

# **DEVELOPMENT OF A NATIONAL VDATUM, AND ITS APPLICATION TO SEA LEVEL RISE IN NORTH CAROLINA**

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## **INTRODUCTION**

VDatum is a software tool developed by the National Ocean Service (NOS) for transforming bathymetric/topographic data among 28 tidal, orthometric and ellipsoidal vertical datums. The ability to properly reference data to multiple vertical datums is critical to a variety of applications in the coastal zone, and it also serves to extend the capabilities of emerging technologies in providing state-of-the art products. After a pilot demonstration project in Tampa Bay, VDatum has been created for the New York Bight, northern California, southeast Louisiana, Delaware Bay, and Puget Sound. Currently, VDatum applications are in development for North Carolina, Louisiana's Calcasieu River and Lake Charles, the Chesapeake Bay, New York Harbor and the Long Island Sound, the Gulf of Maine, and the Strait of Juan de Fuca. The goal is to develop a national VDatum database, starting with the continental U.S. and followed by Alaska and Hawaii.

A national VDatum will complement NOS work in developing a national bathymetry database, which can be combined with the National Elevation Dataset of the U.S. Geological Survey (USGS) in providing seamless data products across the land-water interface. Together, these products will also enable a consistent, accurate national shoreline to be defined relative to the tidal datums. Other applications that benefit from VDatum include storm surge simulations, tsunami prediction, sea level rise studies, ecosystem modeling, and coastal zone management. VDatum also enhances the capabilities of technologies such as kinematic GPS (K-GPS) for vertical referencing of hydrographic survey depths, use of topographic and bathymetric LIDAR for determining MLLW and MHW shorelines, and development of digital elevation models (DEMs).

To exemplify the types of products and applications that are enabled by the availability of VDatum in a coastal region, we examine its utility in a sea level rise project for North Carolina. To assist the development of environmental models for assessing the impact of sea level rise, VDatum was developed and used in creating an integrated DEM for coastal North Carolina using LIDAR measurements, topographic data, and hydrographic surveys. The resulting DEM is being used to support storm surge and coastal flooding simulations coupled with biogeophysical models to help in forecasting environmental changes caused by sea level rise.

## DEVELOPMENT OF A NATIONAL VDATUM

The development of a national VDatum tool is vital to improving the effectiveness of using bathymetric and topographic data in the protection, management and study of coastal zone processes. The need for accurate data in the coastal zone is increasing, and many federal agencies, universities, state and local governments, and other organizations are addressing this need by collecting high-resolution bathymetry, topography and shoreline data. The largest barrier to gathering all such data into merged datasets across the land-water interface is the need for a tool to properly reference all data to a common vertical datum (National Research Council, 2004).

To address this issue of the need for a vertical transformation tool, NOS coordinated with the U.S. Geological Survey (USGS) on a pilot project of developing VDatum in Tampa Bay (Milbert and Hess, 2001). The algorithms developed through this pilot project would serve as a template for the implementation of a national VDatum tool. The vertical datums incorporated into VDatum were thus selected so as to accommodate the wide variety of bathymetric and topographic data sources that could potentially be used as input to the transformation software. Vertical datums can be classified as either being a tidal datum (tidally-derived surface), an orthometric datum, or a 3D ellipsoidal datum. Examples of the types of data that are referenced to these categories of datums include bathymetry that is usually referenced to a tidal datum, topographic data that is often surveyed relative to an orthometric datum such as the North American Vertical Datum of 1988 (NAVD88), and LIDAR data that is referenced to an ellipsoidal datum.

Figure 1 shows the transformations that are needed to convert between these three main categories of vertical datums. This conversion relies on the use of a primary datum within each category. Thus, any other datums within a given category will need to first be converted to that category's primary datum before it can be converted to a datum in a different category. The primary datums used in VDatum are mean sea level (MSL) for the tidal datums, NAVD88 for the orthometric datums, and the North American Datum of 1983 (NAD83(86)) for the ellipsoidal datums. The VDatum software also transforms data that are georeferenced to the North American Datum of 1927 (NAD27), a non-geocentric horizontal datum, to the NAD83(86) primary ellipsoidal datum.

It is instructive to go through an example of first converting data referenced to a tidal datum to an orthometric datum, and then converting from the orthometric datum to an ellipsoidal datum. Hydrodynamic models are used to simulate tides for a given area, such as Tampa Bay, and the results are used to compute the tidal datums. These include mean higher high water (MHHW), mean high water (MHW), mean tide level (MTL), diurnal tide level (DTL), mean sea level (MSL), mean low water (MLW), and mean lower low water (MLLW). These tidal datums are computed relative to specific time periods called National Tidal Datum Epochs (NTDE) with the 1983-2001 NTDE in use today. Data that is referenced to one of these tidal datums may then use these model-computed fields to convert to the primary tidal datum, MSL. Next, to convert from MSL to the primary orthometric datum, NAVD88, a topography of the sea surface (TSS) must first be

computed. This is accomplished by spatially interpolating NAVD88-MSL differences that are observed at official National Geodetic Survey (NGS) benchmark locations. Once the data has been converted to NAVD88 using the TSS, it may also be related to the older NGVD29 orthometric datum through the use of NGS' VERTCON software (Milbert, 1999) Finally, the data now referenced to NAVD88 may be converted to the primary ellipsoidal datum, NAD83(86), through the use of the GEOID99 geoid model (Smith and Roman, 2000, 2001). Transformations to 18 other ellipsoidal datums may then be carried out using 7-parameter Helmert transformations.

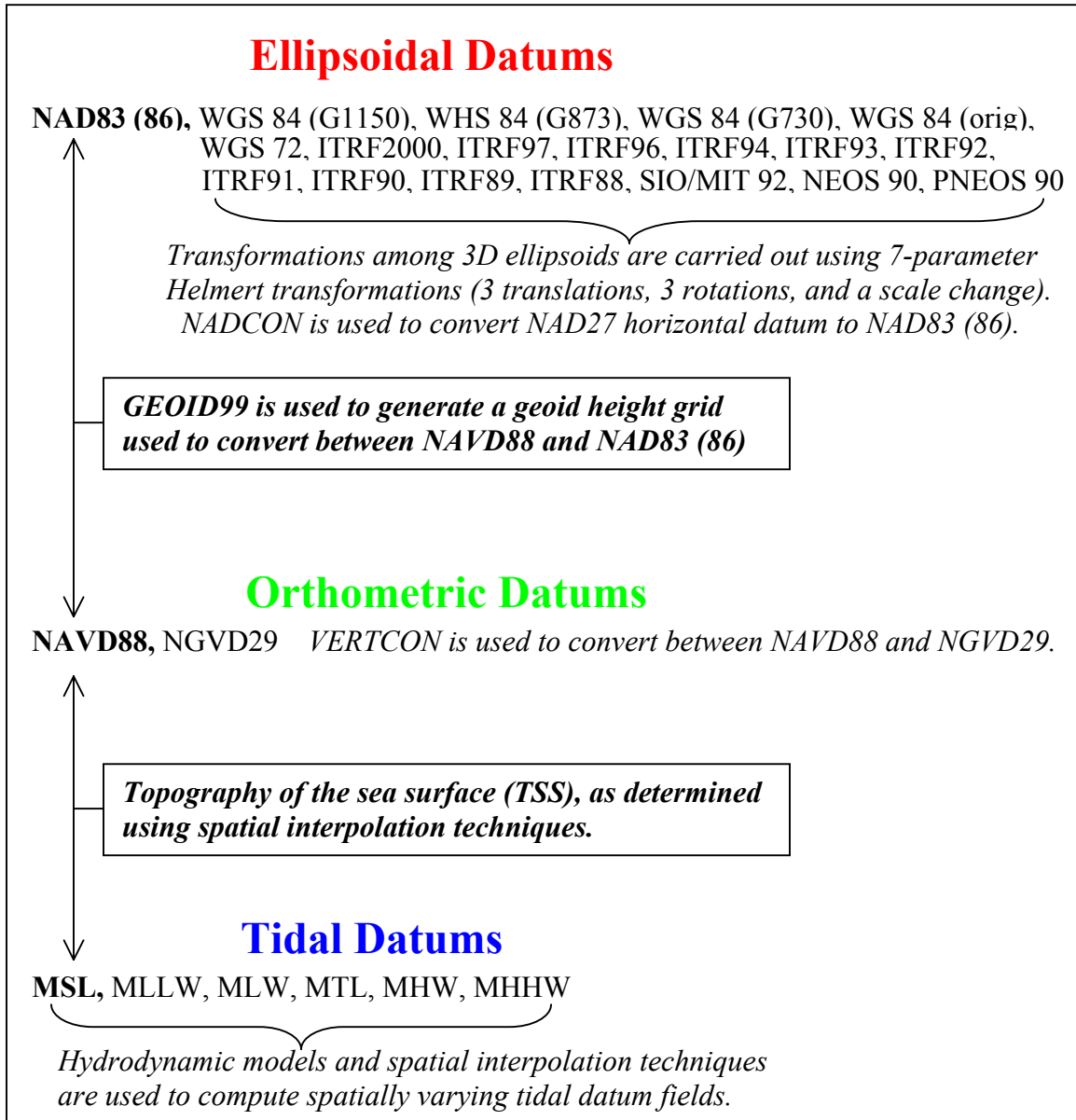


Figure 1. Transformations used by VDatum to convert between and among the 28 ellipsoidal, orthometric, and tidal datums. The software also transforms from the North American Datum of 1927 (NAD27) horizontal datum to NAD83(86).

In all, 29 different datums are currently accounted for by the VDatum software. For Tampa Bay, these transformations were used to merge NOS bathymetric sounding data with USGS orthometric survey data to create a seamless digital elevation model (DEM) for the region. The successful implementation of the Tampa Bay pilot served as a template upon which VDatum is being expanded to nationwide coverage (Parker et al., 2003). Figure 2 shows the VDatum projects that have since been developed as the first steps toward a national tool. The New York Bight project was developed in support of an offshore aggregates project with the USGS and U.S. Army Corps of Engineers (USACE). The Delaware Bay VDatum was performed to support bathymetric data transformations in support of K-GPS hydrographic surveys. NOAA's National Marine Sanctuaries program supported the northern California VDatum to help in merging bathymetric data in the offshore marine sanctuaries. The Puget Sound VDatum was done in support of NOAA's tsunami modeling efforts in the Pacific Northwest. Finally, the southeast Louisiana project was made in collaboration with the University of Louisiana and the USGS in support of development of a DEM for the Port Fourchon area.

While each of these VDatum applications were made in support of specific applications, the resulting transformation software for each region are now publicly available for any of the myriad of applications and technologies that can benefit from VDatum. A few examples include K-GPS hydrographic surveying, use of LIDAR to determine the tidally-defined shorelines such as MHW and MLLW, storm surge modeling, sea level rise studies, tsunami inundation mapping, ecosystem modeling, and coastal zone management issues. VDatum projects are underway for North Carolina, Louisiana's Calcasieu River and Lake Charles, the Chesapeake Bay, New York Harbor and the Long Island Sound, the Gulf of Maine, and the Strait of Juan de Fuca. As these regional applications begin to overlap, a seamless national VDatum tool will emerge that will cover all of the U.S. coastal area, from estuaries out to 25 nautical miles from land.



Figure 2. VDatum applications currently available.

## **METHODOLOGY**

The implementation of a national VDatum database that is both accurate and efficient requires a consistent methodology in the steps taken to develop each application. There are three primary steps that are taken to develop a VDatum application. First, bathymetric and shoreline data are gathered for the region of interest and are evaluated under quality control measures before they are used as input to the tide modeling. Hydrodynamic models are then developed to simulate tidal propagation, and the results are analyzed to compute spatially varying fields of the tidal datums. Finally, this information is provided to the National Geodetic Survey for inclusion in the VDatum software with the ellipsoidal datum algorithms, the geoid model results, and the topography of the sea surface analysis. Within each of these steps, as described below, tools and approaches are chosen so as to best improve the accuracy and consistency of the VDatum applications as viewed from a national perspective.

### ***Bathymetry and Coastline Data used by VDatum***

#### *Digital Vector Shoreline*

Digital vector shoreline is used to define the land-water boundary of the numerical tide models. The MHW coastline used for the finely resolved tidal models are compiled from the NOAA Office of Coast Survey's (OCS) extracted shoreline series at map scales of 1:80,000 or greater, as well as from the Coastline and Shoreline Construction object classes of NOAA's Electronic Navigational Charts (ENCs). Originally digitized from NOAA Raster Nautical Charts, ENCs comprise the official charting database provided in International Hydrographic Office (IHO) native S-57 vector format, a data standard used for the global exchange of digital hydrographic data. Vector shorelines are compiled in longitude-latitude pairs with precision up to 0.000001 decimal degrees referenced to the World Geodetic System of 1984 (original), a geospatial framework that is essentially equivalent to the NAD83(86) ellipsoid used in the U.S. Also used is the older medium-resolution shoreline, manually extracted from paper nautical charts.

#### *Bathymetric Data*

Several sources of bathymetric data are evaluated and processed for the development of numerical tidal models, as shown in Table 1. Sounding points are initially selected from the 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 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 to be the data collection method for surveys before 1940. Water depths are recorded by echo sounders from 1940 onward. For some regions

of the coastal United States, the OCS bathymetric database includes high-density multibeam measurements from hydrographic surveys since 1980.

Table 1. Sources of bathymetry used by the VDatum project.

% Original MLW or LWD datums may be marked as MLLW on NOAA Charts.

\* Depth values that were used to generate the CRM were non-uniformly georeferenced.

Data Format	Horizontal Resolution	Horizontal Accuracy	Vertical Resolution	Vertical Accuracy	Horizontal Datum	Vertical Datum
National Ocean Service (NOS) Hydrographic Survey Database Point Soundings	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
U. S. Army Corps of Engineers regional channel surveys Point Soundings	various	3m nearshore 20-75m offshore	various	0.3m at 0-20m depth 0.5-1m at 20-100m depth	NAD83	MLW%
NOAA Nautical Charts - Digitized Point Soundings	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
National Geophysical Data Center Coastal Relief Model (CRM) Structured Grid	~90m	undetermined	0.1-1m	undetermined	mixed* NAD83 other	mixed* MLLW MLW LWD

Soundings from each survey are most often vertically referenced to either MLLW or MLW. Bathymetric soundings are filtered sequentially by date using a series of raster layers whose spatial resolutions are determined by sounding point density. In addition to the temporally filtered soundings from the OCS bathymetric database, the Coastal Relief Model (CRM) at NGDC is an alternative source of historical NOS bathymetry that is available in an interpolated, gridded format at a horizontal resolution of 3 arc-seconds, or approximately 90 m, with seafloor elevations vertically resolved to 0.1 m. CRM bathymetric grids are interpolated from unfiltered soundings whose depths are uncorrected from their horizontal datum and vertical datum.

Recent bathymetry data from inlets and channels, multibeam subsets of NOS hydrographic surveys, and soundings from many older surveys that are unavailable from NGDC are collected from the latest editions of NOAA ENC's, whose depth values have been processed and validated for publication by OCS. Depths within navigable inlets and channels that are published in the ENC's are provided by the U.S. Army Corps of Engineers (USACE). USACE surveys are usually georeferenced to NAD83(86) and local MLW. Where applicable, USACE depth values blend with or supersede the historical NOS bathymetry.

The implementation of multi-purpose national bathymetric and shoreline databases complement the National VDatum philosophy (Figure 3). VDatum is critical to the

implementation of a seamless bathymetric database as an operational national archive. The NOS bathymetric database will incorporate data from historical hydrographic surveys presently maintained by NGDC's GEODAS, multibeam surveys, local spot soundings, LIDAR measurements, USACE dredging areas, and other sources. VDatum will transform all depth values to a standard datum (MLLW) used in NOAA nautical charts and IHO S-57 vector products. The transformed data sources will be used to produce bathymetric surface models, such as the Navigation Surface (Smith et al., 2002; Smith, 2003), and national shorelines that are consistently defined by the tidal datums.

## NOAA NOS Bathymetric Database

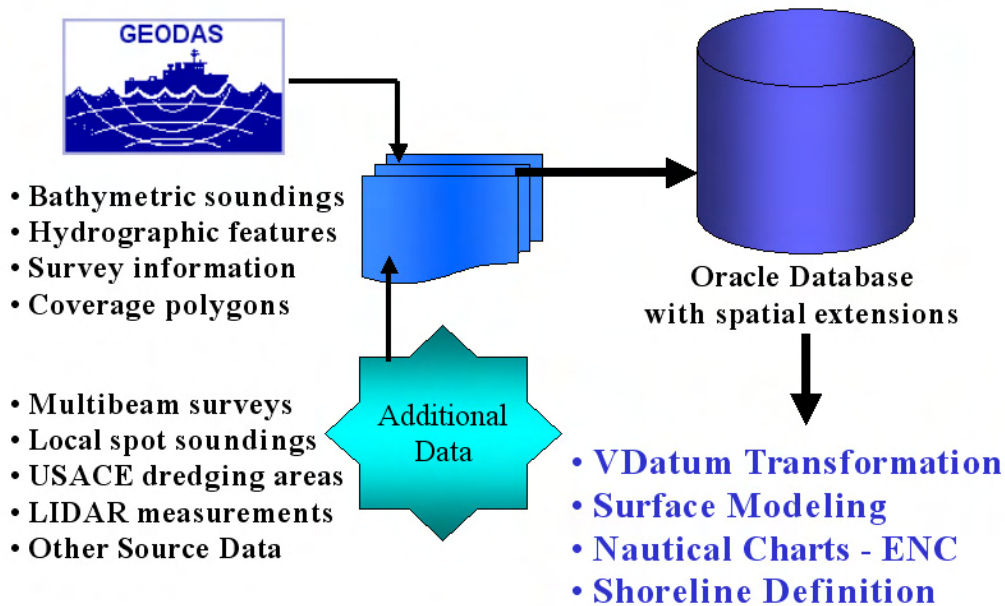


Figure 3. Strategy for development of a national bathymetric database for NOS data.

### *Modeling the Tidal Datums*

A tidal datum is a base elevation from which relative heights and depths may be determined (Gill and Schultz, 2001). It can be measured by analyzing time series of water levels from observational data. Mean sea level (MSL) is an example of a tide datum, taken as the arithmetic mean of hourly water observations over the NTDE (presently the 1983-2001 NTDE). Other tidal datums are calculated based upon recorded high or low water values, including MHHW, MHW, MLW, MLLW, DTL and MTL. Since each of these datums depends upon the tide characteristics of a particular location, there is a spatial variation in the fields in between observation locations.

To resolve the spatially varying nature of the tidal datums in between observation locations, hydrodynamic models and spatial interpolation techniques are developed for each VDatum application that simulate the tidal propagation characteristics in the region of interest. Keeping in mind that all of the individual VDatum applications will ultimately merge together to form a continuous national VDatum product, a consistent methodology for computing the tidal datums is adopted here. The approach consists of first using the bathymetric and coastline data to generate a grid to be used by the model, then calibrating a hydrodynamic model to best simulate the observed tidal datum characteristics for the region, correcting the model-data errors using a spatial interpolation technique, and finally providing the corrected modeled datums on a structured grid of points to be used by the VDatum software.

The first step is the generation of a grid to be used by the hydrodynamic model. Currently, tide modeling applications for VDatum are using the ADCIRC (Luettich et al. 1992) hydrodynamic model. ADCIRC uses triangular unstructured grids in its solution of the hydrodynamic equations for time- and spatially-varying parameters such as water levels and velocities. The generation of unstructured grids for each VDatum region is presently being made with a software tool called SMS (Surfacewater Modeling System). SMS allows the user to control the distribution of triangular elements between the coastlines and the open ocean boundary in a facile manner. For example, since the wavelength of propagating tides is decreased in shallow water, more triangular elements are needed there to properly resolve the features of the waves. Higher resolution is also more ideal near the shorelines to better represent land-water interface geometry and its effect on tidal propagation. Examples of some triangular grids used in recent VDatum projects are displayed in Figure 4.

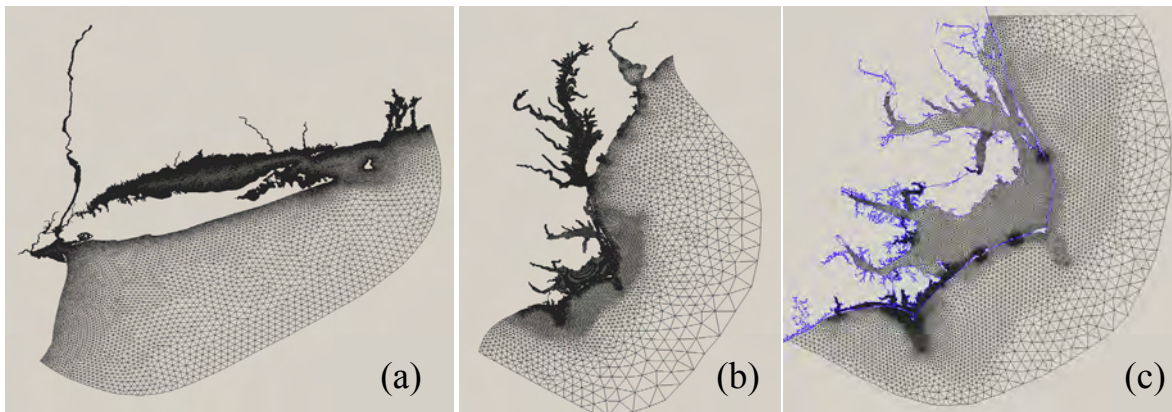


Figure 4. Examples of triangular unstructured grids used in (a) Long Island / New York Harbor, (b) Chesapeake Bay, and (c) coastal North Carolina.

Once an unstructured triangular grid is constructed for a region, it may then be used in numerical simulations of the tides. ADCIRC is a finite element model that uses the generalized wave continuity equation to solve for water levels and the momentum equations to solve for velocities. Time steps used by the model vary according to the



smallest size of triangles in a grid, and they are typically on the order of a few seconds or less. Simulations are normally carried out for 37 days, and the model must therefore process several million time steps for completion. On a single processor computer, this would normally take approximately one month to run. Development of tide models for all of the nations' coastal areas would be hindered by this time to complete the simulations, and therefore access to clustered computer systems at NOAA's Forecast Systems Laboratory (FSL) was granted for running our tide models using an MPI (Message Passing Interface) version of the ADCIRC model. The simulations are typically distributed in parallel among 48-72 processors, thus reducing the time to run the model down to approximately 12-24 hours.

The models are first calibrated to best reproduce observed datums by adjusting such model input parameters as bottom friction, viscosity, the connectivity and shapes of the triangular elements, and the representation of the bathymetry on the grid (each node has a depth assigned to it, and the depths vary linearly within each triangular element). The boundary of the grid along the open ocean is used to force the tides into the model through specification of amplitudes and phases for the  $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_2$ ,  $K_1$ ,  $O_1$  and  $Q_1$  tidal constituents. These tidal boundary conditions must be obtained from a larger model of the tides. Regional models for the Eastern North Pacific (Foreman et al., 2000; Myers and Baptista, 1999; Spargo, 2002) and Western North Atlantic (Mukai et al., 2001) are ideally suited for providing this information to the more localized VDatum modeling applications. The Eastcoast2001 (Mukai et al., 2001) regional model grid for the western North Atlantic Ocean, Gulf of Mexico and Caribbean Sea is displayed in Figure 5.

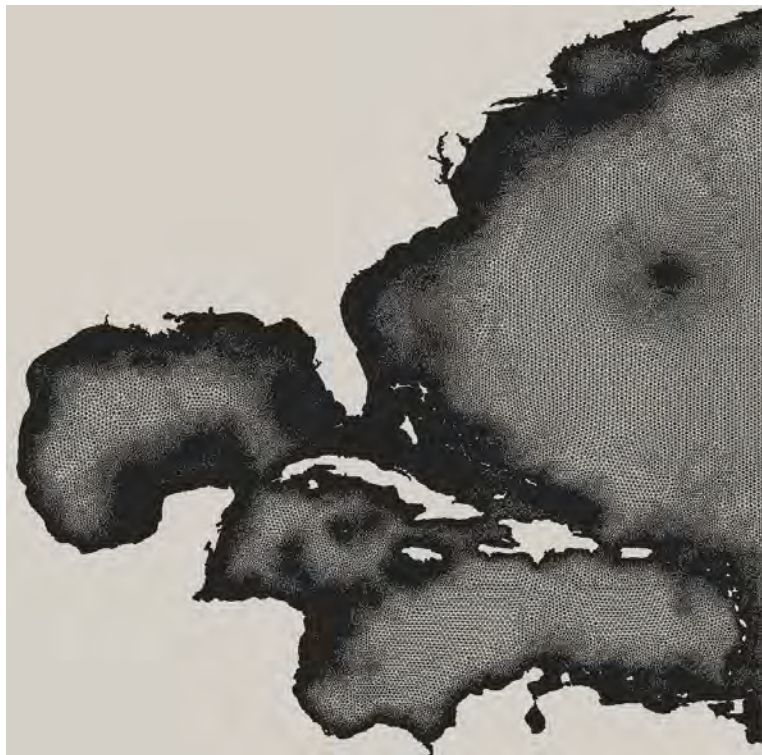


Figure 5. Eastcoast2001 regional grid.

After the model parameters have been calibrated, simulations are made to adjust the bathymetry to be vertically referenced to MSL. As most bathymetry is referenced to MLLW, an initial guess of the MSL to MLLW difference is made to correct the bathymetry for a tide simulation. After that initial simulation is complete, the model output is used to compute new MLLW-MSL differences that are then used as a new correction to the bathymetry. The process is repeated until the computed corrections do not change from one simulation to the next.

A final hydrodynamic model simulation with the calibrated parameters and corrected bathymetry is then made, and the results are used to compute tidal datum fields. These modeled tidal datums are compared with observed datums, and the model-data differences are spatially interpolated using TCARI (Hess et al. 1999; Hess, 2002, 2003). TCARI (Tidal Constituent and Residual Interpolation) solves the Laplace equation using internal boundary conditions where observations are available. In this case, the observations used in TCARI are the model-data differences. Once TCARI has spatially interpolated these differences, the resulting fields may be used as corrections to the modeled datums. The corrected modeled datums will now match exactly at locations where observations are available.

VDatum incorporates the corrected version of the modeled tidal datums through the use of a marine grid. This is a regularly spaced set of data points, onto which the corrected model results are interpolated. Using the high resolution shoreline data, each marine grid point is evaluated as to whether it falls inside (water) or outside (land) this shoreline. A small buffer is also taken into account, such that marine grid points that fall just slightly on the land (within 0.1 nautical miles) may still be assigned a tidal datum value. There may also be areas for which the hydrodynamic model grid does not fully extend through the entire water domain as defined by the shoreline data, and interpolation techniques are used to extend the tidal datums in these regions. The final marine grid of tidal datum fields is provided as input to the VDatum software. A user-supplied longitude/latitude pair to VDatum will thus interpolate from the marine grid the desired tidal datum.

### ***Ellipsoidal, Orthometric and TSS Transformations***

The VDatum software (Milbert, 2002) encodes a four-step traversal path along a minimal spanning tree whose nodes represent the vertical datums grouped into 3D ellipsoidal datums, orthometric datums, and tidal datums: (1) transformations from the 3D ellipsoidal datums to the NAD83(86) primary datum; (2) transformation between the NAD83(86) primary ellipsoidal datum and the NAVD88 primary orthometric datum; (3) transformations between NAVD88 and the MSL primary tidal datum; and (4) transformations between MSL and the tidal datums. Conversions between the 3D ellipsoidal datums apply the 7-parameter Helmert transformations which ascribe the three-dimensional distance, rotation, and scale changes. Data that are referenced to the NAD27 horizontal datum are transformed to NAD83(86). The topography of the sea

surface (TSS) for each region relates NAVD88 and MSL. TSS is calibrated from measurements of tidal values, NAVD88 orthometric datum values, and regional tide model predictions. The NAD83(86) and NAVD88 primary datums are related directly by the GEOID99 height model (Smith and Roman, 2000, 2001) which will be updated to GEOID03 (Roman et al., 2004).

The geoid models developed by NGS are based on the Earth Gravity Model 1996 in which geopotential heights are expressed as spherical harmonic coefficients complete to 360 degrees. GEOID03 will reflect ellipsoidal heights that are constantly being updated to new reference frames. GEOID03 is supported by densified benchmarks from GPS networks and additional data from remote regions and Canada. With an increase from 6169 data points used in GEOID99 to 14,185 available points for GEOID03, the newer geoid model is more finely resolved both analytically and spatially. Revised modeling techniques capture the elevational short wavelength features. Whereas a single filter was used for GEOID99 to resolve features at about 800 km wavelength, two filters are used for GEOID03 at about 1300 km and 120 km to capture the longer and shorter wavelengths, respectively, which better resolve the actual signal. As a result, in contrast to GEOID99 which has about 2.5 cm national error over a 20-40 km wavelength, the GEOID03 model has a national error of only 1 cm over a 5-10 km wavelength. For VDatum, GEOID03 will be used to convert between the NAD83(86) and NAVD88 datums reliably up to the centimeter level within the conterminous U.S.

VDatum requires a gridded topography of the sea surface (TSS), which is the difference between the elevation of NAVD88 and MSL. A regional TSS field can be generated by spatially interpolating the observed NAVD88-MSL differences from NOAA tide stations. In the future, TSS will be replaced by an improved Mean Dynamic Topography derived from LIDAR altimetry measurements in conjunction with gravity field observations.

## **VDATUM USE IN A NORTH CAROLINA SEA LEVEL RISE STUDY**

### ***Motivation***

VDatum in North Carolina was developed to study the impacts of long-term sea level rise on the coastal ecosystems in the sounds and nearby estuaries (Auer et al., 2004; Hess et al., 2004). Sea level rise presents a serious challenge in North Carolina, which contains over 300 miles of ocean beaches and over 4000 miles of estuarine shoreline. The most profound effects of sea level rise are the gradual inundation of estuarine lands, beach erosion, more frequent and severe flooding, and increasing salinity of rivers, wetlands and aquifers, all of which affect the health and livelihood of North Carolina's coastal population.

The approach is to simulate projected sea level variations for the coastal region using a coastal flooding model (CFM) that combines a hydrodynamic model of water levels with a high-resolution digital elevation model (DEM). As an initial step, a hydrodynamic

model of the tides was developed to compute the tidal datum fields. Water depths were then adjusted first to MSL and then to NAVD88 using VDatum. Bathymetry for a sub-region of the study area was integrated with the land elevations from recent airborne LIDAR data sponsored by the Federal Emergency Management Agency (FEMA) and the National Elevation Dataset from the USGS to create the DEM. The CFM will be used to simulate long-term rises in water levels and to delineate areas where sea level rise changes inundation due to astronomic tides, winds and waves, and storm surges. Coastal wetland and forest ecosystems as well as human-made structures are to be added to the CFM to assess their influences and alterations. The DEM and CFM will be coupled with other biogeophysical models to predict and assess ecosystem impacts that will promote proactive coastal management decisions.

## ***Development of VDatum in Coastal North Carolina***

### *Bathymetric and Shoreline Data Compilation*

More than 200 NOS hydrographic surveys were conducted within the North Carolina project area between the years 1851-2002. Approximately 1,980,120 soundings from 158 surveys were accessible and processed from NGDC's GEODAS. NOS soundings were sorted, and then merged by year (Figure 6) and by original vertical datum.

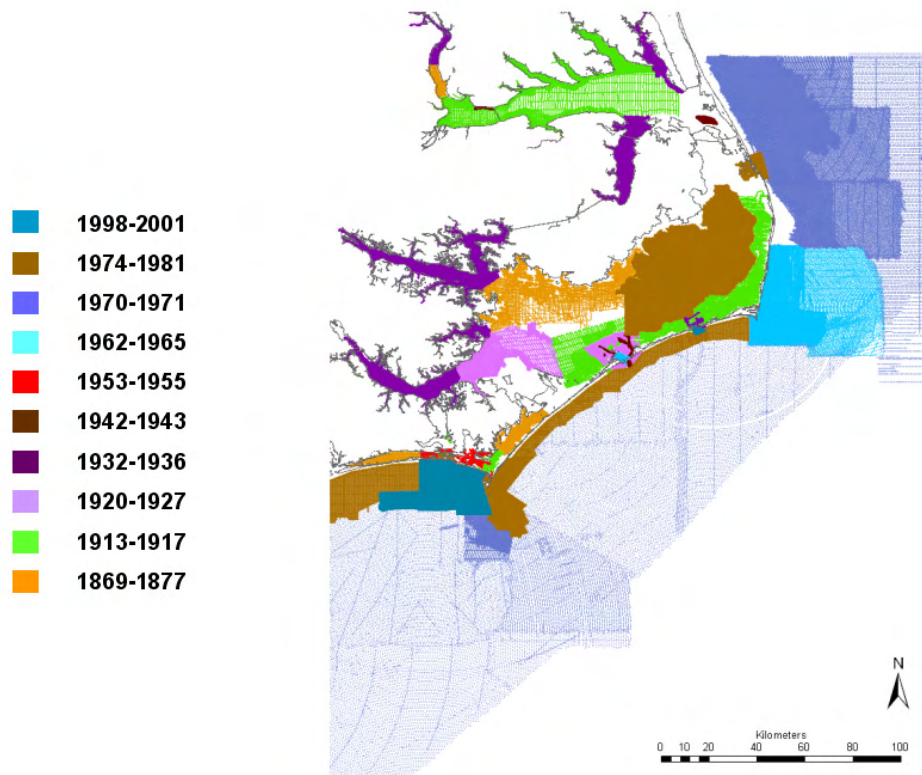


Figure 6. Dates and locations of NOS soundings available in North Carolina.

Soundings in each survey were checked against adjacent and overlapping surveys to ensure continuous coverage. Thirty-four separate spatial-temporal filters, consisting of gridded raster layers resolved by date and sounding density, were generated to compile the best available soundings from the OCS hydrographic survey database. An additional 61,570 soundings referenced to local MLW were processed from 54 recent field surveys conducted by the USACE which superseded the historical NOS bathymetry within North Carolina's channels and inlets. In areas with inaccessible survey data, depth values were compiled from digitized NOAA Nautical Charts and from NGDC's Coastal Relief Model.

Digital shorelines were acquired from the OCS Extracted Vector Shoreline project, which provides coastline from NOS' finest scale Nautical Charts. The MHW outline depicts the land-intertidal, or sometimes land-marsh boundary at a time when the water elevation is equal to MHW, while the MLLW outline depicts the intertidal-water, or sometimes marsh-water, boundary at a time when the water elevation is equal to MLLW.

#### *Tide, Water Level, and Sea Level Rise Data*

Tidal datums, harmonic constants, and time series of water elevations were analyzed from 45 regional stations operated by the NOS Center for Operational Oceanographic Products and Services (Figure 7).

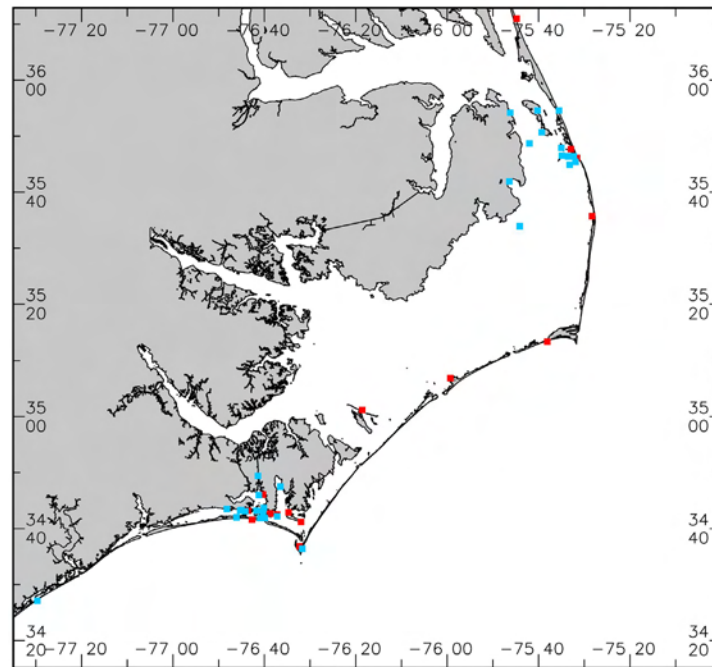


Figure 7. Locations of 45 water level stations used in the North Carolina study. Datums at locations denoted by red squares have been updated to the 1983-2001 tidal datum epoch, while datums at other locations are for earlier epochs.

Observations made in a limited time period are adjusted to represent equivalent values for a 19-year NTDE. These are used for comparison with the model output.

An in-depth analysis of historical water level data was carried out as part of the project (Zervas, 2004). MSL and tidal datum trends will be applied to the coastal DEM for North Carolina in order to predict shoreline movements and to map submerged zones that may occur 25 to 50 years in the future. MSL trends were obtained from monthly data from eight North Carolina stations (Duck, Oregon Inlet Marina, Cape Hatteras, Beaufort, Atlantic Beach, Wilmington, Southport, and Yaupon Beach). Where there were significant gaps in the data, comparisons were made with the stations with more complete records to narrow the trend confidence intervals. The calculated MSL rise increases with latitude from 1.79 mm/yr at Yaupon Beach in the south to 4.27 mm/yr at Duck in the north, with an overall average rise of 2.74 mm/yr. Average seasonal cycles were similar for all stations, with the highest monthly water levels in the early fall and lowest monthly water levels in the winter. The longest time series (68 years at Wilmington) shows no significant changes in the average rate of rise over the period of the data.

The mean and great diurnal ranges were analyzed to determine any long-term changes in tidal range. Oregon Inlet Marina, Beaufort, and Wilmington have large (greater than 3 mm/yr) and statistically significant increases in tidal range. The observed increases in the amplitude of the largest tidal constituent ( $M_2$ ) agree with the calculated increases in tidal range. For these three stations, MHHW, MHW, MLW, and MLLW trends were calculated. Continual dredging of the channels connecting these stations to the ocean has resulted in significant variation in the trends of the different tidal datums. High water datums have been rising at a rate significantly faster than the MSL trend. Whether or not this difference in trend continues depends on future dredging and on the opening or closing of inlets in North Carolina's chain of barrier islands.

#### *Tidal and Hydrodynamic Modeling*

To obtain the tidal datum fields, the ADCIRC model was used to simulate tidal propagation in coastal North Carolina. An initial model grid for this region was extracted from the Eastcoast 2001 grid shown earlier in Figure 4, and additional cells were added to better refine areas that were critical to the DEM. The resulting grid (see Figure 4c) contains 36,409 nodes, with the smallest cell size on the order of 20 m. The model grid was populated with NOS bathymetry selectively filtered from several sources, each of which was vertically referenced to either MLLW, MLW, or LWD.

The outer coastal boundary of the regional grid is forced with periodic water level variations to simulate astronomical tides. Harmonic constants along the coastal ocean boundary were prescribed through interpolation from the Eastcoast2001 tidal database. The model was run to simulate astronomical tides, and the time series of water levels were analyzed to determine tidal datums. The datums at each node in the grid were determined by extracting the high and low waters from results recorded every 6 minutes for the last 30 days of the 37 day simulation, categorizing them as highs, higher highs, lows, or lower lows, then averaging. The root mean square (RMS) difference between the

modeled and observed MHHW, MHW, MLW, and MLLW datum values, relative to MSL, was 5.1 cm.

The NOS bathymetry was adjusted to MSL using the hydrodynamic model to iteratively compute MSL-to-MLW, MSL-to-MLLW, and MSL-to-LWD differences. These were then averaged in all triangular elements of the grid and applied to all bathymetric sounding data falling within each element. Depth adjustments at most locations converged to within 1 cm of their final values after three simulations. 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. The modeled MSL tidal datum field is shown in Figure 8.

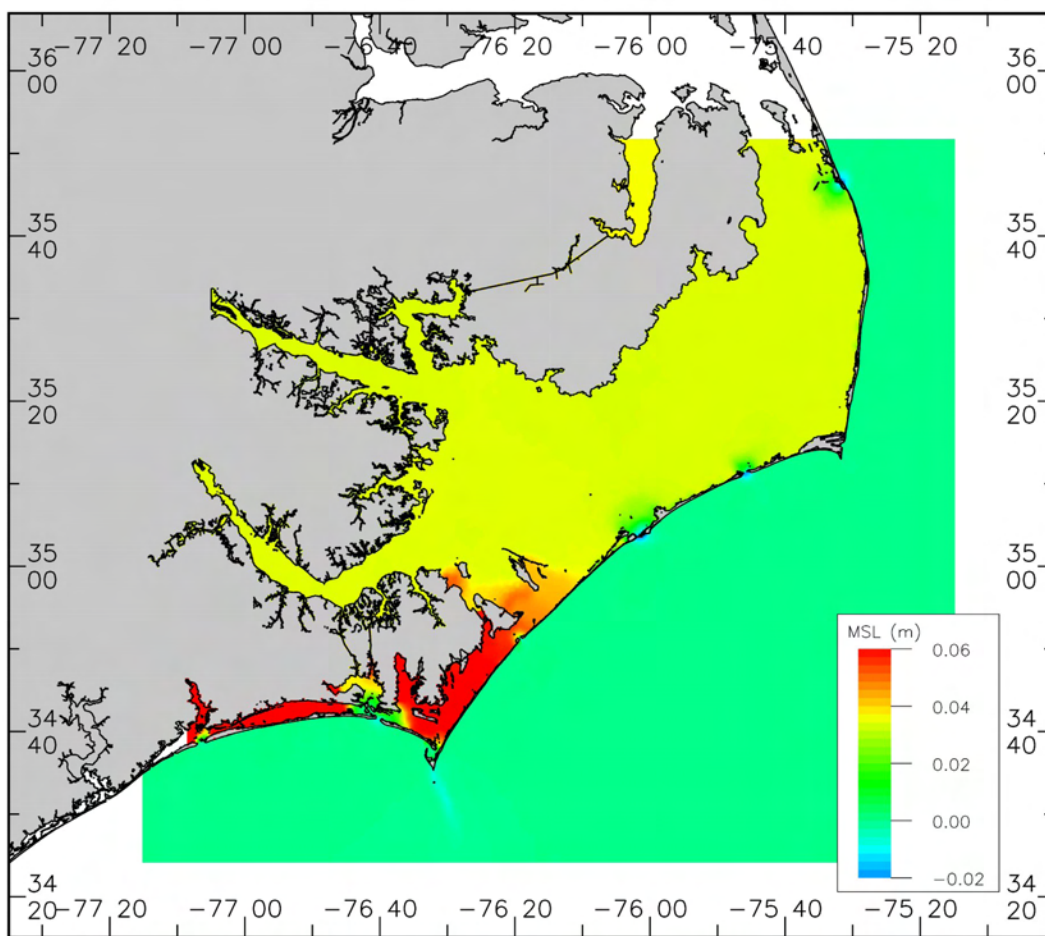


Figure 8. Mean sea level as computed by the hydrodynamic model.

Freshwater flows for the Neuse, Pamlico-Tar, Roanoke, and Chowan Rivers were added to the water level model to assess their influence on mean levels. Differences between the tide-only and the tide plus river forcing were negligible, except in the upper reaches on the rivers, where the differences were less than 1 cm (Amein and Airan, 1976).

#### *Adjusting the Computed Tidal Datums*

The tidal datum fields computed by the hydrodynamic model do not correspond exactly to the datums at the stations based on observed water levels. The modeled MHHW, MHW, MLW, and MLLW tidal datum fields were then adjusted by subtracting an interpolated error field. This error field was generated using TCARI to spatially interpolate the errors between the water level stations. As a result, the corrected tidal datum fields match the observed datums at the water level stations. The MTL and DTL datum fields were derived from the four corrected tidal datums by taking the average between MHW and MLW, and between MHHW and MLLW, respectively. These final six tidal datums (MHHW, MHW, MLW, MLLW, MTL and DTL) were used to populate the VDatum marine grid. In addition, the topography of the sea surface was computed by spatially interpolating the known NAVD88-MSL differences at NOAA tide stations.

#### *Population of Tidal Datums on the VDatum Marine Grid*

The VDatum marine grid consists of points with uniform spacing in longitude and latitude. The regular VDatum grid for North Carolina was generated with  $\Delta x$  and  $\Delta y$  of approximately 0.1 nautical miles, which was then populated by the tidal datum fields produced on the unstructured ADCIRC model grid. Points designated as water are populated by tidal datums and the MSL-to-NAVD88 conversions. The datum conversion at any geographic point is determined by a distance-weighted average of the datum values of the surrounding four points. The region in North Carolina consisting of Pamlico and Albermarle Sounds is separated from the ocean by a series of narrow barrier islands, with significantly different tidal datums on each side. Therefore, the region was divided into two marine grids to eliminate the possibility that VDatum points representing the ocean and the Sounds might be adjacent.

### ***Creation of the North Carolina Coastal DEM***

#### *Land Elevation Data*

For developing a combined topographic/bathymetric DEM for North Carolina, the following data sources for land elevations were evaluated: (1) LIDAR data from FEMA, (2) Shuttle Radar Topographic Mission (SRTM) data, and (3) USGS's digital National Elevation Dataset (NED). The SRTM data have a horizontal resolution of approximately 28 meters and an absolute vertical height accuracy of 16 meters or better, but they were



deemed too coarse in horizontal resolution and not accurate enough in the vertical component to meet the requirements of this project.

The FEMA LIDAR utilized consisted of three formats: raw point data, bare-earth point data, and regular gridded data. The FEMA LIDAR data has a horizontal resolution of approximately 6 m and a vertical accuracy of 20 cm in coastal counties and 25 cm in inland counties. The raw point data is the original LIDAR data with all returns. The bare-earth data are the original point data that have been thinned to consist of only the LIDAR returns that represent the ground surface. This includes removing LIDAR returns capturing vegetation, buildings, power lines, birds, etc. However, once the original LIDAR point data were thinned, there were holes and gaps in the resulting point cloud, a mass assortment of LIDAR returns.

The bare-earth data have two formats: the point data and the regularly gridded data. The latter format is a regular raster grid representing a bare earth surface. These raster cells have approximately 6 m spacing and are filled with a z-value depicting the vertical elevation within the bounds of the cell. The raster dataset was obtained by first creating a Triangular Irregular Network (TIN) from the bare-earth point data. A regular grid was then populated through the extraction of elevation information for each grid cell from the corresponding TIN using linear interpolation. The use of tinning, however, produces artificial elevations along coastal areas where water bodies are not properly masked out. Therefore, the LIDAR bare-earth point data were primarily used to construct the DEM.

#### *Bathymetry/Topography Data Merge*

The bathymetric datasets from NOAA and USACE were combined with the land elevation data to create a DEM at 6 m horizontal and 0.20-0.25 m vertical resolution. The FEMA LIDAR bare-earth point data was prioritized to be integrated initially with the bathymetric data. In order to help fill the void in areas where the bare-earth LIDAR point data was not made available, other datasets that were acquired and analyzed were utilized. The priority was to make use of the regular grid bare-earth data. The regular grids were converted to point data and the water surfaces masked out. If the regular grid bare-earth data was not available, raw LIDAR was used. A bare-earth routine was used to remove features in the Digital Surface Model, an elevation model depicting buildings, trees, towers, etc. that are not representative of the ground surface. This data was then integrated with the other datasets. In areas without LIDAR data, land elevations were acquired from USGS's NED. An image of the resulting DEM is shown in Figure 9.

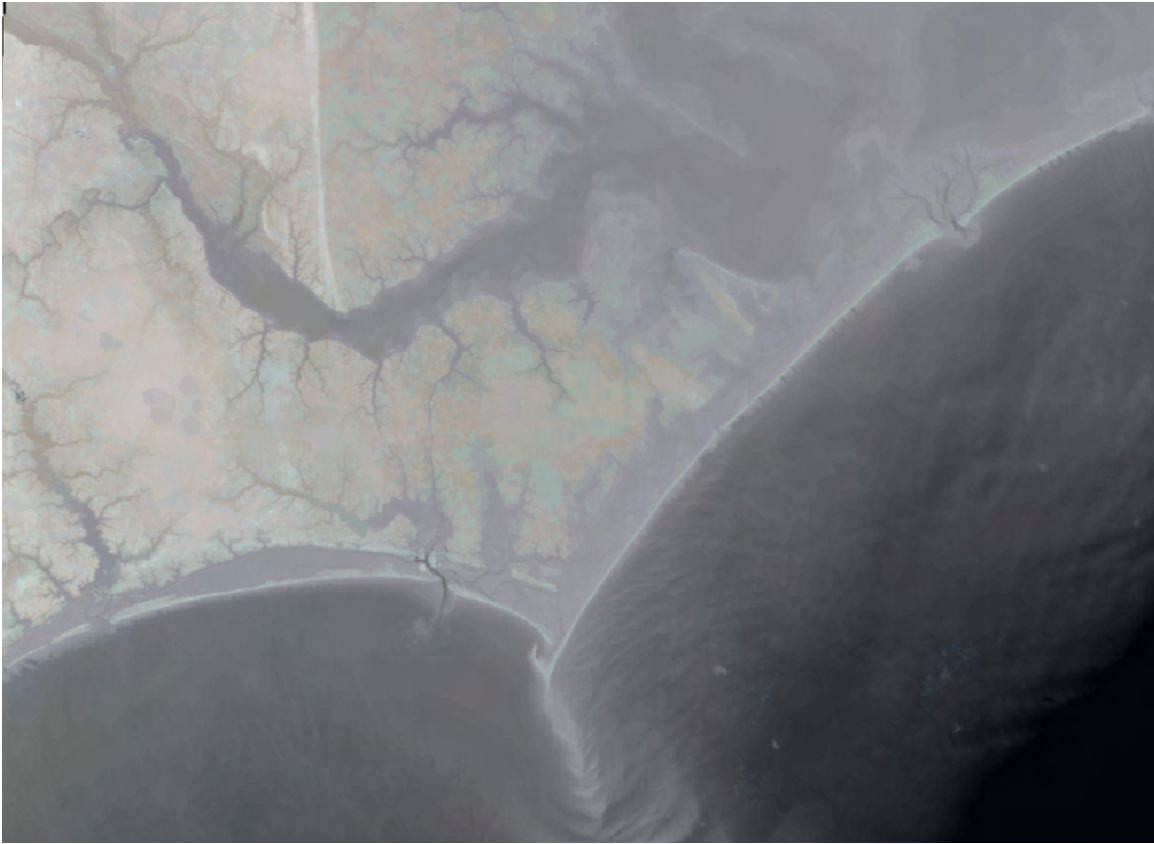


Figure 9. Integrated bathymetric/topographic DEM created for the North Carolina Sea Level Rise project. Prior to merging, all coastal elevations (heights and depths) were uniformly referenced to NAVD88 using the VDatum transformation software. The DEM's horizontal spacing is 6 m, with elevations resolved from 0.20 m to 0.25 m.

### ***Model Applications using the North Carolina VDatum and DEM***

The VDatum transformations and DEM for North Carolina are being used to study sea level rise effects on coastal inundation. To facilitate this, a high-resolution coastal flooding model (CFM) is in development for simulations accounting for tides, winds, and storm surge. The grid for these simulations, shown in Figure 10, extends across the land-water interface (up to the 15m land elevation contour) to allow for flooding in the model. A detailed view of the grid and the DEM are displayed in Figures 11a-b near Beaufort Inlet. The depths of the water and the elevations of the land in the grid are interpolated from the DEM and have been vertically referenced to NAVD88 using VDatum. Hydrodynamic model forcing is also provided relative to NAVD88, thus permitting the CFM simulations to output water levels in a uniform vertical reference frame.

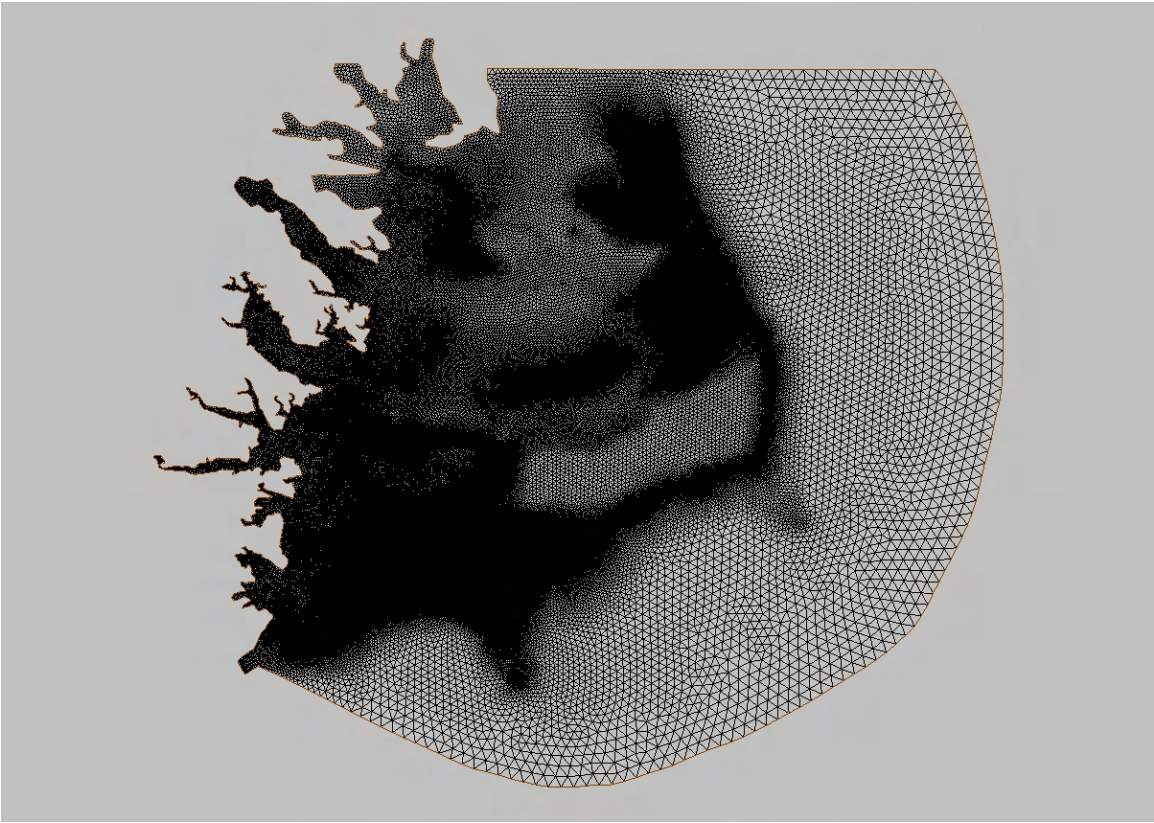


Figure 10. Finite element grid of North Carolina's Coastal Flooding Model (CFM) developed by expanding the existing tide model grid to cover low-lying land areas.

The CFM is being tested by examining changes in tidal response due to a 30 cm rise in sea level. Tidal simulations over 30 days are used to compute how tidal datums such as MHW and MLLW would change under such a sea level increase. These tidal datums are constructed as spatially distributed fields over the CFM grid, and then are used to determine where they intersect with the DEM contours in order to determine corresponding shorelines. For example, using present day water levels, the MHW shoreline near Morehead City, NC, was constructed from hydrodynamic model output. Then the CFM was used to simulate tidal response following a 30 cm rise in sea level, which is applied by raising both the initial water level and offshore boundary forcing by 30 cm. Tidal datum fields were again constructed from CFM output and used to determine the MHW shoreline near Morehead City. The two shorelines can be compared when placed on the NOAA raster nautical chart of the area, as shown in Figure 12. In this case, only a portion of the CFM was used, but the model is being developed for use across North Carolina.

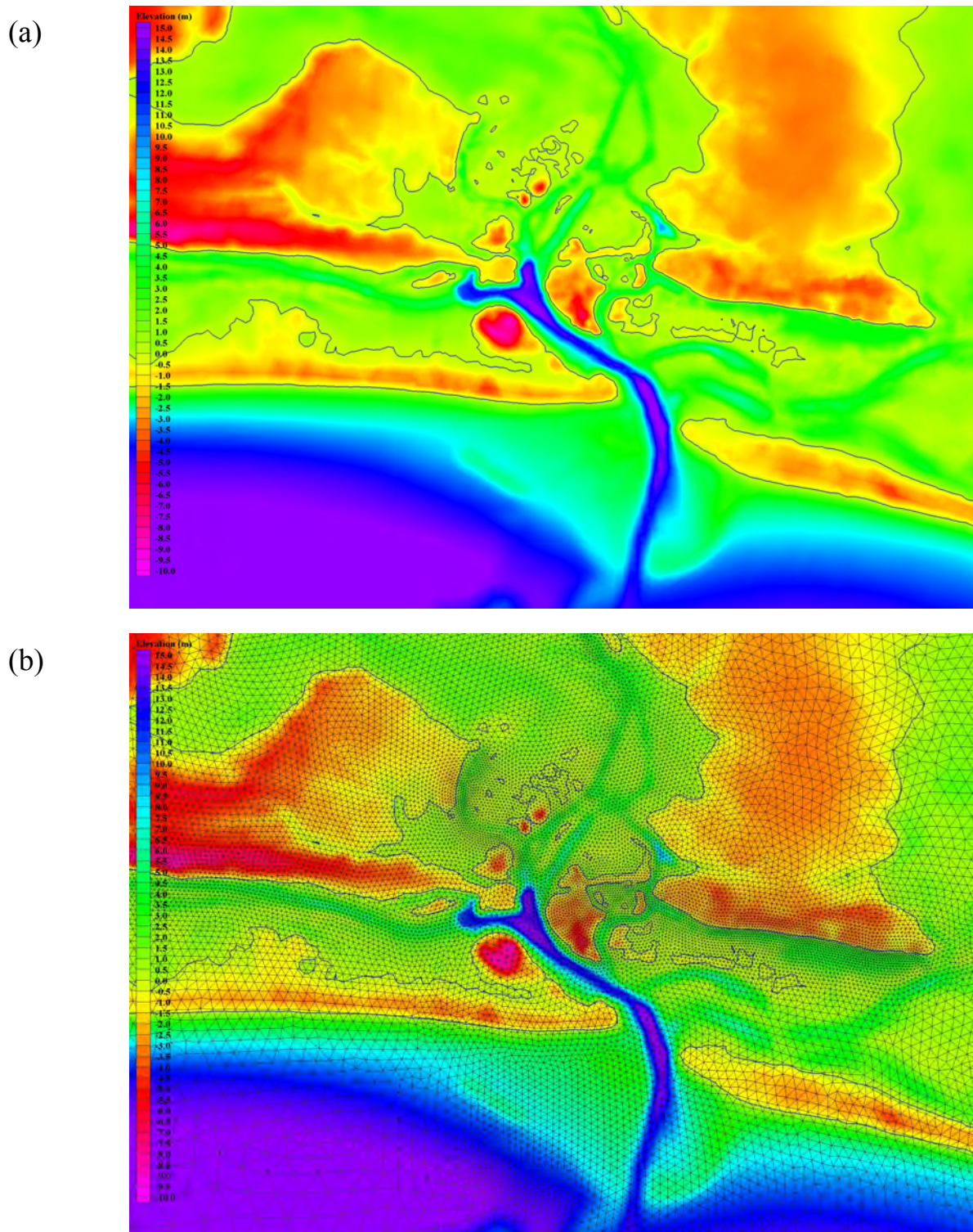


Figure 11. The DEM (a) covered by the CFM's finite element grid (b) around Beaufort Inlet. Coastal elevations and the CFM simulations are vertically referenced to NAVD88.

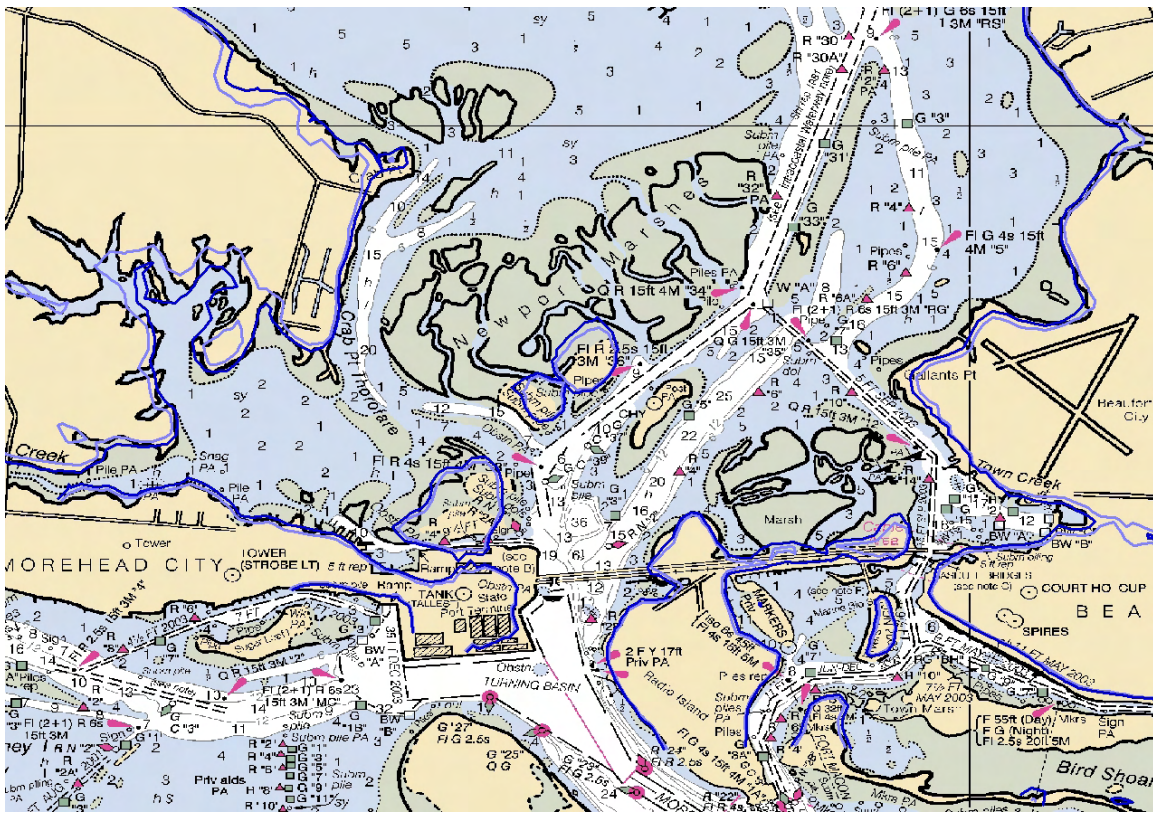


Figure 12. Present-day MHW shoreline (dark blue) compared to the predicted MHW shoreline (light blue) caused by 30 cm rise in sea level near Morehead City, NC.

In addition to simulating changes in hydrodynamic response due to sea level rise, the CFM will be coupled with ecological submodels that will allow the prediction of ecosystem response to sea level rise. These submodels are under development by independent researchers and could include examination of changes in extent and health of local environments (including marsh, oyster reef, submerged aquatic vegetation, and wetland forest), study of marsh accretion, prediction of shoreline erosion and change, and health of local inhabitants such as invertebrates, fish, and waterfowl. The DEM will be revised to include roadways, drainage ditches, and other features affecting inundation. The goal is to significantly improve the ability of coastal managers to assess the potential ecosystem changes due to rising sea levels.

## **FUTURE WORK AND FURTHER APPLICATIONS**

The VDatum applications developed thus far are laying the foundation for the construction of a national VDatum database. Neighboring regional applications will gradually be merged together in an effort to ultimately produce a single VDatum transformation tool for all of the nation's coastal regions. The methods used in each step of VDatum's development are continuously being evaluated as to how to best advance new projects and to update existing regional applications in an effort to provide optimal consistency and accuracy to the final suite of tools.

Not only does VDatum provide the means by which to properly merge bathymetric and land elevation data, it also enables new technologies to produce such data in innovative approaches. For example, NOS has traditionally had to vertically reference bathymetry by maintaining an array of water level stations during a hydrographic survey. Tidal zoning techniques along with settlement and squat corrections for the ship would also be required to adjust the survey measurements. VDatum offers the possibility, though, of using K-GPS technology to more simply make measurements relative to an ellipsoid which may then be adjusted to MLLW through the appropriate vertical datum transformations. This offers a more robust and consistent manner by which survey data may be collected. As another example, shoreline data may be more accurately determined through the use of VDatum corrections applied to LIDAR data. Topographic (bathymetric) LIDAR flown near the time of low (high) water can be vertically corrected from an ellipsoid datum to MHW (MLLW) to construct an accurate depiction of the MHW (MLLW) shoreline. This is a much more accurate method of measuring the shoreline than what traditional approaches provide (see Parker, 2001; Parker, 2003).

The ability to properly georeference existing coastal elevation data and to use new technologies for collecting bathymetry, topography and shoreline data will facilitate other types of databases to be developed concurrently. A national bathymetric database is currently being developed at NOS, while shoreline metadata standards are paving the way to appropriately assemble the best available shorelines in a manner that preserves consistent vertical referencing of the data. DEMs will thus become more practical to create in a way that fully accounts for vertical datum differences. The USGS is building a publicly accessible database of consistently integrated coastal DEMs. NOAA and USGS are coordinating on the blending of bathymetric/topographic/shoreline databases into common products that can be delivered in Web-based applications. VDatum transformations will also be available through an interactive Website, rather than as downloadable software, to enable greater accessibility to the database of applications.

The applications that ultimately benefit from availability of VDatum are numerous. As exemplified by the North Carolina project, VDatum and the high-resolution DEM are being used to examine sea level rise effects, storm surge studies, and biogeophysical models of effects upon ecosystems. Such studies are vital tools to coastal zone management and the mitigation of natural hazards. Other applications include delineation of marine boundaries, circulation studies, and tsunami inundation modeling. A national

VDatum database and associated bathymetric/topographic/shoreline databases enable such applications to have greater confidence in the accuracy and consistency of the data representing the coastal zone transition between water and land.

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## REFERENCES

- Amein, M., and D. S. Airan. 1976. Mathematical Modeling of Circulation and Hurricane Surge in Pamlico Sound, N. C. University of North Carolina Sea Grant Publication UNC-SG-716-12, 202 pp.
- Auer, C., K. Hess, G. Stafanski, R. Stumpf, and E. Turner. 2004. A White Paper on the Ecological Effects of Sea Level Rise: Summary of the February 2004 workshop held in Beaufort, North Carolina. National Ocean Service, National Centers for Coastal Ocean Science, National Oceanic and Atmospheric Administration, Silver Spring, Maryland.
- Foreman, M.G.G., W.R. Crawford, J.Y. Cherniawsky, R.F. Henry and M.R. Tarbotton. 2000. A high-resolution assimilating tidal model for the northeast Pacific Ocean. *Journal of Geophysical Research*. C. Oceans 105(C12), 28629 – 28651.
- Gill, S.K. and J.R. Schultz. 2001. Tidal Datums and Their Applications. NOAA Special Publication NOS CO-OPS 1. 111 p.
- Hess, K.W., 2002. Spatial interpolation of tidal data in irregularly-shaped coastal regions by numerical solution of Laplace's equation. *Estuarine, Coastal and Shelf Science*, 54, 175 – 192.
- Hess, K., 2003. Water level simulation in bays by spatial interpolation of tidal constituents, residual water levels, and datums. *Continental Shelf Research*, 23, 395-414.

Hess, K., D. Milbert, S. Gill, and D. Roman, 2003. Vertical datum transformation for kinematic-GPS hydrographic surveying. U.S. Hydrographic Conference, Biloxi, Mississippi, 24 – 27 March 2003.

Hess, K.W., R.A. Schmalz, C. Zervas, and W.C. Collier. 1999. Tidal Constituent And Residual Interpolation (TCARI): A New Method for the Tidal Correction of Bathymetric Data. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1315 East-West Highway, Silver Spring, Maryland. NOAA Technical Report NOS CS 4, 99 pp.

Hess, K.W., S.A. White, J. Sellars, E.A. Spargo, A. Wong, S.K. Gill, C. Zervas. 2004. North Carolina Sea Level Rise Project: Interim Technical Report. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, NOAA Technical Memorandum NOS CS 5, 25 p.

Luetlich, R.A., J.J. Westerink, and N.W. Scheffner, 1992. ADCIRC: an advanced three-dimensional circulation model of shelves, coasts and estuaries, Report 1: theory and methodology of ADCIRC-2DD1 and ADCIRC-3DL, Technical Report DRP-92-6, Department of the Army, Vicksburg, MS.

Milbert, D.G. and K.W. Hess, 2001. Combination of Topography and Bathymetry through Application of Calibrated Vertical Datum Transformations in the Tampa Bay Region. Proceedings of the Second Biennial Coastal GeoTools Conference, Charleston, South Carolina, 8 – 11 January 2001.

Milbert, D.G., 2002. Documentation for VDatum and VDatum Tutorial: Vertical Datum Transformation Software, Version 1.06.

Mukai, A., J.J. Westerink, R.A. Luetlich and D. Mark. 2001. A Tidal Constituent Database for the Western North Atlantic Ocean, Gulf of Mexico and Caribbean Sea. Technical Report, U.S. Army Engineer Research and Development Center, Vicksburg, MS, September 2001.

Myers, E. P., and A. M. Baptista. 1999. Inversion for tides in the Eastern North Pacific Ocean. *Advances in Water Resources*. 24, 505 – 519.

National Research Council, 2004. *A Geospatial Framework for the Coastal Zone*. The National Academies Press, Washington, D.C., 149 p.

Parker, B., 2001. Where is the shoreline? *Hydro International*, July/August 2001, 6 – 9.

Parker, B., K.W. Hess, D. Milbert, and S. Gill, 2003. A national vertical datum transformation tool. *Sea Technology*, 44 (9), 10 – 15.



Roman, D.R., Y.M. Wang, W. Henning, and J. Hamilton, 2004. Assessment of the New National Geoid Height Model, GEOID03. In *Proceedings of the American Congress on Surveying and Mapping*, Nashville, Tennessee, 16 – 21 April 2004.

Smith, D.A. and D.R. Roman, 2000. Recent Advances in the Acquisition and Use of Terrain Data for Geoid Modelling over the United States, presented at IAG Session G3/W of the IUGG meeting, Birmingham, England, United Kingdom, 8 – 30 July 1999.

Smith, D.A. and D.R. Roman, 2001. GEOID99 and G99SSS: One arc-minute models for the United States. *Journal of Geodesy*, 75, 469 – 490.

Smith, S.M., 2003. The Navigation Surface: A mutlipurpose bathymetric database. Master's thesis, Center for Coastal and Ocean Mapping and National Oceanic and Atmospheric Administration / University of New Hampshire Joint Hydrographic Center.

Smith, S. M., L. Alexander, and A.A. Armstrong, 2002. The Navigation Surface: A new database approach to creating multiple products from high density surveys. *International Hydrographic Review*, 3(2):12 – 26.

Spargo, E., J. Westerink, R. Luetlich, and D. Mark. 2004. Developing a tidal constituent database for the Eastern North Pacific Ocean. In *Proceedings of the 8th International Conference on Estuarine and Coastal Modeling*, Monterey, CA, 3 – 5 November 2003.

Zervas, C., 2004. North Carolina Bathymetry/Topography Sea Level Rise Project: Determination of Sea Level Trend. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, NOAA Technical Report NOS CO-OPS 041, 31 p.