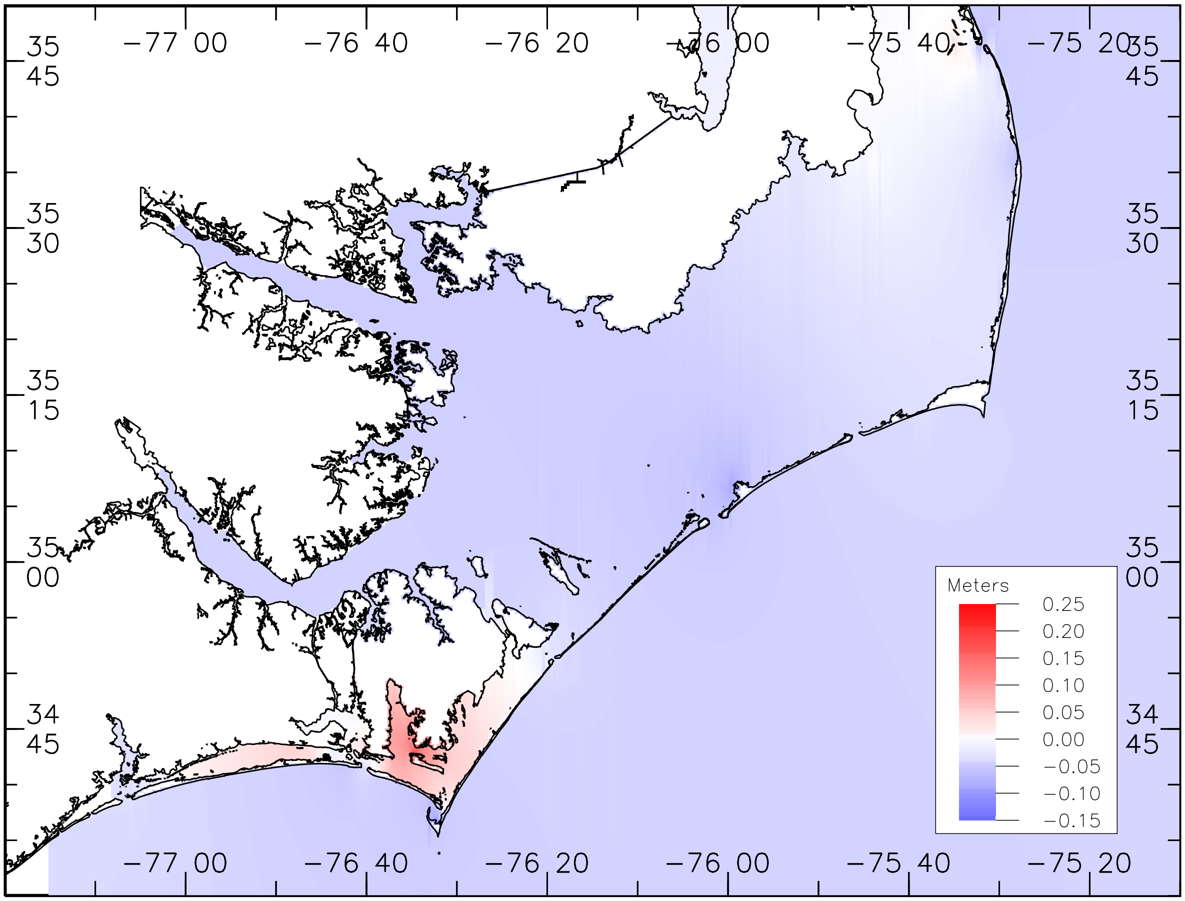


Figure 15. Error (modeled value minus observed value) in the MHHW datum field as interpolated by the TCARI method.

4. THE TIDAL MARINE GRIDS

The tidal marine grid for a specific region consists of points with uniform spacing in the longitudinal and latitudinal directions. Points designated as water are populated by tidal datums, while other points are designated as land and given the default, or null, value of −88.8888. The tidal datums used to populate the marine grid are produced by the hydrodynamic model and corrected by spatial interpolation. The datum values are then spatially interpolated to the points in the marine grid. The sea surface topography is interpolated to another marine grid and is described in Section 5.

It is important to note that, in the VDatum software, the final datum conversion values at any geographic point within the marine grid are determined by a distance-weighted average of the datum values at the surrounding four points. Therefore, if even one of the four surrounding points is non-null, a datum value will be returned. Hence, the marine grid's point spacing puts a limit on the size of geographic features that can be recognized.

However, the region in North Carolina consisting of Pamlico and Albemarle Sounds is separated from the ocean by a series of narrow barrier islands which have significantly different tidal datums on each side. Some islands are so narrow that the marine grid spacing would have to be in the order of 10s of meters to represent them. Therefore, the entire VDatum region was divided into two separate areas, each with a distinct marine grid. Having two marine grids eliminates the possibility that VDatum points representing the ocean and the sound might be adjacent in the same grid. The border between the regions was defined by a set of points approximating the centerline of the barrier islands. The grid covering the sounds is called the Pamlico Sound Grid and the grids representing the area oceanward of the barrier islands are called the Coastal North Grid and the Coastal Central Grid.

4.1. Grid Point Location

The location of the points in each marine grid is completely defined by the geographic coordinates of the origin (i.e., the most southwesterly point), the latitude and longitude spacing between points, and the maximum number of points in the eastward and northward directions. The grid origin is at $latitude_0$ and $longitude_0$, and extends to $latitude_1$ and $longitude_1$. The longitudinal spacing between points is *delx*, and the latitudinal spacing is *dely*. The VDatum grid consists of points as defined by

$$longitude_i = longitude_0 + (i - 1)delx$$

$$latitude_j = latitude_0 + (j - 1)dely$$

where the index *i* denotes longitude and index *j* denotes latitude. The range of *i* is 1 to *imax* and the range of *j* is 1 to *jmax*, where

$$imax = 1 + (longitude_1 - longitude_0)/delx$$

$$jmax = 1 + (latitude_1 - latitude_0)/dely$$

For the North Carolina coastal area in the present study, three separate grids were needed to (a) properly represent the influence of the narrow barrier islands and (b) to keep file sizes small (under one million points in the grid). The values for the grids, called the Pamlico Sound, Coastal Central, and Coastal North, are given in Table 3.

Table 3. Parameters for the North Carolina tidal marine grids. Latitude is positive northward, and longitude is positive eastward.

Region	$latitude_0$ (degrees)	$longitude_0$ (degrees)	*dely* (degrees)	*delx* (degrees)	*Jmax*	*Imax*
Pamlico Sound Grid	34.594	282.745 (-77.255)	0.002	0.0025	639	723
Coastal Central Grid	34.026	282.745 (-77.260)	0.002	0.0025	640	965
Coastal North Grid	35.296	284.050 (-75.950)	0.002	0.0025	732	443

4.2. Population of the Marine Grids

There are two main steps in creating and populating the marine grids. In the first step, all points in the marine grid are given a latitude and longitude (using values given in Table 3), and then set to be either land or water. Points are set to water if they are located within a half a grid spacing of a coastline segment that defines either the mainland or an island; otherwise they are land (see Hess and White, 2004, for a detailed discussion). This step is accomplished by the Fortran program vgridder5.f.

The next step consists of filling the water values with the tidal datum values. For the North Carolina region, the datum values have been generated by the hydrodynamic model and corrected to match the station data (Section 3). Recall that each cell in the hydrodynamic model's unstructured mesh is defined by the three nodes which form the vertices, and each node is the vertex of one or more elements. For each water point, the closest node in the unstructured grid is found. If the water point lies inside a hydrodynamic model grid element, the value for the marine grid is linearly interpolated from the values at the nodes. If the water point lies outside all hydrodynamic model cells, it is filled by one of two methods. In the first method, if the closest node is less than a user-specified distance (the variable *radius,* here 0.002 deg) from the water point, the datum value is defined as the distance-weighted (by inverse square) mean of the values at the vertices of all elements which have the closest node in common. In the second method, if the closest node is not less than the user-specified distance, the water point is filled by an iterative procedure. At each iteration, all water points (in this category) are set to the mean of the surrounding water point values. The iterative procedure is complete when the maximum value over the entire marine grid of the difference between the new value at a point and its preceding value (for points in this category) falls below a given level (5 x 10^{-5} m). Note that a few marine water points cannot be filled by any of these methods because they are too distant from the hydrodynamic model grid or are physically separated from the filled water points by intervening land; these points remain unfilled. This second step in the process is accomplished by the Fortran program `vpop11.f`.

4.3. Illustration of Problems at Barrier Islands

To illustrate the problem of filling a marine grid that crosses a barrier island, consider the filling of a single marine grid that covers both the sound side and the ocean side of a barrier island. In Figure 16, three values of the difference between MHHW (relative to MSL) in two rows of the marine grid have been filled by the methods described above. In the upper row the values are 13.7, 30.0, and 58.0 cm, and in the lower they are 14.1, 14.4, and 57.9 cm. The first and last values in each row were filled by interpolation from the values at the hydrodynamic model's nodes, since they lie inside a model cell. These values adequately represent the hydrodynamic model values, which reflect the large tide range to the east of the barrier island and the small tide range to the west. Note that the middle value in the upper row, 30.0 cm, was determined by the mean of the surrounding values. However, it is not realistic because it averages values from both sides of the barrier island.

Consider how VDatum would interpolate to find the values at Points A and B in Figure 16. At A, the interpolated datum (using the values at the four surrounding water points) is approximately 22 cm, which is too large for the small tide range on the western side (the correct value should be 14 cm). At B, the value is approximately 42 cm, which is too small for the eastern side (the correct value should be 57 cm). A simple way to correct this problem is to use a dividing line to restrict `vpop11.f`'s selection of nodes in the hydrodynamic model.

Suppose that the centerline of the barrier island in Figure 16 was a dividing line. When the selection of nodes is carried out, the marine grid points to the left of the line will use only hydrodynamic nodes to the left of that line, and similarly for the points and nodes to the right of the line. Then the marine grid values selected will be as shown in Figure 17. The values are now much more realistic. Note that the middle value in the upper row, which without the dividing line was 30.0 cm, is now 13.3 cm. Again, consider Points A and B in Figure 17. At A, the interpolated datum (using the values at the four surrounding water points) is approximately 14 cm, and at B, the value is approximately 58 cm; these are much more realistic values. The concepts in the dividing line are now extended to the bounding polygons.

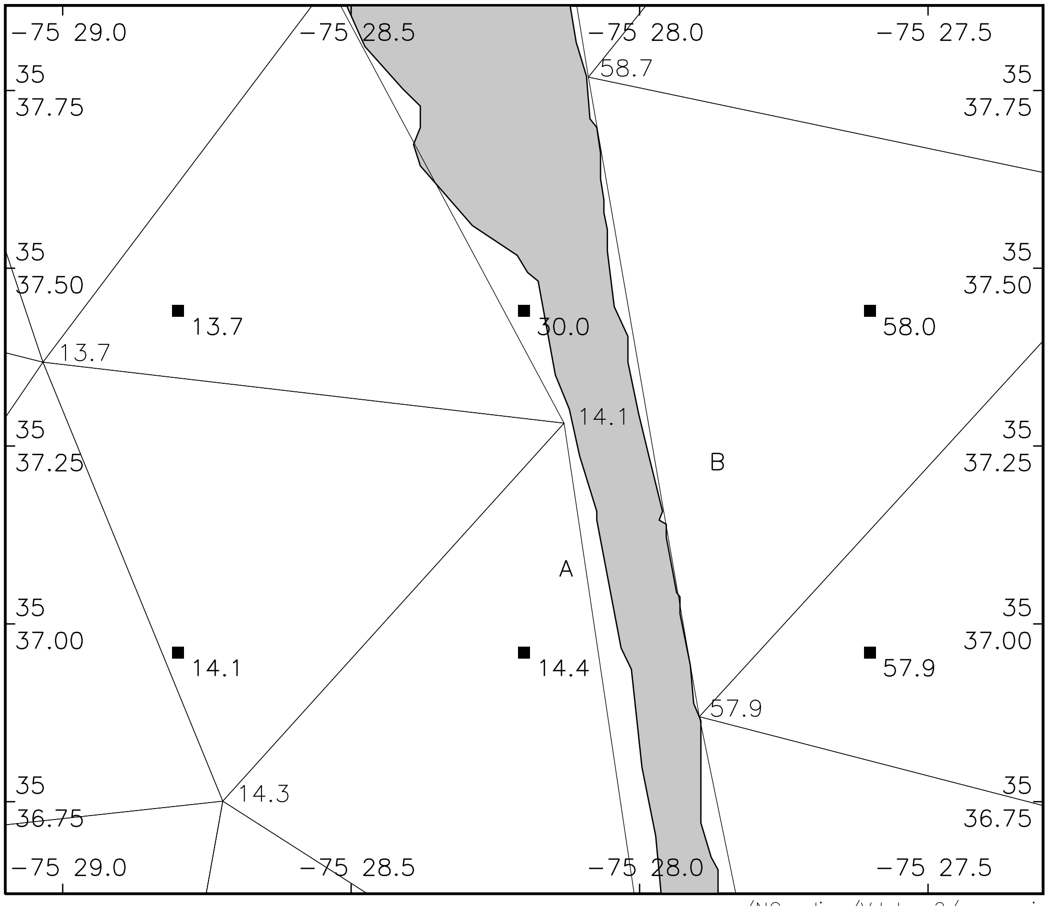


Figure 16. Sample region with marine grid points (solid squares) and their numerical datum values (cm), hydrodynamic model grids (large triangles) with datum values at their vertices (cm), narrow barrier island (gray area), and test points A and B.

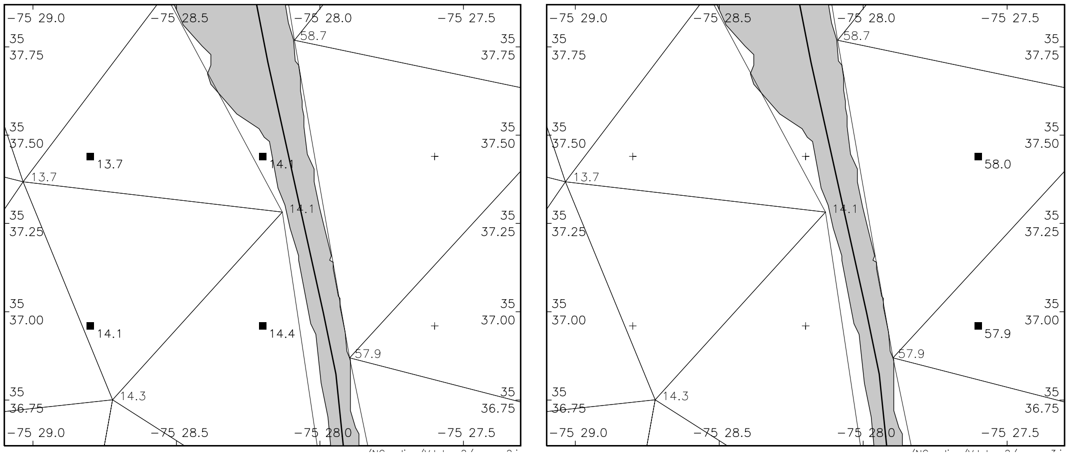


Figure 17. Sample region with marine grid points (solid squares) and their datum values (cm), hydrodynamic model grids (large triangles) with their MHHW to MSL datum values (cm) at the vertices, a narrow barrier island (curved lines), and the bounding polygon (solid line inside barrier island).

4.4. The Bounding Polygons

As mentioned above, the presence of barrier islands can lead to the marine grid being filled with erroneous values. This problem can be rectified by introducing one or more bounding polygons that limit the selection of hydrodynamic model nodes when filling the marine grid. For the barrier islands of North Carolina, we generated three polygons. First, we created a line that approximated the centerline of the barrier islands. To create the offshore, or coastal ocean, polygons, the upper end of the centerline line was extended eastward to a distance somewhat beyond 25 nmi (the outer limit of coverage of national VDatum). To this were added five straight line segments that approximately followed the 25 nmi line and stayed within the hydrodynamic model grid (Figure 18). The final line segment joined the westernmost point of the centerline. This polygon was the divided into two parts, the Coastal Northern and the Coastal Central polygons, separated at 35.30°.

To create the Pamlico Sound polygon, a point on the centerline just north of Oregon Inlet was selected. The latitude of the point, 35° 35.78′, ensures that Albemarle Sound is excluded from the polygon. This exclusion was necessary because the astronomical tides in this area are so small that wind tides may be dominant, in which case a tidally-defined shoreline may not be meaningful. Next, a line segment was extended westward to the longitude of the westernmost point of the centerline, and another line segment was extended southward to meet the centerline. From this initial polygon three areas were excluded. The areas were the Alligator River on the north border of the polygon, since it is part of Albemarle Sound; the southwest corner west of White Oak River, since that area is not in the hydrodynamic model grid; and a section of the Harlowe Canal which also is not in the hydrodynamic model grid. This polygon is shown in Figure 18. Since the sstronomical tides in Albemarle and Currituck Sound are so small and there is so little tidal data for these areas, no marine grid was developed to cover them.

The bounding polygons were then used to create and populate the final marine grids. As before, during the gridding process (using program vgridder5.f), points within land polygons were set to land. Also, points outside the bounding polygon were also set to land. During the population process (using program vpop11.f), water points were filled with values from the hydrodynamic model. However, nodes in the hydrodynamic model had to be within the bounding polygon to be used. An exception to this restriction is that if any of the nodes defining the elements vertices fell within the bounding polygon, the remaining vertices could be used. A plot of the marine grid and values around Oregon Inlet are shown in Figure 19.

To test the continuity of datums, values of MHHW were extracted at points along a track that crossed the bounding polygon. The 10 points in the track are shown in Figure 19. The extracted tidal datums were plotted in Figure 20, along with values extracted from a coastal marine grid with twice the point spacing. The smaller spacing eliminates the discontinuity in datum values at the boundary.

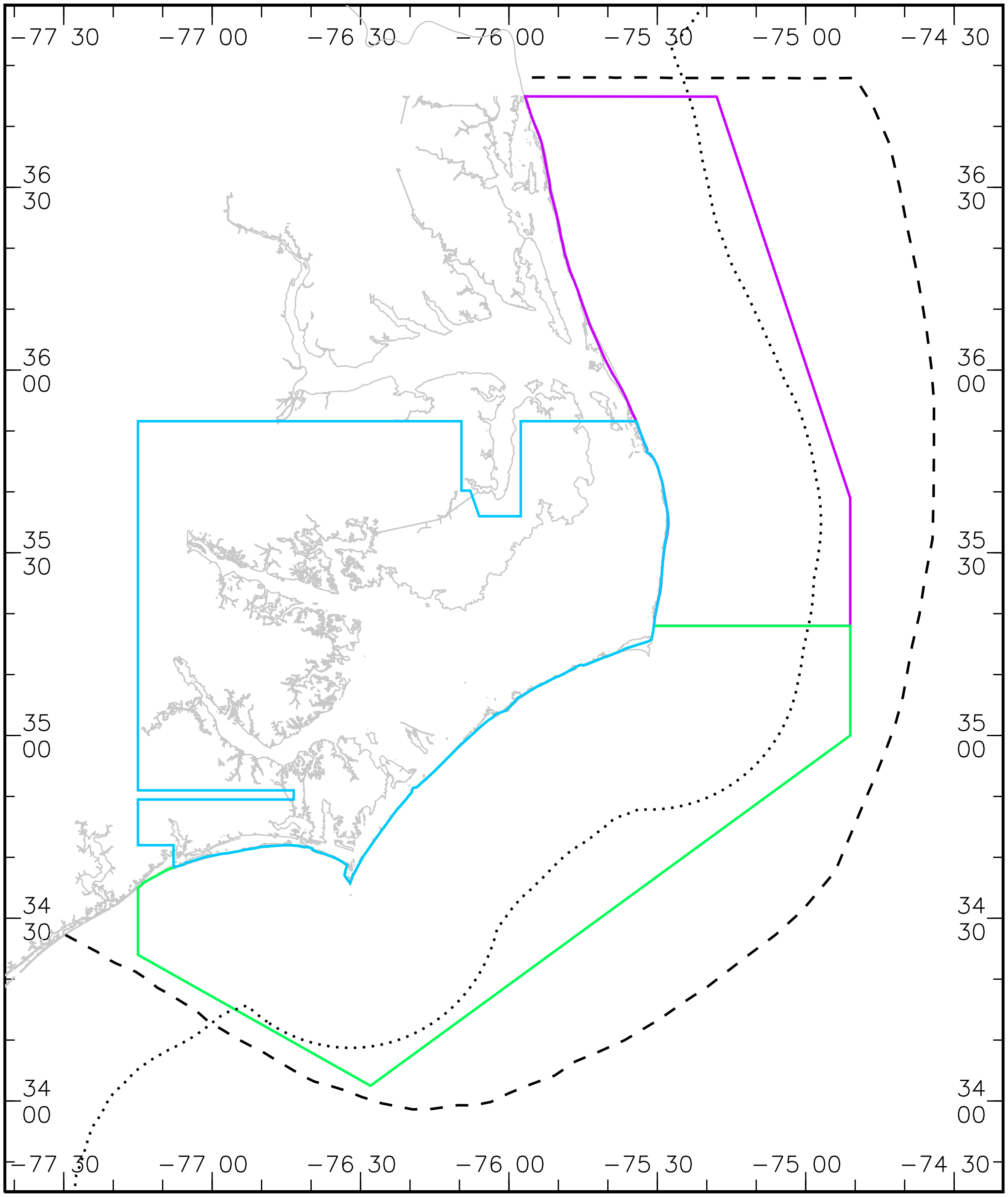


Figure 18. The bounding polygons for the Coastal North area (purple line), Coastal Central area (green line), and Pamlico Sound area (blue line). Also shown are shoreline (gray) line, the hydrodynamic model's offshore boundary (dashed black line) and the 25 nmi limit (dotted black line).

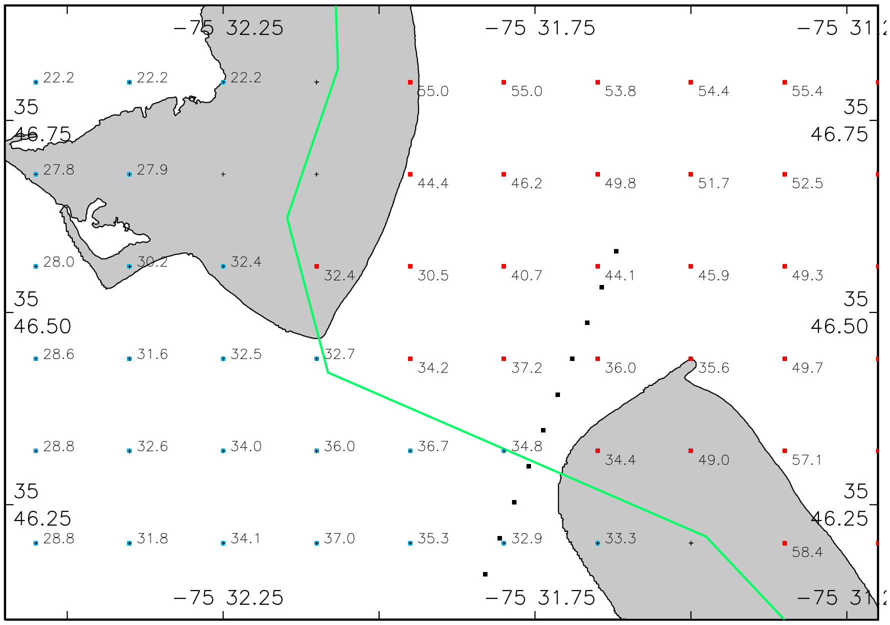


Figure 19. Area around Oregon Inlet showing the locations of the tidal marine grid points for the Pamlico Sound grid (blue squares) and the Coastal North grid (purple squares). The plus signs represent null points for each grid. The value (cm) of the tidal datum (here the difference between MHHW and MSL) is shown next to the non-null points. Points along a track crossing the bounding polygon are shown as black squares.

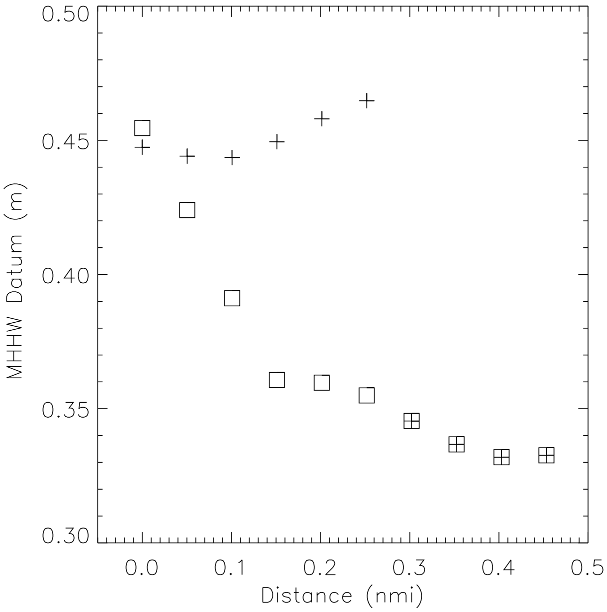


Figure 20. Datum values along a 10-point track from northeast to southwest (see Figure 19) from (a) both grids having equal spacing of approximately 0.24 nmi (open squares), and (b) a Pamlico grid with spacing of 0.24 nmi and a coastal grid with spacing of 0.48 nmi (plus signs). Notice the discontinuity of 0.11 m at an along-track distance of 0.25 nmi.

4.5. Assessment of Errors in the Marine Grid

Probable errors in the VDatum tidal transformation fields are extremely difficult to assess in a direct way. However, they may be assessed indirectly by three methods: (1) analyzing the errors in the tidal hydrodynamic model results, (2) analyzing the interpolated fields of errors, and (3) comparing values in the marine grids with known datums at the tide stations. The most conservative method is the first, and it yields a probable RMS error of about 5 cm. In all likelihood, since an error correction field has been added to the hydrodynamic model output, the RMS error is less than 5 cm.

For the first method, as was discussed in Section 3.5, the mean RMS error from the hydrodynamic model at the 44 stations used in the comparison (Appendix B) was 5.2 cm. The RMS errors for each individual datum were 5.8 cm for MHHW, 5.0 cm for MHW, 5.1 cm for MLW, and 4.7 cm for MLLW. Maximum absolute errors in MHHW and MHW (20.7 cm and 19.0 cm, respectively) occurred at the Harkers Island Bridge tide station (865-6503), although the errors in the MLW and MLLW datums for that location were under 5.0 cm. Maximum absolute error in the MLW datum, 20.4 cm, occurred at Spooners Creek tide station (865-6467), although the errors in the other datums at that location were under 5.5 cm. The maximum absolute error in the MLLW datum, 12.9 cm, occurred at Cape Lookout Inside tide station (865-6841). The absolute errors in the other datums there were all between 10 and 12 cm. Errors in the hydrodynamic model's datum values probably result from using coastline, bathymetry, and tidal observations from several different time periods.

The second method is the assessment of the fields of interpolated error. Recall that hydrodynamic model errors were compensated for by subtracting from the modeled field of values an interpolated error field that matches the error value at the tide stations. This compensation process eliminates the error at the tide stations, but the effect on errors elsewhere is not precisely known. However, Figure 15 shows that the error field for MHHW is spatially consistent within the outer coastal area, Pamlico Sound, and the Beaufort Inlet area. Negative values in Pamlico Sound indicate that the hydrodynamic model under-predicts the tidal datum there, while positive values around Beaufort Inlet indicate that the model over-predicts the datum there. Therefore, even accounting for the fact that the interpolated error field may be somewhat unrealistic around some of the input locations, the overall effect is probably to reduce the errors in the datum fields. An examination of the values in the fields shows that the RMS value of the interpolated error field is 3.9 cm for MHHW, 3.1 cm for MHW, 4.2 cm for MLW, and 3.4 cm for MLLW, for an overall value of 3.7 cm.

As a final assessment of error, the datum values extracted from the tidal marine grid at the locations of the tide stations were compared (using program `cp3.f`) to the tidal datums obtained from observations. This assesses errors that may occur when transferring the corrected tidal model results to the uniformly-spaced marine grid. Errors may arise because the model values are represented at the nodes in an unstructured mesh with triangular elements of varying sizes. Transfer of values is accomplished by spatial interpolation or extrapolation, or by the iterative solution of Laplace's Equation, depending on the closeness of the marine grid point to points in the unstructured mesh. The results (Appendix E) show that the mean RMS error for the 40 tide stations within the three marine grids and all four datums was 1.1 cm, with the maximum error of 3.7 cm at Sea Level, Core Sound (865-5875).

As a consistency check, we can examine the maximum point-to-point differences in values in the marine grid using program `cp3.f`. Differences are generally small except in regions near the inlets, where differences in adjacent point values can be as much as 15 cm. These differences are reasonable, given the rapid spatial changes in tidal water levels in these regions.

5. SEA SURFACE TOPOGRAPHY

VDatum requires a gridded Topography of the Sea Surface (TSS), which is defined here as the elevation of the North American Vertical Datum of 1988 (NAVD 88) relative to local mean sea level (LMSL). The TSS links the tidal datums with NAVD 88 and thus to land-based elevation reference systems. Values at the tide stations that were used to create the gridded field are shown in Table 4. Except for a single station, these values have been updated to the latest tidal datum epoch. The general picture shows that NAVD 88 is about 13 cm above MSL in the offshore area (e.g., Duck Pier), but only 1 or 2 cm above MSL inside the sounds (e.g., Rodanthe). Thus MSL in Pamlico Sound may be about 12 cm higher than MSL outside the barrier islands, probably due to water density differences and non-linear effects.

Table 4. Observed values of NAVD 88 relative to LMSL. The data are based on the most recent National Tidal Datum Epoch (1983-2001) unless noted, and a positive value means that the NAVD 88 elevation lies above the LMSL surface.

N	Station Name	NOS Number	NAVD 88	Notes
1	Virginia Bch, Rudee Inlet	863-9208	0.206	
2	Duck Pier	865-1370	0.128	
3	Oyster Creek, Croatan Snd	865-2437	0.012	
4	Oregon Inlet Marina	865-2587	0.026	
5	Rodanthe	865-3215	0.009	
6	Cape Hatteras Pier	865-4400	0.135	
7	Ocracoke Is.	865-4792	0.027	Older Epoch
8	Cedar Island	865-5151	-0.003	
9	New River, Jacksonville	865-6394	0.020	
10	Beaufort (Duke Lab)	865-6483	0.112	
11	Morehead Cty Harbor	865-6502	0.118	
12	Harkers Is. Brdg.	865-6503	0.066	
13	Taylor Creek	865-6518	0.126	
14	Lenox Pt, N. River Chnl.	865-6539	0.085	
15	Atlantic Bch SSS Pier	865-6590	0.133	
16	Calico Jacks Marina	865-6612	0.094	
17	Wilmington Bch	865-8559	0.216	

An initial gridded TSS data set was generated as follows. First a uniform grid, which has the attributes shown in Table 5, was created. Then, with Surfer® software, a minimum curvature algorithm interpolated the values at the tide stations on to the uniform grid. In the interpolation, contours on the outer-coastal region were separated from those in the Pamlico Sound region by the use of break lines. The break lines were a series of line segments running along the middle of the barrier islands, and having gaps at the inlets. This line was constructed from the barrier island centerline described in Section 4.3. Because of the problem with interpolating across the barrier islands and the limits on file size, the bounding polygons that were used in the tidal datum grid (Section 4.3) were used to create three new, smaller TSS grids. The attributes of the new TSS grids, two for the outer coastal area and one for the Sounds, are the same as those in Table 5. The three TSS fields are plotted in Figure 21.

Table 5. Parameters for the initial North Carolina sea surface topography (TSS) grid. Latitude is positive North, longitude is positive East.

Region	*latitude$_0$* (degrees)	*longitude$_0$* (degrees)	*dely* (degrees)	*delx* (degrees)	*Jmax*	*Imax*
Initial TTS Grid	34.000	282.700 (-77.300)	0.001	0.001	2801	2501

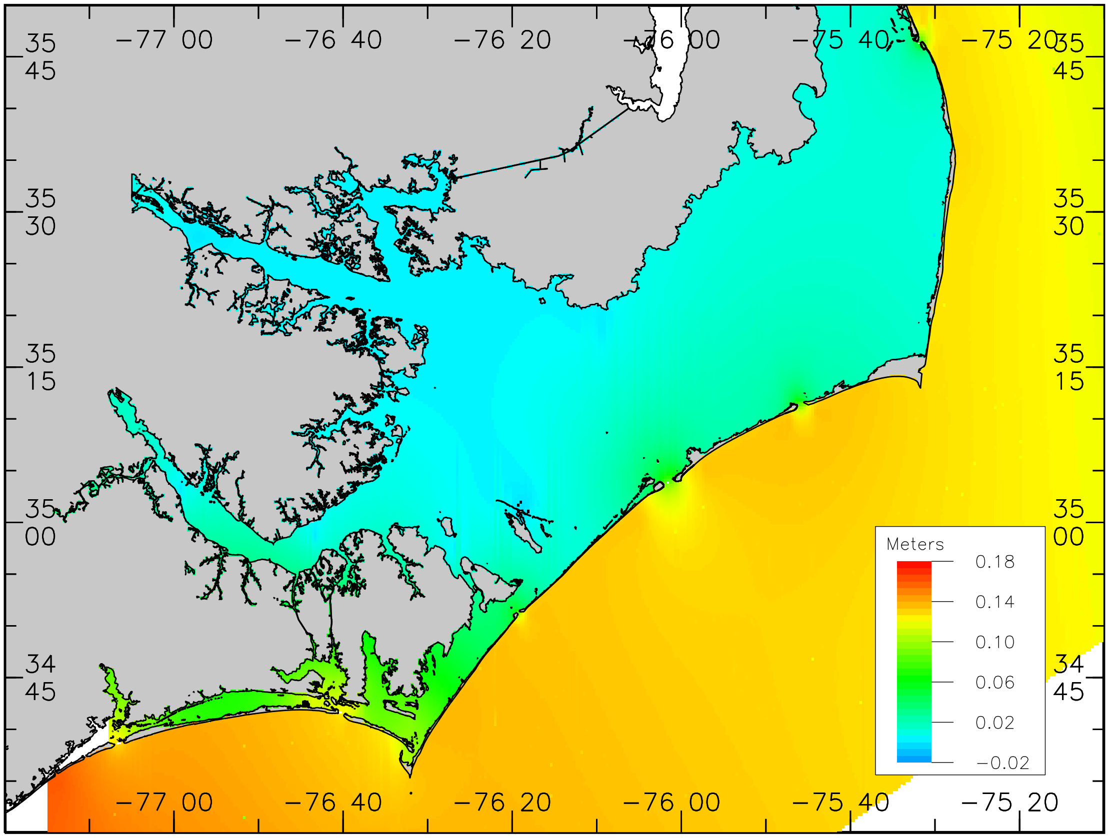


Figure 21. The computed sea surface topography (TSS). Elevations are in meters.

6. SUMMARY AND CONCLUSIONS

In support of the national VDatum program, tidal datums in North Carolina were generated from a hydrodynamic model (ADCIRC). The tidal model used NOS bathymetry, corrected by an iterative procedure to compute water depths relative to MSL, and to the model's zero elevation. Digital coastline was used to create the finite element grid. Tidal datums from the model were compared to NOS data at tide stations and corrected with the TCARI spatial interpolation. The datums were then transferred to three regular VDatum grids, two for the coastal ocean area (Coastal North and Coastal Central) and one covering Pamlico, Core, Back, and Bogue Sounds. The topography of the sea surface (TSS) was computed by spatially-interpolating the values at tide stations onto an initial, uniform grid. The final TSS grids were created for three areas, two for the coastal ocean and one for the sounds.

Tidal datum values for the most recent available epoch were obtained from CO-OPS. A potential problem came with the use of tidal data from different tidal datum epochs. To decide whether older data could be used, we compared datums at stations in the North Carolina region which had values for both the most recent (1983 to 2001) and the previous (1960 to 1978) epochs. Since the datums have changed only a few percent between these two periods, we chose to use the older values when newer ones were not available. However, we recognize that there will be a few stations where significant changes are possible.

The RMS error of the tidal model was computed to be 5.2 cm for 44 stations and four datums. The largest errors (10 to 20 cm for MHHW) occurred at the U.S. Coast Guard Station at Oregon inlet, Harkers Island, and inside Cape Lookout. The most probable reason for these errors is that the tidal data were collected several decades ago, while the hydrodynamic model uses coastline and bathymetry representing more recent conditions. Since the tidal data were collected, there have been numerous changes in channel position and depth (Oregon Inlet), intertidal areas (Harkers Island), and spit shoal areas (Cape Lookout). The hydrodynamic model's datums were corrected by subtracting an error field for each datum field. The error field was constructed by interpolating the error values at the tide stations throughout the grid

The division into three grids was necessitated by the existence of North Carolina's barrier islands, which are too narrow to be represented adequately in the marine grids, and on a limit on the number of points in a marine grid (under 1 million). The solution was the creation of the three bounding polygons that were used to separate the regions on each side of the narrow barrier islands. The polygons were based on the break lines used in making the TSS fields; the break lines were hand-extracted from the digitized coastline data set. To create the bounding polygons, the break line segments were joined at the inlets to create the centerline.

It has been decided that VDatum will cover navigable waters for which the NOAA nautical charts shows depth values, and will range from the heads of estuaries and bays out past the oceanic coastline to a distance on 25 nmi from that coastline. This requirement helped to determine the outer boundary of the coastal ocean polygon.

Because there are three separate grids, there may be a small mismatch in datum conversion values at locations where the two meet, usually at the inlets (see Figures 12 and 21). Recall that VDatum performs a distance-weighted averaging of the non-null values in the marine and TSS grids. At these marine grid cells, often there will be only two or three non-null values, a situation which makes the interpolation less accurate. In addition, at the inlets the spatial gradients in the tidal fields are large and changing rapidly.

Albemarle and Currituck Sounds have not been included in this application of VDatum because astronomical tides are small there. Typical tide ranges are 10 cm or less. Wind tides in these sounds, however, can be quite large. Therefore, VDatum for this sound will have to be postponed until a relationship between charted MHW and water level fluctuations is established.

Future work may include extending VDatum to more of the southern coast of North Carolina, and extending the grids to Albemarle and Currituck Sounds.

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APPENDIX A. BATHYMETRIC DATA SOURCES

Table A.1. Sources of bathymetric data that were evaluated and processed for the development of the water level model and VDatum marine grid.
Accuracies reported for point soundings datasets employ the rigorous standards specified by the International Hydrographic Office. Where possible, the original horizontal coordinates of sounding points were converted to North American Datum of 1983 (NAD83) with the Geodetic Reference System 1980 ellipsoid, which closely corresponds to World Geodetic System 1984. Vertical datums are expressed as tidal Mean Low Water (MLW), Mean Lower Low Water (MLLW) or local Low Water Datum (LWD). The gridded bathymetric datasets were generated by interpolating water depths without common re-referencing of the various original horizontal and vertical datums; i.e, bathymetric grids were derived from non-uniformly geo-referenced soundings.

Format	Source	Horizontal Resolution	Horizontal Accuracy	Vertical Resolution	Vertical Accuracy	Horizontal Datum	Vertical Datum
Point Soundings	National Ocean Service (NOS) Hydrographic Survey Database	various	2-15m nearshore 20-75m offshore	various	0.3m at 0-20m depth 0.5-1m at 20-100m depth 1% of depth > 100m	NAD83	by survey MLLW MLW LWD
Point Soundings	U. S. Army Corps of Engineers Regional channel surveys	various	3m nearshore 20-75m offshore	various	0.3m at 0-20m depth 0.5-1m at 20-100m depth	NAD83	MLW
Point Soundings	NOAA Nautical Charts - Digitized	various	2-15m nearshore 20-75m offshore	various	0.3m at 0-20m depth 0.5-1m at 20-100m depth 1% of depth > 100m	NAD83	by chart MLLW MLW LWD
Structured Grid	National Geophysical Data Center Coastal Relief Model (CRM)	~90m grid	undetermined	0.1-1m	undetermined	mixed* NAD83 other	mixed* MLLW MLW LWD
Structured Grid	NOS Special Projects Office (SPO) Estuarine Bathymetry[#]	~30m grid ~90m grid	~3m nearshore[#]	2m	~2% of depth[#]	mixed[#] NAD83 other	mixed[#] MLLW MLW LWD

* Although CRM grids are distributed in NAD83 and Mean Sea Level, point soundings were not uniformly georeferenced prior to gridding.

Evaluated but not used.

SPO's reported accuracies do not account for errors resulting from mixing the various georeference systems of soundings compiled to create bathymetric grids.

Although SPO grids are distributed in North American Datum 1927 and MLW, point soundings were not uniformly georeferenced prior to gridding.

APPENDIX B. WATER LEVEL STATION DATA

Tidal data were extracted from the CSDL database TideSheet101, which has the latest CO-OPS tidal datums as of April 2005.

Table B.1. **Tidal and orthometric datums (meters) and tidal datum epochs for the North Carolina stations used in this study. All datums are referenced to local mean sea level. -9.999 denotes a missing value. Where the tidal epoch is unknown, the values '0-0' are shown for the years. An '*' following the epoch indicates that only the NAVD88 values were used.**

No.	Station	Latitude	Longitude	MHHW	MHW	MLW	MLLW	NAVD88	Epoch	
1	8639208	36 49.90	-75 58.10	0.573	0.487	-0.514	-0.551	0.206	1983-2001	*
2	8651370	36 11.00	-75 44.80	0.585	0.487	-0.495	-0.539	0.128	1983-2001	
3	8651375	36 10.40	-75 45.50	0.021	0.012	-0.012	-0.021	-9.999	0- 0	
4	8652226	35 54.60	-75 35.50	0.609	0.518	-0.488	-0.549	-9.999	0- 0	
5	8652232	35 54.60	-75 40.20	0.082	0.066	-0.026	-0.060	-9.999	1960-1978	
6	8652247	35 54.20	-75 46.20	0.058	0.050	-0.044	-0.066	-9.999	1983-2001	
7	8652437	35 50.70	-75 39.30	0.090	0.064	-0.062	-0.093	-9.999	1983-2001	
8	8652547	35 48.70	-75 42.00	0.088	0.062	-0.061	-0.093	-9.999	1983-2001	
9	8652587	35 47.70	-75 32.90	0.180	0.135	-0.137	-0.176	0.026	1983-2001	
10	8652591	35 47.90	-75 35.00	0.092	0.061	-0.061	-0.091	-9.999	0- 0	
11	8652648	35 46.50	-75 34.90	0.135	0.095	-0.102	-0.140	-9.999	1983-2001	
12	8652657	35 46.40	-75 33.50	0.214	0.183	-0.183	-0.213	-9.999	0- 0	
13	8652659	35 46.40	-75 32.30	0.336	0.275	-0.305	-0.335	-9.999	0- 0	
14	8652678	35 46.10	-75 31.60	0.366	0.305	-0.294	-0.321	0.158	1983-2001	
15	8652715	35 45.40	-75 31.90	0.274	0.244	-0.275	-0.305	-9.999	0- 0	
16	8652737	35 44.90	-75 33.20	0.153	0.122	-9.999	-0.152	-9.999	0- 0	
17	8652905	35 41.90	-75 46.40	0.094	0.068	-0.072	-0.103	-9.999	1983-2001	
18	8653215	35 35.70	-75 28.30	0.168	0.115	-0.105	-0.131	0.009	1983-2001	
19	8654400	35 13.40	-75 38.10	0.564	0.455	-0.456	-0.492	0.135	1983-2001	
20	8654792	35 6.90	-75 59.30	0.199	0.161	-0.140	-0.159	0.030	1983-2001	
21	8655151	35 1.20	-76 18.60	0.082	0.071	-0.042	-0.045	-0.003	1983-2001	
22	8655875	34 52.50	-76 20.60	0.100	0.088	-0.087	-0.120	-9.999	1983-2001	
23	8656084	34 49.40	-76 41.40	0.407	0.336	-0.308	-0.334	-9.999	1960-1978	
24	8656225	34 47.50	-76 36.50	0.330	0.284	-0.256	-0.280	-9.999	1960-1978	
25	8656298	34 46.00	-76 41.20	0.606	0.515	-0.430	-0.491	-9.999	1960-1978	
26	8656306	34 46.10	-76 40.30	0.560	0.472	-0.467	-0.505	-9.999	1983-2001	
27	8656394	34 44.70	-77 26.20	0.091	0.080	-0.084	-0.112	0.020	1983-2001	*
28	8656451	34 43.70	-76 40.10	0.531	0.451	-0.472	-0.518	-9.999	1960-1978	
29	8656467	34 43.50	-76 48.20	0.229	0.195	-0.021	-0.204	-9.999	1960-1978	
30	8656483	34 43.20	-76 40.20	0.558	0.470	-0.477	-0.521	0.112	1983-2001	
31	8656486	34 43.20	-76 45.30	0.354	0.302	-0.302	-0.332	-9.999	1960-1978	
32	8656495	34 43.20	-76 41.70	0.552	0.470	-0.487	-0.533	-9.999	1960-1978	
33	8656499	34 43.10	-76 44.20	0.457	0.396	-0.336	-0.366	-9.999	1960-1978	
34	8656502	34 43.20	-76 43.60	0.541	0.458	-0.481	-0.524	0.118	1983-2001	
35	8656503	34 42.90	-76 34.70	0.145	0.095	-0.224	-0.248	0.066	1983-2001	
36	8656518	34 42.70	-76 38.70	0.496	0.419	-0.440	-0.483	-9.999	1983-2001	
37	8656539	34 42.50	-76 37.20	0.428	0.356	-0.365	-0.402	-9.999	1983-2001	
38	8656554	34 42.20	-76 37.20	0.360	0.299	-0.311	-0.341	-9.999	1960-1978	
39	8656566	34 42.00	-76 46.10	0.268	0.225	-0.257	-0.287	-9.999	1960-1978	
40	8656569	34 41.90	-76 39.90	0.634	0.542	-0.433	-0.494	-9.999	1960-1978	
41	8656571	34 41.90	-76 40.90	0.546	0.464	-0.487	-0.533	-9.999	1960-1978	
42	8656590	34 41.60	-76 42.70	0.654	0.550	-0.563	-0.610	0.147	1983-2001	
43	8656612	34 41.20	-76 32.00	0.318	0.257	-0.266	-0.295	0.094	1983-2001	
44	8656841	34 36.80	-76 32.30	0.722	0.614	-0.620	-0.669	-9.999	1983-2001	
45	8656937	34 36.50	-76 31.70	0.629	0.520	-0.527	-0.572	-9.999	1983-2001	
46	8657419	34 27.10	-77 29.70	0.735	0.637	-0.642	-0.690	-9.999	1960-1978	
47	8658559	34 1.90	-77 53.60	0.747	0.643	-0.639	-0.686	0.216	1983-2001	*

Table B.2. **NOS Water Level Station Names.**

No.	Station	Name
1	8639208	VIRGINIA BEACH RUDEE INL
2	8651370	DUCK FRF PIER
3	8651375	CURRITUCK SOUND NO 1 NC
4	8652226	JEANETTES PEIR NC
5	8652232	MANTEO SHALLOWBAG BAY
6	8652247	MANNS HARBOR CROATAN SOU
7	8652437	OYSTER CREEK CROATAN SOU
8	8652547	ROANOKE MARSHES LIGHT CR
9	8652587	OREGON INLET MARINA NC
10	8652591	ROANOKE SOUND CHANNEL NC
11	8652648	OLD HOUSE CHANNEL NC
12	8652657	OREGON INLET CHANNEL NC
13	8652659	OREGON INLET BRIDGE NC
14	8652678	USCG LIFEBOAT STATION ORE
15	8652715	PEA ISLAND #2 NC
16	8652737	DAVIS SLOUGH NC
17	8652905	LAKE WORTH STUMPY POINT
18	8653215	RODANTHE PAMLICO SOUND NC
19	8654400	CAPE HATTERAS FISHING PIE
20	8654792	OCRACOKE ISLAND
21	8655151	CEDAR ISLAND NC
22	8655875	SEA LEVEL CORE SOUND
23	8656084	CORE CREEK BRIDGE NC
24	8656225	NORTH RIVER BRIDGE BETTIE
25	8656298	NEWPORT RIVER NC
26	8656306	MOREHEAD-BEAUFORT Y C NEW
27	8656394	NEW RIVER JACKSONVILLE NC
28	8656451	GALLANT CHANNEL NC
29	8656467	SPOONERS CREEK NC
30	8656483	BEAUFORT DUKE MARINE LAB
31	8656486	N C A R STATE FISHERIES N
32	8656495	PORT TERMINAL NC
33	8656499	ATLANTIC BEACH BRIDGE NC
34	8656502	MOREHEAD CITY HARBOR HARB
35	8656503	HARKERS ISLAND BRIDGE NC
36	8656518	BEAUFORT TAYLOR CREEK NC
37	8656539	LENOXVILLE POINT NORTH RI
38	8656554	CHANNEL MARKER LIGHT #59
39	8656566	CORAL BAY ATLANTIC BEACH
40	8656569	BEAUFORT INLET CHANNEL RA
41	8656571	FORT MACON NC
42	8656590	ATLANTIC BEACH TRIPLE S P
43	8656612	CALICO JACKS MARINA NC
44	8656841	CAPE LOOKOUT (INSIDE) NC
45	8656937	CAPE LOOKOUT ATLANTIC OC
46	8657419	OCEAN CITY FISHING PIER
47	8658559	WILMINGTON BEACH NC

APPENDIX C. HYDRODYNAMIC MODEL PARAMETERS

C.1. Bottom Friction

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 option,

$$\tau_* = C_f$$

where C_f is the user specified bottom friction coefficient (and is constant in time, but may vary in space). For the quadratic friction option,

$$\tau_* = \frac{C_f (U^2 + V^2)^{1/2}}{H},$$

where H is the bathymetric depth at the node. For the so-called hybrid friction, the same formula for τ_* is used, although C_f is not assigned by the user but is calculated 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_{break} (the so-called break depth) is a specified by the user such that in waters deeper than 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. This formulation allows for increasing values of bottom friction coefficients in very shallow water.

For the North Carolina tidal simulations, the hybrid quadratic formulation was used, with values as follows: $C_{fmin} = 0.0025$, $H_{break} = 2$ m, $\theta = 10$, and $\gamma = 4/3$. Effective values of C_f for various depths are shown in the table below.

Depth (m)	0.1	0.5	2.0	5.0	10.0
C_f	0.1357	0.0159	0.0027	0.0025	0.0025

C.2. Other Parameters

A time step of 3 s was used, with a linear ramp-up time for tidal forcing of 5 days. The dimensionless *tau0* value, which increases mass conservation, was set to 0.005 for water depths greater than 10 m, and 0.020 elsewhere.

APPENDIX D. SUMMARY OF HYDRODYNAMIC MODEL ERRORS

Table D.1. Summary of errors (modeled value minus observed value) at stations within the model grid. Values are in m. RMSE is root mean square error for the four datums at that station, and Amax is the maximum absolute error. Mean RMS error = 0.052 m.

n	NOS	MHHW	MHW	MLW	MLLW	RMSE	Amax
1	8651370	-0.013	-0.007	0.010	0.036	0.020	0.036
2	8651375	-0.015	-0.007	0.007	0.014	0.012	0.015
3	8652226	-0.055	-0.058	0.023	0.067	0.054	0.067
4	8652232	-0.032	-0.022	-0.012	0.018	0.022	0.032
5	8652247	-0.017	-0.013	0.010	0.027	0.018	0.027
6	8652437	-0.002	0.014	-0.018	0.007	0.012	0.018
7	8652547	-0.002	0.015	-0.017	0.009	0.012	0.017
8	8652587	0.004	0.018	-0.029	0.002	0.017	0.029
9	8652591	0.008	0.024	-0.033	-0.009	0.021	0.033
10	8652648	0.057	0.066	-0.075	-0.046	0.062	0.075
11	8652657	-0.002	-0.005	-0.010	0.011	0.008	0.011
12	8652659	-0.086	-0.060	0.044	0.063	0.065	0.086
13	8652678	-0.108	-0.085	0.044	0.061	0.079	0.108
14	8652715	-0.055	-0.061	0.076	0.097	0.074	0.097
15	8652737	0.031	0.031	-9.999	-0.028	0.030	0.031
16	8652905	0.006	0.024	-0.015	0.008	0.015	0.024
17	8653215	-0.070	-0.024	0.019	0.035	0.042	0.070
18	8654400	-0.030	-0.017	0.014	0.028	0.023	0.030
19	8654792	-0.093	-0.066	0.034	0.040	0.063	0.093
20	8655151	-0.048	-0.052	0.023	0.023	0.039	0.052
21	8655875	0.031	0.012	-0.012	-0.001	0.018	0.031
22	8656084	0.048	0.039	-0.007	0.003	0.031	0.048
23	8656225	0.034	0.006	-0.024	-0.018	0.023	0.034
24	8656298	-0.040	-0.043	0.021	0.064	0.044	0.064
25	8656306	0.005	-0.001	0.057	0.077	0.048	0.077
26	8656451	0.047	0.035	-0.005	0.016	0.030	0.047
27	8656467	0.051	0.023	-0.204	-0.053	0.109	0.204
28	8656483	0.024	0.021	-0.010	0.008	0.017	0.024
29	8656486	0.016	0.001	-0.015	-0.022	0.015	0.022
30	8656495	0.037	0.029	-0.021	-0.003	0.026	0.037
31	8656499	-0.009	-0.022	-0.049	-0.051	0.038	0.051
32	8656502	-0.031	-0.028	0.036	0.048	0.036	0.048
33	8656503	0.207	0.190	-0.042	-0.046	0.144	0.207
34	8656518	-0.021	-0.021	0.029	0.043	0.030	0.043
35	8656539	0.039	0.036	-0.039	-0.032	0.037	0.039
36	8656554	0.097	0.084	-0.089	-0.089	0.090	0.097
37	8656566	0.046	0.025	-0.007	-0.011	0.027	0.046
38	8656569	-0.045	-0.041	-0.084	-0.050	0.058	0.084
39	8656571	0.039	0.031	-0.024	-0.006	0.028	0.039
40	8656590	-0.022	-0.015	0.021	0.042	0.027	0.042
41	8656612	0.048	0.040	-0.023	-0.021	0.035	0.048
42	8656841	-0.117	-0.104	0.107	0.129	0.115	0.129
43	8656937	-0.083	-0.069	0.074	0.094	0.080	0.094
44	8657419	-0.048	-0.050	0.052	0.072	0.056	0.072

APPENDIX E. SUMMARY OF VDATUM ERRORS

Error summary for all 40 tide stations: avg. rmse = 0.01100, max. rmse = 0.03699, avg. std = 0.00964, and max. std = 0.03627. The following tables show the errors in the Pamlico Sound region (Table E.1), the Coastal Central region (Table E.2) and the Coastal North region (Table E.3).

Table E.1. Pamlico Sound Tide Station Comparisons (Errors in m).

n	NOS	lat	lon	rmse	std
1	8652437	35.84500	-75.65500	0.00210	0.00209
2	8652547	35.81167	-75.70000	0.00236	0.00202
3	8652587	35.79500	-75.54833	0.00148	0.00145
4	8652591	35.79833	-75.58334	0.00637	0.00633
5	8652648	35.77500	-75.58167	0.00691	0.00683
6	8652657	35.77333	-75.55833	0.00208	0.00207
7	8652659	35.77333	-75.53833	0.00636	0.00308
8	8652678	35.76833	-75.52666	0.01175	0.00769
9	8652715	35.75667	-75.53167	0.01495	0.01387
10	8652737	35.74833	-75.55334	0.02171	0.02173
11	8652905	35.69833	-75.77333	0.00582	0.00193
12	8653215	35.59500	-75.47166	0.00267	0.00260
13	8654792	35.11500	-75.98833	0.02651	0.02643
14	8655151	35.02000	-76.31000	0.00067	0.00061
15	8655875	34.87500	-76.34333	0.03699	0.03627
16	8656084	34.82333	-76.69000	0.01552	0.01522
17	8656225	34.79167	-76.60833	0.01232	0.01191
18	8656298	34.76667	-76.68667	0.01612	0.01278
19	8656306	34.76833	-76.67167	0.00737	0.00606
20	8656451	34.72833	-76.66833	0.00352	0.00209
21	8656467	34.72500	-76.80334	0.01393	0.01253
22	8656483	34.72000	-76.67000	0.00267	0.00236
23	8656486	34.72000	-76.75500	0.00289	0.00288
24	8656495	34.72000	-76.69500	0.00524	0.00522
25	8656499	34.71833	-76.73666	0.01478	0.00738
26	8656502	34.72000	-76.72667	0.02297	0.02145
27	8656503	34.71500	-76.57833	0.02064	0.01485
28	8656518	34.71167	-76.64500	0.01316	0.01257
29	8656539	34.70833	-76.62000	0.00286	0.00286
30	8656554	34.70333	-76.62000	0.01765	0.01764
31	8656566	34.70000	-76.76833	0.00888	0.00607
32	8656569	34.69833	-76.66500	0.00764	0.00271
33	8656571	34.69833	-76.68166	0.01550	0.01114
34	8656612	34.68667	-76.53333	0.00159	0.00128
35	8656841	34.61333	-76.53833	0.01776	0.01776

```
Error summary for tide Pamlico Sound stations
     number    =       35
     avg. rmse =  0.01062     max. rmse =  0.03699 at n=  15
     avg. std  =  0.00919     max. std  =  0.03627 at n=  15
```

Table E.2. Coastal Central Tide Station Comparisons (Errors in m).

n	NOS	lat	lon	rmse	std
1	8654400	35.22333	-75.63500	0.00072	0.00069
2	8656590	34.69333	-76.71167	0.03077	0.02792
3	8656937	34.60833	-76.52834	0.03140	0.03137

```
Error summary for Coastal Central tide stations
     number    =        3
     avg. rmse =  0.02096     max. rmse =  0.03140 at n=   3
     avg. std  =  0.02000     max. std  =  0.03137 at n=   3
```

Table E.3. Coastal North Tide Station Comparisons (Errors in m).

n	NOS	lat	lon	rmse	std
1	8651370	36.18333	-75.74667	0.00196	0.00183
2	8652226	35.91000	-75.59167	0.00221	0.00213

```
Error summary for Coastal North tide stations
     number    =        2
     avg. rmse =  0.00209     max. rmse =  0.00221 at n=   2
     avg. std  =  0.00198     max. std  =  0.00213 at n=   2
```