NOAA Technical Memorandum NESDIS NGDC-64

DIGITAL ELEVATION MODELS OF MOREHEAD CITY, NORTH CAROLINA: PROCEDURES, DATA SOURCES AND ANALYSIS

P.R. Grothe
L.A. Taylor
B.W. Eakins
K.S. Carignan
M.R. Love
E. Lim
D.Z. Friday

National Geophysical Data Center
Marine Geology and Geophysics Division
Boulder, Colorado
August 2012

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / National Environmental Satellite, Data, and Information Service

NOAA Technical Memorandum NESDIS NGDC-64

DIGITAL ELEVATION MODELS OF MOREHEAD CITY, NORTH CAROLINA: PROCEDURES, DATA SOURCES AND ANALYSIS

Pamela R. Medley[1]
Lisa A. Taylor[2]
Barry W. Eakins[1]
Kelly S. Carignan[1]
Matthew R. Love[1]
Elliot Lim[1]
Dorothy Z. Friday[1]

[1]Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder

[2]NOAA, National Geophysical Data Center, Boulder, Colorado

National Geophysical Data Center
Marine Geology and Geophysics Division
Boulder, Colorado
August 2012

UNITED STATES DEPARTMENT OF COMMERCE

Rebecca Blank
Acting Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Jane Lubchenco
Under Secretary for Oceans and Atmosphere/Administrator

National Environmental Satellite, Data, and Information Service

Mary E. Kicza
Assistant Administrator

NOTICE

Mention of a commercial company or product does not constitute an endorsement by the NOAA National Environmental Satellite, Data, and Information Service. Use of information from this publication concerning proprietary products or the test of such products for publicity or advertising purposes is not authorized.

Corresponding project contact:
Lisa A. Taylor
NOAA National Geophysical Data Center
Marine Geology and Geophysics Division
325 Broadway, E/GC 3
Boulder, Colorado 80305
Phone: 303-497-6767
Fax: 303-497-6513
E-mail: Lisa.A.Taylor@noaa.gov
http://www.ngdc.noaa.gov/mgg/coastal/

Also available from the National Technical Information Service (NTIS)

Contents

List of Figures

List of Tables

Digital Elevation Models of Morehead City, North Carolina: Procedures, Data Sources and Analysis

1. Introduction

In April 2011 the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed two bathymetric–topographic digital elevation models (DEMs) of Morehead City, North Carolina (Fig. 1). First, a 1/3 arc-second[1] DEM referenced to North American Vertical Datum of 1988 (NAVD 88) was developed and evaluated using diverse digital datasets available for the region (grid boundary and sources shown in Fig. 3). Then, a 1/3 arc-second conversion grid was created to represent the relationship between NAVD 88 and Mean High Water (MHW) vertical datums in the Morehead City region. Finally, a 1/3 arc-second MHW DEM was developed by combining the NAVD 88 DEM and the vertical datum conversion grid. The MHW DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Morehead City DEMs.

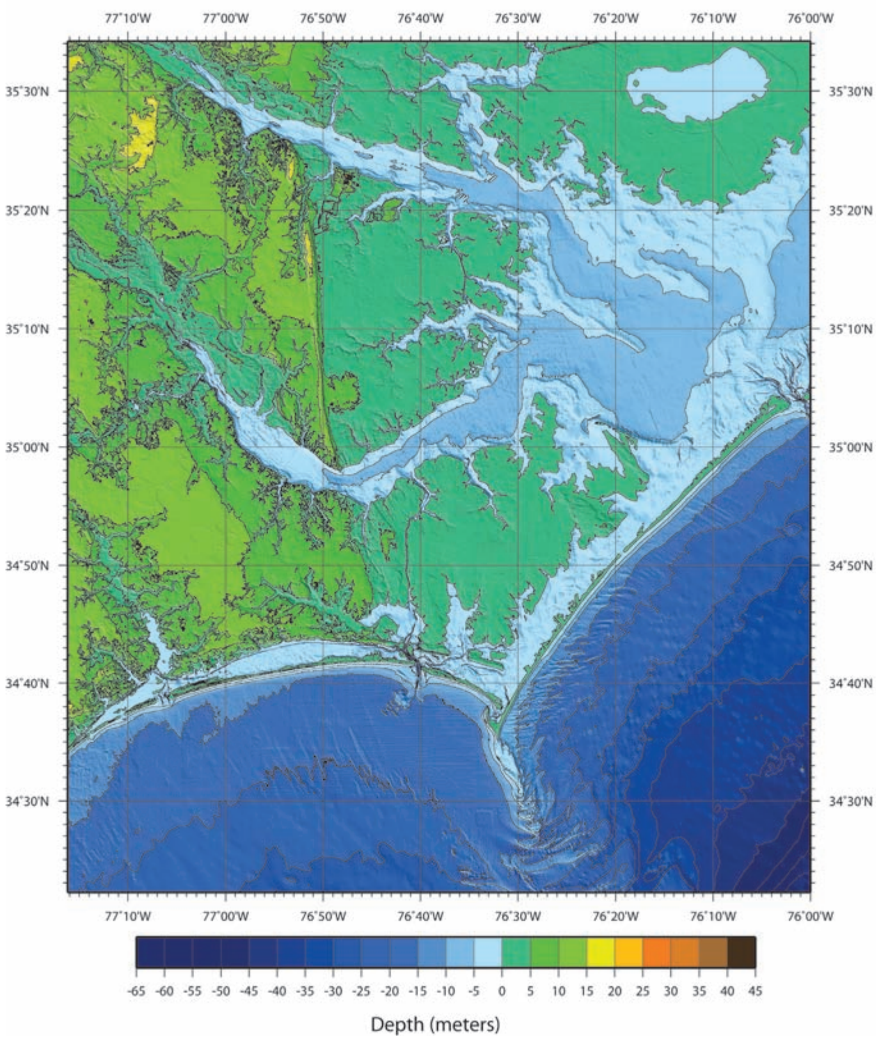

Figure 1. Shaded-relief image of the Morehead City NAVD 88 DEM. Contour interval is 5 meters. Image is in Mercator projection.

1. The Morehead City DEMs are built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems such as UTM zones (in meters). At the latitude of Morehead City, (34°43'23"N, 76°43'34"W) 1/3 arc-second of latitude is equivalent to 10.27 meters; 1/3 arc-second of longitude equals 8.48 meters.

2. Study Area

The Morehead City DEMs were constructed to meet PMEL specifications (Table 1), based on input requirements for the development of Reference Inundation Models (RIMs) and Standby Inundation Models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The DEMs extend from the southern tip of Ocracoke Island, abutting NGDC's Cape Hatteras DEM, to just north of Jacksonville (Table 1; Fig. 2).

The DEM is centered on the port, Morehead City, but also encompasses the adjacent populated towns of Beaufort and Atlantic Beach. Low lying barrier islands dictate this regions dynamic morphology which is constantly changing from year to year. The coastal islands are a popular tourist destination for beach-goers. The back island marsh and the Pamlico Sound seperate the mainland from the barrier islands, limiting the access for each barrier island. Although the region has a small risk for tsunamis, storm surge from hurricanes is a hazard. These hazards make it imperative to have emergency plans in place to evacuate a large population off the islands quickly.

Table 1. Specifications for the Morehead City DEMs

DEM Type	Structured
Grid Area	Morehead City, North Carolina
Coverage Area	76.00º to 77.27º W; 34.37º to 35.57º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Units	Meters
Vertical Datum	a) North American Veritical Datum of 1988(NAVD 88) b) Mean High Water (MHW)
Grid Spacing	1/3 arc-second
Grid Format	ESRI Arc ASCII raster grid

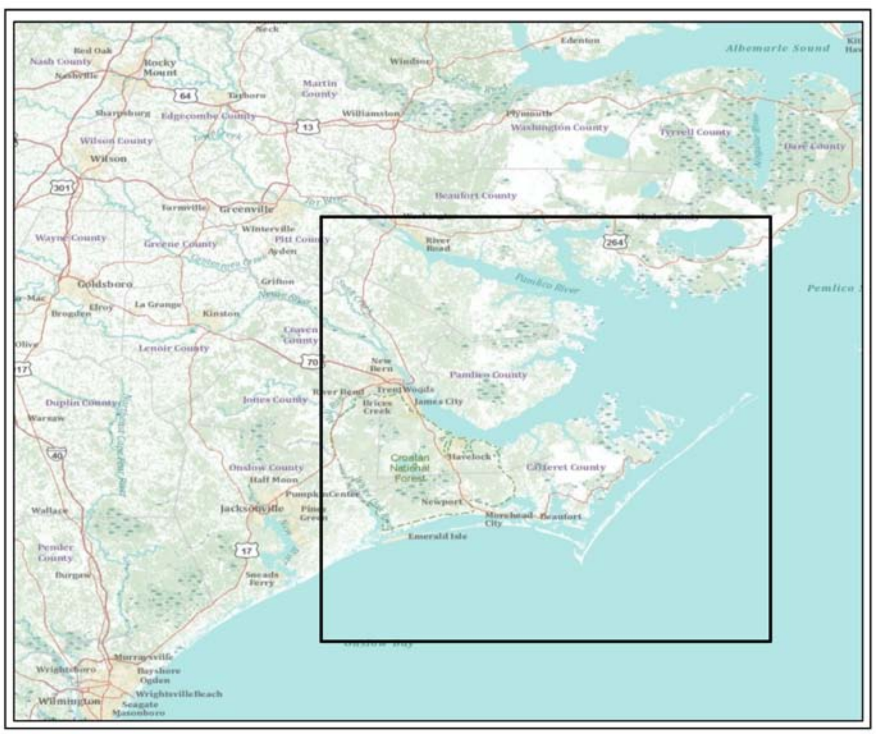

Figure 2. Overview map of the Morehead City, NC DEM region. Black box outlines the 1/3 arc-second DEM boundary. ArcMap 10.0 topographic basemap in backgroud.

3. SOURCE ELEVATION DATA

The best available bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum 1983 (NAD 83)[2] and NAVD 88. Data were gathered in an area slightly larger (5%) than the DEM extents. This data 'buffer' ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

3.1 Data Sources and Processing

Coastline, bathymetric, bathymetric/topographic, and topographic digital datasets (Tables 2, 3, and 4; Fig. 3) were obtained from the following U.S. federal and state agencies: NOAA's NGDC and Coastal Services Center (CSC), U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE), North Carolina Department of Environment and Natural Resources (NCDENR), and North Carolina Division of Emergency Management (NCDEM). Datasets were displayed with Earth Systems Research Institute's (ESRI) *ArcGIS* to assess data quality and manually edit datasets.

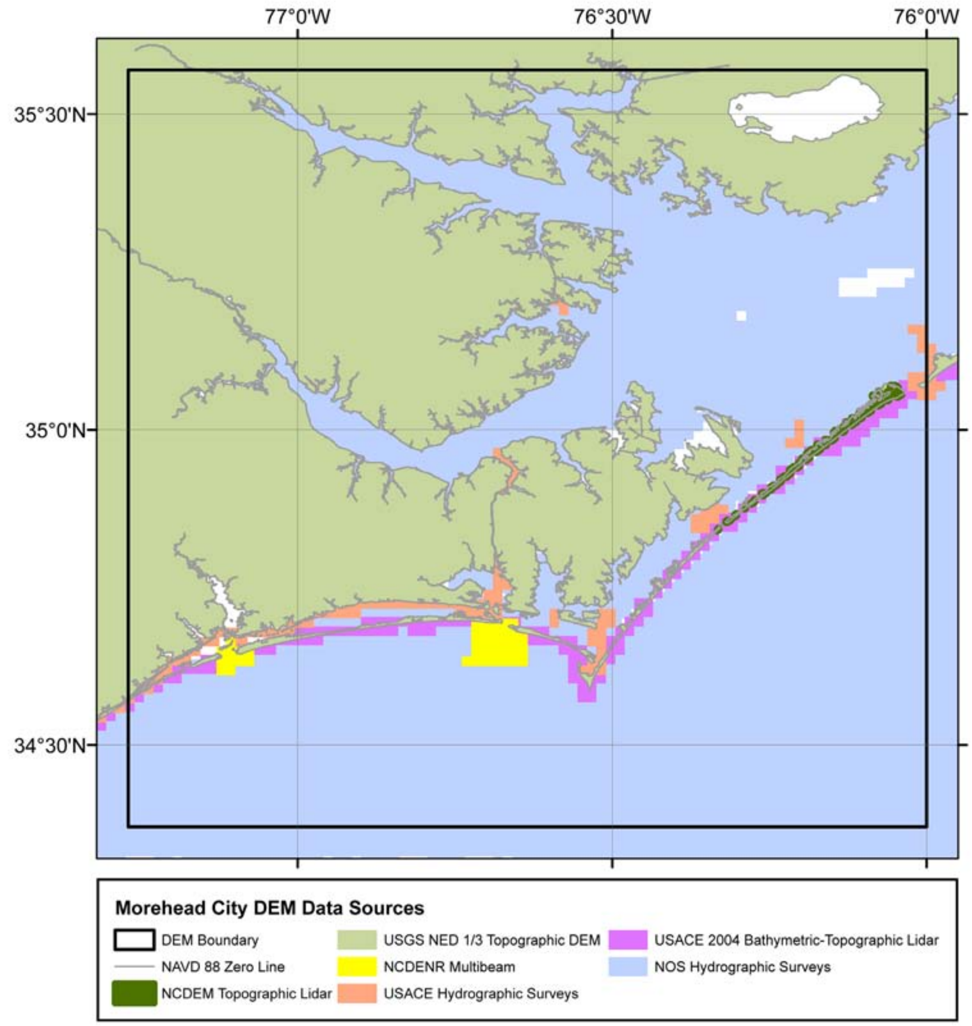

Figure 3. Data sources used in building the 1/3 arc-second Morehead City DEMs. White areas denote no data.

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (1984) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Many GIS applications treat the two datums as identical and do not transform data between them. The error introduced by not converting between the datums is insignificant for NGDC purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the waves passage across ocean basins. This DEM is identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geogprahic. At the scale of the DEM, WGS 84 and NAD 83 are identical and may be used interchangeably.

3.1.1 *Coastline*

Available coastline datasets of the Morehead City region are of low-resolution and are out-of-date compared to the rapidly changing morphology and continual building of coastal engineering structures. To make the most effective coastline for the purpose of clipping elevation data to it, NGDC created a NAVD 88 zero contour line of the USGS NED 1/3 topographic DEM. The NAVD 88 zero contour line was edited to represent the morphology based on *Google Earth* satellite imagery from 2011.

3.1.2 *Bathymetry*

Bathymetric datasets available in the Morehead City region included NOS hydrographic surveys, USACE hydrographic surveys, and NCDENR high-resolution multibeam swath sonar. (Table 2).

Table 2. Bathymetric datasets used in building the Morehead City NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1869 to 2003	NOS hydrographic survey soundings	Ranges from 5 meters to 2 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	Undetermined, United States Standard Datum 1901, NAD 1913 geographic, NAD 1927 geographic, NAD 83 geographic	Local Low Water (LLW), Mean Low Water (MLW) , and Mean Lower Low Water (MLLW) (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NCDENR	2005	Multibeam swath sonar survey	10 feet	NAD 83 geographic	National Geodetic Vertical Datum of 1929 (feet)	N/A
USACE	2002 to 2011	Hydrographic channel surveys	Ranges from 2 and 30 meters	NAD 83 North Carolina State Plane, US foot	MLW (feet)	http://www.saw.usace.army.mil/nav/

1) **National Ocean Service hydrographic survey data**

A total of 94 hydrographic surveys conducted between 1869 and 2003 were available in the Morehead City region (see Appendix A). Surveys were extracted as xyz files using *GEODAS* from NGDC's online NOS Hydrographic database with a buffer 0.05 degrees (~5%) larger than the Morehead City DEM extent to support data interpolation along grid edges. The hydrographic survey data were downloaded with vertical datums referenced to either mean low water (MLW), mean lower low water (MLLW), or local low water (LLW) datum. The surveys were originially refererenced to several horizontal datums (see Table 2) but were transformed to NAD 83 geographic during download by *GEODAS*.

Data point spacing for the NOS surveys varies by collection date. In general, earlier surveys had greater point spacing than more recent surveys. The data were displayed in ESRI's *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to various topographic and bathymetric datasets, the coastline, and Office of Coast Survey (OCS) Raster Nautical Charts (RNCs). Older sounding data were clipped to remove soundings that have been superseded by more recent surveys.

2) **North Carolina Department of Environment and Natural Resources multibeam swath sonar survey**

NCDENR provided NGDC with one multibeam swath sonar survey of Beaufort Inlet. The data were collected by Geodynamics Geologic and Oceanographic Services in June of 2005, contracted by the North Carolina Division of Coastal Managament (NCDCM). The purpose of the survey was to perform a comprehensive hydrographic survey of Beaufort Inlet as part of the Regional Sediment Management plan being implemented by the USACE Wilmington District and NCDCM. The data were provided in an ESRI Arc ASCII grid format with a 10 foot cell size, horizontally referenced to NAD 83 and vertically referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). The data is of high-quality and did not require any editing.

3) **U.S. Army Corp of Engineers hydrgraphic surveys**

USACE hydrographic surveys were available from the Wilmington District. Recent surveys from 2010 and 2011 were downloaded from their navigation project web site. Several areas had not been surveyed in the last year and were not available on the web site. These surveys were provided to NGDC by Adam Faircloth from the USACE Wilmington District. Surveys ranged from 2002 to 2011 and covered the Atlantic Intracoastal Waterway, inlets and crossings, rivers, small harbors, and Morehead City and Beaufort Harbors (see Figure 3). The surveys had an original horizontal datum of NAD 83 North Carolina State Plane, US foot, and an original vertical datum of MLW. Point spacing varied by survey but typically had 5 meter spacing along profile and 30 meter spacing between profile lines.

3.1.3 Bathymetry-Topography

Two bathymetric-topographic datasets were using to build the 1/3 arc-second Morehead City DEMs: NCDENR DEM and CSC's 2004 USACE bathymetric-topographic lidar.

Table 3. Bathymetric-Topographic datasets used in building the Morehead City DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NCDENR	2005	DEM	20 feet	NAD 83 geographic	National Geodetic Vertical Datum of 1929 (feet)	N/A
CSC	2004	XYZ	3 meters	NAD 83 geographic	NAVD 88	http://www.csc.noaa.gov/digitalcoast/

1) **North Carolina Department of Environment and Natural Resources DEM**

NCDENR provided NGDC with a seamless bathymetric-topographic DEM of Bogue Inlet. The data were collected by Geodynamics Geologic and Oceanographic Services in June 2005, contracted by NCDCM. Swath-based multibeam and spatially derived singlebeam sonar were used to generate a DEM surface of the beach topography and seafloor bathymetry. The DEM is also part of the Regional Sediment Management plan being implemented by the USACE Wilmington District and NCDCM. The data were provided in an ESRI Arc ASCII grid format with a 20 foot cell size, horizontally referenced to NAD 83 and vertically referenced to NGVD 29. The DEM is of high-quality and did not require any editing.

2) **Coastal Service Center 2004 US Army Corp of Engineers bathymetric-topographic lidar**

NGDC downloaded USACE 2004 bathymetric-topographic lidar data from the CSC Digital Coast web site. The data were downloaded as xyz files in a horizontal datum of NAD 83 geographic and vertical datum of NAVD 88. NGDC split the negative values from the positive values and created shapefiles for viewing in ArcMap. The topographic values were not used to make the 1/3 arc-second DEM because they are superceded by more recent lidar-derived data (see section 3.1.4) and are not processed to bare earth. The negative values were edited as needed to remove anomolous points and to remove points that overlapped with other bathymetric data sets.

3.1.4 *Topography*

Two topographic datasets were used to build the Morehead City DEMs: USGS NED 1/3 arc-second DEM and NCDEM Floodplain Mapping Program (FPMP) lidar (Tabel 4).

Table 4. Topographic datasets used in building the Morehead DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
USGS	2009	Bare earth topographic DEM	10 meters	NAD 83 geographic	NAVD 88	http://ned.usgs.gov/
NCDEM	2001	Topographic lidar	5 meters	NAD 83, North Carolina State Plane (feet)	NAVD 88 (feet)	http://www.ncfloodmaps.com/

1) US Geological Survey 1/3 arc-second National Elevation Dataset DEM

USGS NED topographic DEM provides complete 1/3 arc-second coverage of the Morehead City DEM coverage area. The data were downloaded from the USGS web site as raster DEMs in NAD 83 geographic and NAVD 88 horizontal and vertical datums. The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters, respectively, but are most likely more accurate than that in low elevation areas. The dataset was derived from lidar data collected for the North Carolina Department of Transportation (NCDOT) in 2007.

2) North Carolina Department of Emergency Management, Floodplain Mapping Program Lidar

The NCDEM-FPMP was established in response to the extensive damage caused by the Hurricane Floyd in 1999, and these data were collected as part of its effort to modernize FEMA Flood Insurace Rate Maps statewide. The data, downloaded in ESRI Arc ASCII grid format, were collected at 5-meter nominal post spacing and referenced to NAD 83 North Carolina State Plane and NAVD 88 horizontal and vertical datums. Only a small section of the data along the northern barrier islands was used to fill gaps in the NED 1/3 arc-second DEM for building the final DEM.

3.2 Establishing Common Datums

3.2.1 *Horizontal datum transformations*

Datasets used to build the Morehead City DEM were downloaded referenced to NAD 83 geographic and NAD 83 North Carolina State Plane (feet). The relationships and transformational equations between the geographic horizontal datums are well established. Transformations to NAD 83 geographic were accomplished using *FME* software or *ArcGIS's* reproject tool.

3.2.2 *Vertical datum transformations*

1) Bathymetric data

Bathymetric datasets used to build the Morehead City DEMs were referenced to MLLW, MLW, LLW and NGVD 29 vertical datums. All hydrographic surveys were transformed to NAVD 88 by adding the xyz data to conversion grids created with *VDatum* (see section 4.3.1 for conversion grid methodology and Appendix B). *VDatum* does not recognize LLW as a vertical datum in North Carolina, therefore data referenced to the LLW vertical datum required an initial transformation to mean sea level (MSL) by adding a constant offset of 0.15 meters from LLW to NAVD 88 (Dr. Kurt Hess, NOAA Office of Coast Survey, Kurt.Hess@noaa.gov, personal communication). Data in NGVD 29 vertical datum were transformed to NAVD 88 directly using *VDatum* software.

2) Topographic data

Topographic datasets used to build the Morehead City DEMs were referenced to NAVD 88 and NGVD 29. Data in NGVD 29 vertical datum were transformed to NAVD 88 directly using *VDatum* software. No further transformations were required for datasets already referenced NAVD 88.

3.2.3 Verifying transformations and consistency between datasets

After horizontal and vertical transformations were applied, dataset were checked for consistency and problems and errors were resolved before proceeding with subsequent gridding steps. All datasets were converted to xyz files using *GDAL* in preparation for gridding.

4. Digital Elevation Model Development

4.1 Smoothing of bathymetric data

The NOS hydrographic survey data are generally sparse relative to the resolution of the 1/3 arc-second Morehead City DEMs. In order to reduce the effect of artifacts in the DEM by low-resolution NOS datasets, and to provide effective interpolation from the deep water into the coastal zone, a 1/3 arc-second-spacing 'pre-surface' bathymetric grid was generated using *Generic Mapping Tools (GMT)*[3]. The coastline elevation value was set to -1 meters to ensure a bathymetric surface below zero in areas where data are sparse or non-existent along the coast.

The point data were median-averaged using the *GMT* command 'blockmedian' to create a 1/3 arc-second grid 0.05 degrees (~5%) larger than the Morehead City DEM gridding region. The *GMT* command 'surface' was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created was converted into an ESRI Arc ASCII grid file, and clipped to the NAVD 88 zero line to eliminate data interpolation into land areas. The resulting surface was compared with original soundings to ensure grid accuracy (Fig. 4) and then exported as an xyz file for use in the final gridding process.

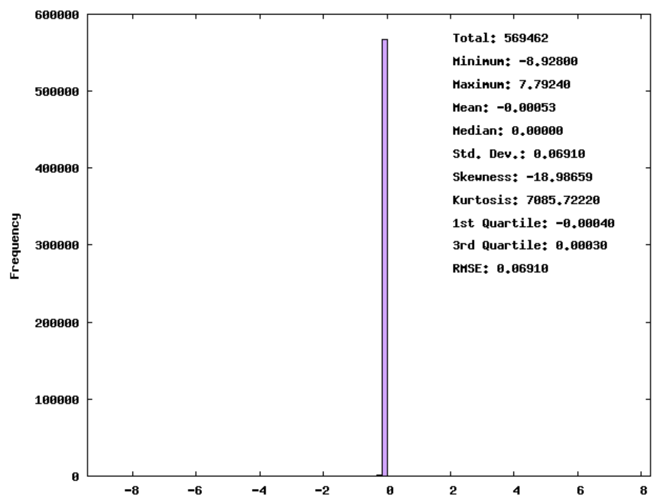

Figure 4. Histogram of the differences between the NOS hydrographic soundings and the Morehead City bathymetric surface.

4.2 Smoothing of topographic data

The topographic data were generally inconsistent along the coast because of morphologic change. Also, some low lying islands in the sound where not included in the flight path of acquired lidar data used to build the Morehead City DEM. In order to created a smooth topographic surface to the coastline and create positive elevations to the islands with missing data, a 1/3 arc-second-spacing 'pre-surface' topographic grid was generated using *GMT*. The coastline was set to 0.5 meters to ensure the topographic surface had values above zero in areas where no data existed. See section 4.1 for more details on the methodology.

3. *GMT* is an open source collection of ~60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. *GMT* supports ~30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. *GMT* is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest.hawaii.edu/ [Extracted from *GMT* web site.]

4.3 Building the NAVD 88 DEM

MB-System was used to create the 1/3 arc-second Morehead City square-cell NAVD 88 DEM. The *MB-System* tool 'mbgrid' was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 5. The resulting binary grid was converted to an Arc ASCII grid using the *MB-System* tool 'mbm_grd2arc' to create the final 1/3 arc-second Morehead City NAVD 88 DEM. Figure 5 illustrates cells in the DEM that have interpolated values (shown in white) versus data contributing to the cell value (shown in black).

Table 5. Data hierarchy used to assign gridding weight in *MB-System*.

Dataset	*Relative Gridding Weight*
NCDENR multibeam	10
NCDENR bathy/topo DEM	10
NCDEM topographic lidar	10
USACE hydrographic surveys	10
CSC USACE bathy/topo lidar	10
USGS NED DEM	10
NOS hydrographic surveys	1
Pre-surface bathymetric grid	0.1
Pre-surface topographic grid	0.1

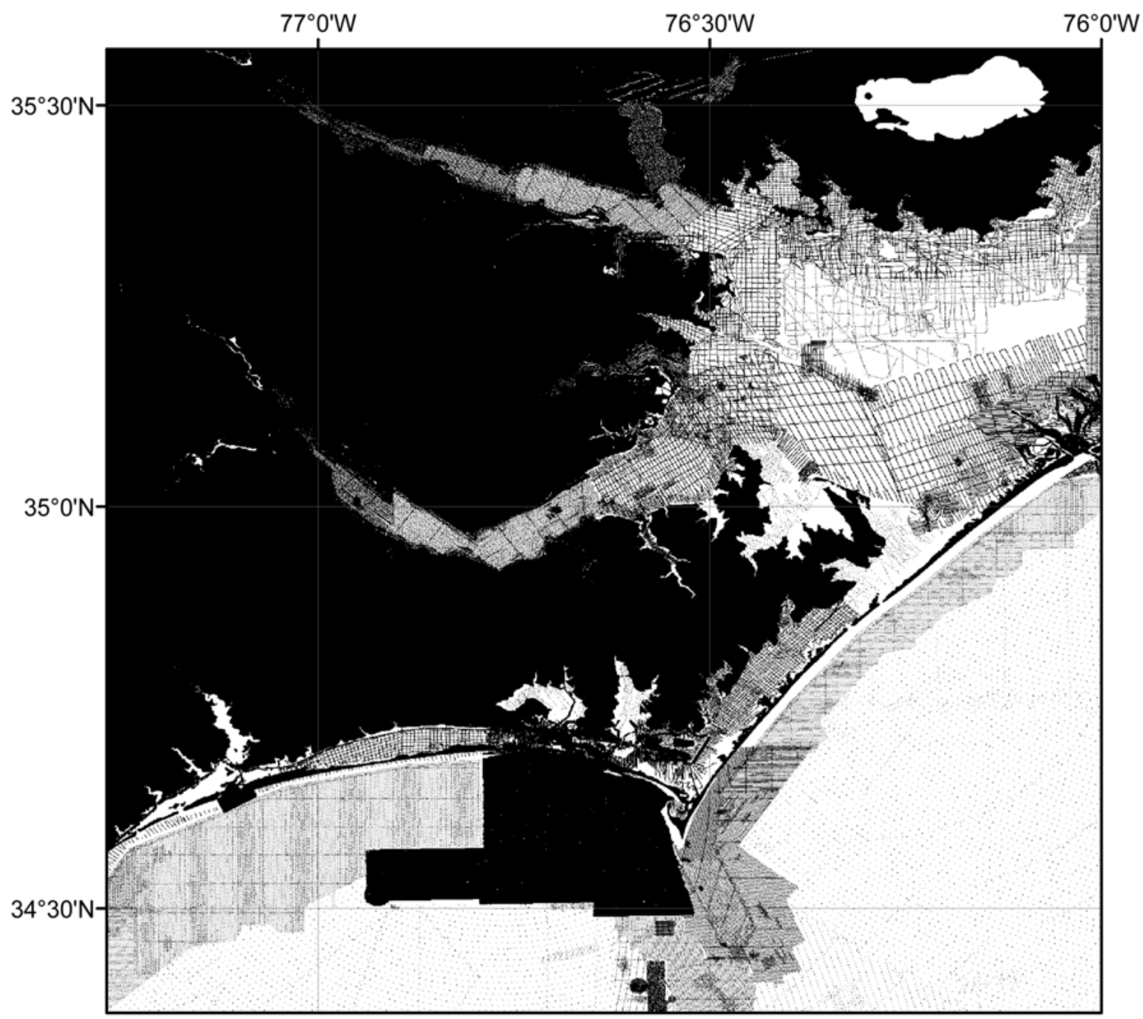

Figure 5. Data density of the Morehead City NAVD 88 DEM; areas where source data were available are depicted in black; areas where grid interpolation was necessary are depicted in white.

4.4 Building the MHW DEM

The MHW DEM was created by adding a 'NAVD 88 to MHW' conversion grid to the NAVD 88 DEM.

4.4.1 Developing the conversion grid

Using extents slightly larger (~5%) than the Morehead City NAVD 88 DEM, an intial xyz file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. The elevation value at each of the points was set to zero. The *GMT* command 'surface' applied a tension spline to interpolate cell values making a zero-value 3 arc-second grid. This zero-grid was then converted to an intermediate xyz file using the *GMT* command 'grd2xyz'. Conversion values from NAVD 88 to MHW at each xyz point were generated using *VDatum* and the null values were removed. The median-averaged xyz file was then interpolated with the *GMT* command 'surface' to create the 1/3 arc-second 'NAVD 88 to MHW' conversion grid with the extents of the Morehead City project area (note that conversion grids from MLLW and MLW to NAVD 88 were created using this same methodology to convert vertical datums of the data to NAVD 88).

4.4.2 Creating the MHW DEM

Once the NAVD 88 DEM was completed and assessed for errors, the conversion grid was added to the NAVD 88 DEM. The resulting MHW DEM was reviewed and assessed using RNCs, USGS topographic maps, and ESRI ArcMap 10.0 imagery.

4.5 Quality Assessment of the DEMs

4.5.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Morehead City DEMs is dependent upon the datasets used to determine corresponding DEM cell values and the cell size of the DEM. The horizontal accuracy is 10 meters for the topographic data. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions have an accuracy approaching that of sub-aerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings, potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys, and by the morphologic change that occurs in this dynamic region.

4.5.2 Vertical accuracy

Vertical accuracy of the Morehead City DEMs are also highly dependent upon the source datasets contributing to DEM cell values. The USGS NED topographic DEM has an estimated vertical accuracy of 7 to 15 meters but is most likely less for low lying areas like Morehead City. Bathymetric areas have an estimated accuracy of between 0.1 meters and 5% of water depth. Those values were derived from the wide range of input data sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations.

4.5.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Morehead City NAVD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 6). The DEM was transformed to UTM Zone 18 North coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the UTM-transformed DEM was accomplished using ESRI *ArcScene.* Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 7 shows a perspective view image of the 1/3 arc-second Morehead City NAVD 88 DEM in its final version.

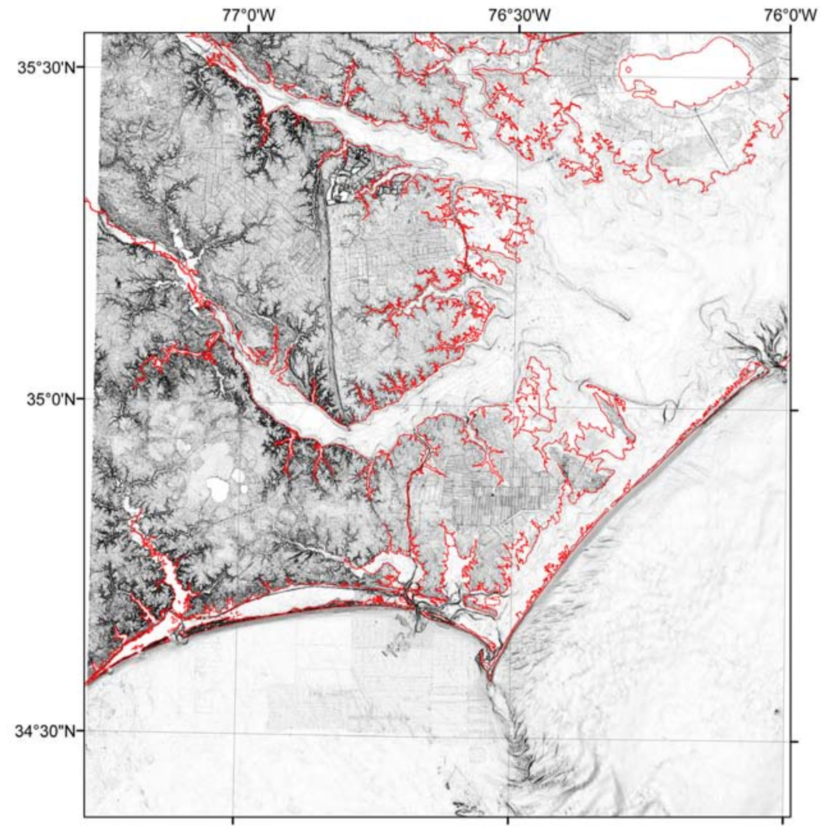

Figure 6. Slope map of the Morehead City NAVD 88 DEM. Flat-lying slopes are white; dark shading denotes steep slopes. NAVD 88 zero line in red.

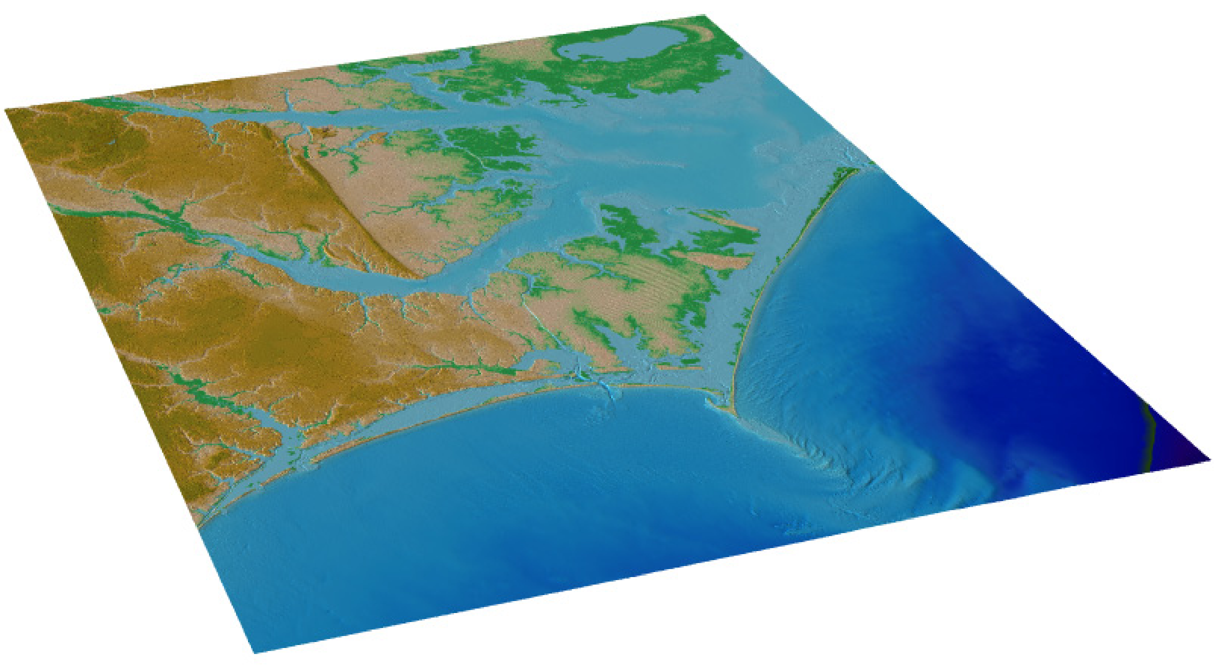

Figure 7. Perspective view from the southeast of the Morehead City NAVD 88 DEM. Ten times vertical exaggeration.

4.5.4 *Comparison of the NAVD 88 DEM with source data files*

To ensure grid accuracy, the Morehead City NAVD 88 DEM was compared to source data files. All bathymetric and topographic source data were compared to the Morehead City NAVD 88 DEM using *Python*, *GDAL*, and *Gnuplot*. Histograms of the differences between individual datasets and the Morehead City NAVD 88 DEM mostly cluster around zero. Largest differences between source datasets and the DEM resulted from the averaging of multiple topographic source datasets where data coverage overlapped (i.e. Fig. 8 and Fig. 9).

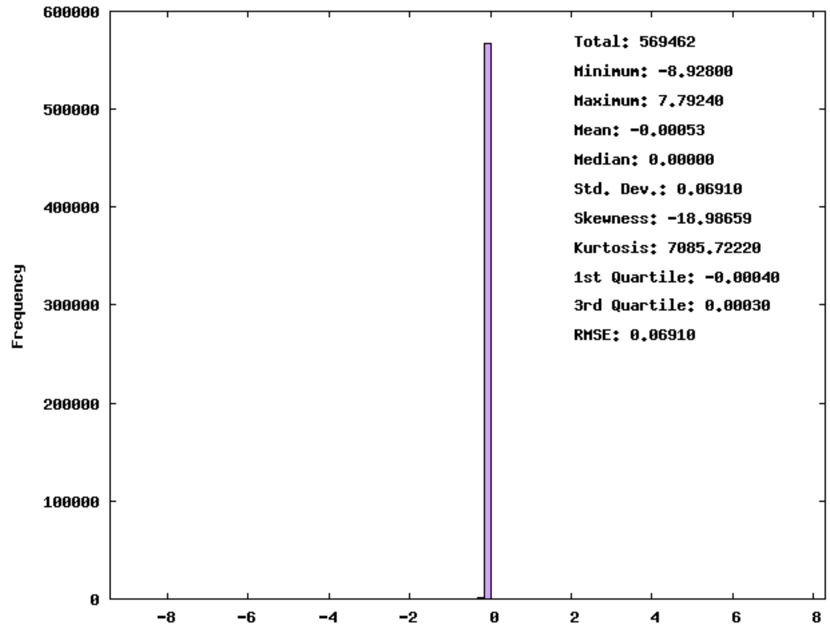

Figure 8. Histogram of the differences between the NOS hydrographic surveys dataset and the Morehead City NAVD 88 DEM.

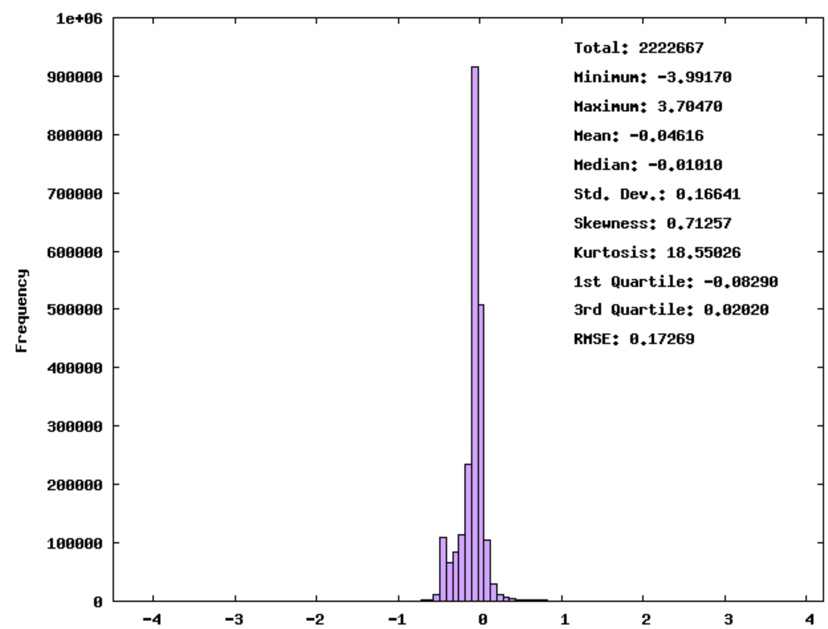

Figure 9. Histogram of the differences between the USGS NED 1/3 arc-second topographic DEM and the Morehead City NAVD 88 DEM.

4.5.5 Comparison with National Geodetic Survey geodetic monuments

The elevations of NOAA National Geodetic Survey (NGS) geodetic monuments (Fig. 10) were extracted from online shapefiles of NGS Geodetic monument datasheets (http://www.ngs.noaa.gov/) which give monument positions in NAD 83 (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Monuments with conditions noted as 'GOOD' or 'MONUMENTED' were only included in the analysis. Monument elevations were compared with elevations of the Morehead City NAVD 88 DEM. Differences between the Morehead City NAVD 88 DEM and the NGS geodetic monument elevations range from -4 to 43 meters, with the majority of them being with +/-1 meter (Fig. 11). Negative values indicate that the monument elevation is less than the DEM elevation. After examination, it was determined that those monuments with the largest deviations do not represent ground surface as they are located on top of an observation tower, light house, or at the apex of other structures.

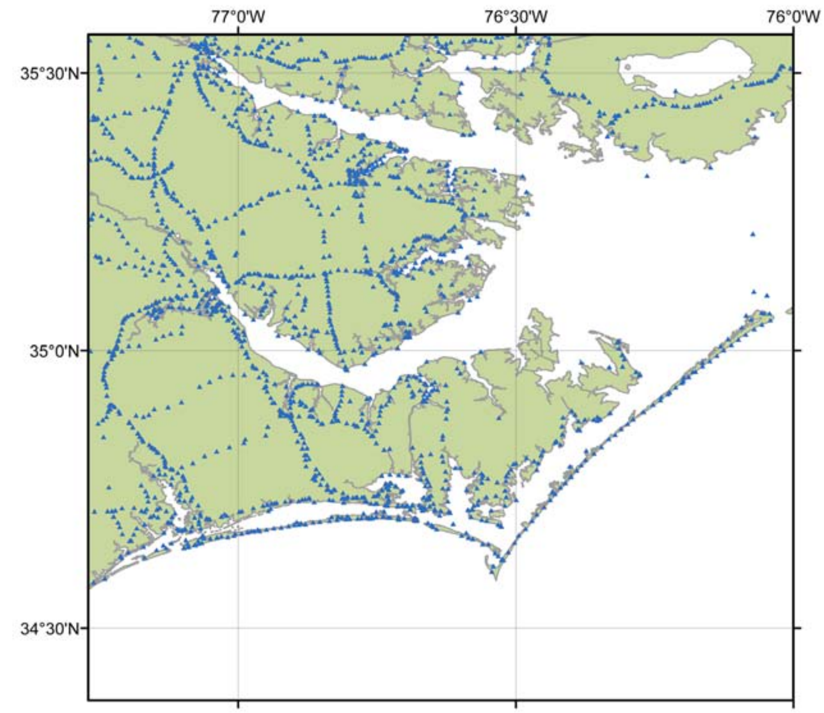

Figure 10. Location of NGS geodetic monuments in the Morehead City region.

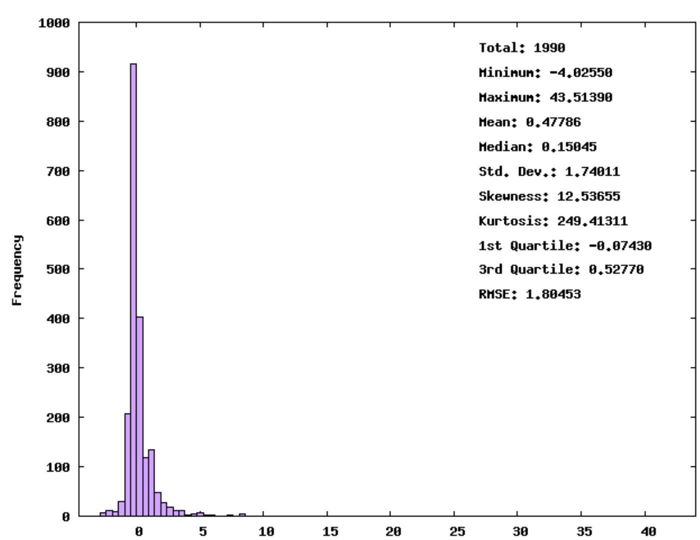

Figure 11. Histogram of the differences between NGS geodetic monument elevations and the Morehead City NAVD 88 DEM.

5. Summary and Conclusions

Two 1/3 arc-second bathymetric–topographic square-cell DEMs of the Morehead City region, one vertically referenced to NAVD 88 and the other to MHW, were developed for the purpose of modeling tsunami inundation and to support other coastal management activities. The best available digital data from U.S. federal, state, and local agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI *ArcGIS*, *FME*, *GMT*, *MB-System*, *QT Modeler*, *GDAL*, *Proj4*, and *Gnunplot* software. *VDatum* was utilized throughout the development to transform data to common vertical datums. Futhermore, NGDC developed a conversion grid derived from *VDatum* that transformed source data to NAVD 88 and the Morehead City NAVD 88 DEM to MHW.

Recommendations to improve the Morehead City DEMs, based on NGDC's research and analysis, include:

- Conduct high-resolution shallow-water bathymetric multibeam surveys to replace late 18th and early 19th century survey.
- Conduct bathymetric-topographic lidar surveys of the near-shore regions to allow for a smooth transition from the bathymetric data to the topographic data.

6. Acknowledgments

The developement of the Morehead City DEMs was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL). The authors would also like to thank Ken Richardson from NCDENR and Adam Faircloth from USACE, for providing NGDC with data not available online.

7. References

Love, M. R., R.J. Caldwell, K.S. Carignan, B.W. Eakins, L.A. Taylor, 2010: Digital Elevation Models of Southern Louisiana: Procedures, Data Sources, and Analysis.

Nautical Chart #13003 (RNC), 50th Edition, 2010. Cape Sable to Cape Hatteras. Scale 1:1,200,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #12200 (RNC), 49th Edition, 2007. Cape May to Cape Hatteras. Scale 1:419,706. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11555 (RNC), 40th Edition, 2006. Cape Hatteras Wimble Shoals to Ocracoke Inlet. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11554 (RNC), 16th Edition, 2001. Pamlico River. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11552 (RNC), 50th Edition, 2010. Neuse River and Upper Part of Bay River. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11550 (RNC), 29th Edition, 2004. Ocracoke Inlet and Part of Core Sound. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11548 (RNC), 40th Edition, 2005. Pamlico Sound - Western Part. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11547 (RNC), 37th Edition, 2007. Morehead City Harbor. Scale 1:15,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11545 (RNC), 63rd Edition, 2008. Beaufort Inlet and Part of Core Sound. Scale 1:40,000. U.S.

Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11544 (RNC), 39th Edition, 2005. Portsmouth Island to Beaufort. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11543 (RNC), 23rd Edition, 2005. Cape Lookout to New River. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11542 (RNC), 17th Edition, 2008. New River. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11542 (RNC), 39th Edition, 2001. Neuse River to Myrtle Grove Sound. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

8. Data Processing Software

ArcGIS v. 10.0 – developed and licensed by ESRI, Redlands, California, Hhttp://www.esri.com/H

FME 2010 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, Hhttp://www.safe.com/.

GDAL v. 1.7.1 – Geogrpahic Data Abstraction Library is a translator library maintained by Frank Warmerdam, http://gdal.org/.

GEODAS v. 5 – Geophysical Data System, freeware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, Hhttp://www.ngdc.noaa.gov/mgg/geodas/.

GMT v. 4.3.4 – Generic Mapping Tools, freeware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, Hhttp://gmt.soest.hawaii.edu/H

Gnunplot v. 4.2, free software developed and maintained by Thomas Williams, Colin Kelley, Russell Lang, Dave Kotz, John Campbell, Gershon Elber, Alexander Woo, http://www.gnuplot.info/.

MB-System v. 5.1.0 – software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, Hhttp://www.ldeo.columbia.edu/res/pi/MB-System/.

Proj4 v. 4.7.0, free software developed by Gerald Evenden and maintained by Frank Warmerdam, http://trac.osgeo.org/proj/.

Python v. 2.4.3, Python is a remarkable pwerful dynamic programming lanuage that is used in a wide variety of application domains. Python is free software, http://python.org/.

Quick Terrain Modeler v. 7.0.0 – LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, Hhttp://www.appliedimagery.com/H

VDatum Transformation Tool, developed and maintained by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Poducts and Services (CO-OPS), http://vdatum.noaa.gov/.

Appendix A. NOS Hydrographic Surveys

Table A1. NOS hydrographic surveys available in the Morehead City, NC region

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
F00247	1983	20,000	MLLW	NAD 1927 geographic
F00447	1998	10,000	MLLW	NAD 83 geographic
H01010	1869	20,000	LLW	Undetermined
H01083	1870	40,000	MLW	Undetermined
H01088	1870	20,000	LLW	Undetermined
H01226A	1874	20,000	LLW	United States Standard Datum 1901
H10222B	1874	20,000	LLW	NAD 1913
H01227	1874	40,000	LLW	Undetermined
H01254	1875	20,000	LLW	Undetermined
H01316B	1876	20,000	LLW	Undetermined
H01348	1877	20,000	LLW	Undetermined
H01846	1886	10,000	MLW	Undetermined
H01848	1886	10,000	MLW	Undetermined
H01850	1886	10,000	MLW	Undetermined
H01853	1886	10,000	MLW	Undetermined
H01854	1886	10,000	MLW	Undetermined
H01855	1886	10,000	MLW	Undetermined
H01858	1886	10,000	MLW	Undetermined
H01859	1886	10,000	MLW	Undetermined
H01867	1887	20,000	MLW	Undetermined
H03529	1913	20,000	LLW	NAD 1913 geographic
H03530	1913	10,000	LLW	NAD 1913 geographic
H03531	1913	10,000	LLW	NAD 1913 geographic
H03902	1916	20,000	LLW	NAD 1913 geographic
H03922	1916	20,000	LLW	NAD 1913 geographic
H04149	1920	20,000	LLW	NAD 1913 geographic
H04150	1920	20,000	LLW	North American Datum 1913
H04151	1920	10,000	LLW	NAD 1913 geographic
H04696	1926	40,000	MLW	Undetermined
H04734	1927	10,000	MLW	NAD 1913 geographic
H04767	1927	40,000	MLW	Undetermined
H04778	1927	20,000	LLW	NAD 1913 geographic
H05277	1933	10,000	MLW	NAD 1927 geographic

NOS Survey ID	Year of Survey	Survey Scale	Original Horizontal Datum	Original Vertical Datum
H05697	1935	10,000	LLW	NAD 1927 geographic
H05829	1935	10,000	LLW	NAD 1927 geographic
H05847	1935	10,000	LLW	NAD 1927 geographic
H05856	1935	10,000	LLW	NAD 1927 geographic
H05873	1935	10,000	LLW	NAD 1927 geographic
H05874	1935	10,000	LLW	NAD 1927 geographic
H05876	1935	10,000	LLW	NAD 1927 geographic
H05903	1935	10,000	LLW	NAD 1927 geographic
H05904	1935	10,000	LLW	NAD 1927 geographic
H05905	1935	10,000	LLW	NAD 1927 geographic
H05911	1935	10,000	LLW	NAD 1927 geographic
H05918	1935	10,000	LLW	NAD 1927 geographic
H05919	1935	10,000	LLW	NAD 1927 geographic
H05926	1935	10,000	LLW	NAD 1927 geographic
H05941	1935	10,000	LLW	NAD 1927 geographic
H05946	1935	10,000	LLW	NAD 1927 geographic
H05950	1935	10,000	LLW	NAD 1927 geographic
H05961	1935	10,000	LLW	NAD 1927 geographic
H05962	1935	20,000	LLW	NAD 1927 geographic
H05963	1935	10,000	LLW	NAD 1927 geographic
H05996	1935	10,000	LLW	NAD 1927 geographic
H05997	1936	10,000	LLW	NAD 1927 geographic
H05998	1936	10,000	LLW	NAD 1927 geographic
H05999	1936	10,000	LLW	NAD 1927 geographic
H06798	1943	10,000	MLW	NAD 1927 geographic
H06834	1943	10,000	MLW	NAD 1927 geographic
H06835	1943	20,000	LLW	NAD 1927 geographic
H06836	1943	10,000	LLW	NAD 1927 geographic
H07963	1952	12,500	MLW	NAD 1927 geographic
H07964	1953	10,000	LLW	NAD 1927 geographic
H08246*	1955	40,000	MLW	NAD 1927 geographic
H08247*	1955	20,000	MLW	NAD 1927 geographic

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
H08253*	1955	10,000	MLW	NAD 1927 geographic
H08291	1956	10,000	MLW	NAD 1927 geographic
H08564*	1960	5,000	MLW	NAD 1927 geographic
H08766	1962	10,000	MLW	NAD 1927 geographic
H09042	1969	20,000	MLW	NAD 1927 geographic
H09043	1969	20,000	MLW	NAD 1927 geographic
H09044	1969	80,000	MLW	NAD 1927 geographic
H09060	1969	80,000	MLW	NAD 1927 geographic
H09421	1974	10,000	MLW	NAD 1927 geographic
H09426	1974	40,000	MLW	NAD 1927 geographic
H09427	1974	40,000	MLW	NAD 1927 geographic
H09431*	1974	5,000	MLW	NAD 1927 geographic
H09432	1974	5,000	MLW	NAD 1927 geographic
H09433*	1974	5,000	LLW	NAD 1927 geographic
H09434	1974	5,000	MLW	NAD 1927 geographic
H09450	1974	40,000	MLW	NAD 1927 geographic
H09451	1974	40,000	MLW	NAD 1927 geographic
H09464	1974	20,000	MLW	NAD 1927 geographic
H09465	1974	20,000	MLW	NAD 1927 geographic
H09821*	1979	20,000	LLW	NAD 1927 geographic
H09863	1980	20,000	LLW	NAD 1927 geographic
H10824	1998	10,000	MLLW	NAD 83 geographic
H10825	1998	10,000	MLLW	NAD 83 geographic
H10826	1998	10,000	MLLW	NAD 83 geographic
H10827	1998	10,000	MLLW	NAD 83 geographic
H10832	1998	10,000	MLLW	NAD 83 geographic
H10844	1998	10,000	MLLW	NAD 83 geographic
H10845	1998	10,000	MLLW	NAD 83 geographic
H11285	2003	20,000	MLLW	NAD 83 geographic

*indicates data were not used due to poor quality or overlapped by more recent survey

Appendix B. Vertical Datum Conversion Grids

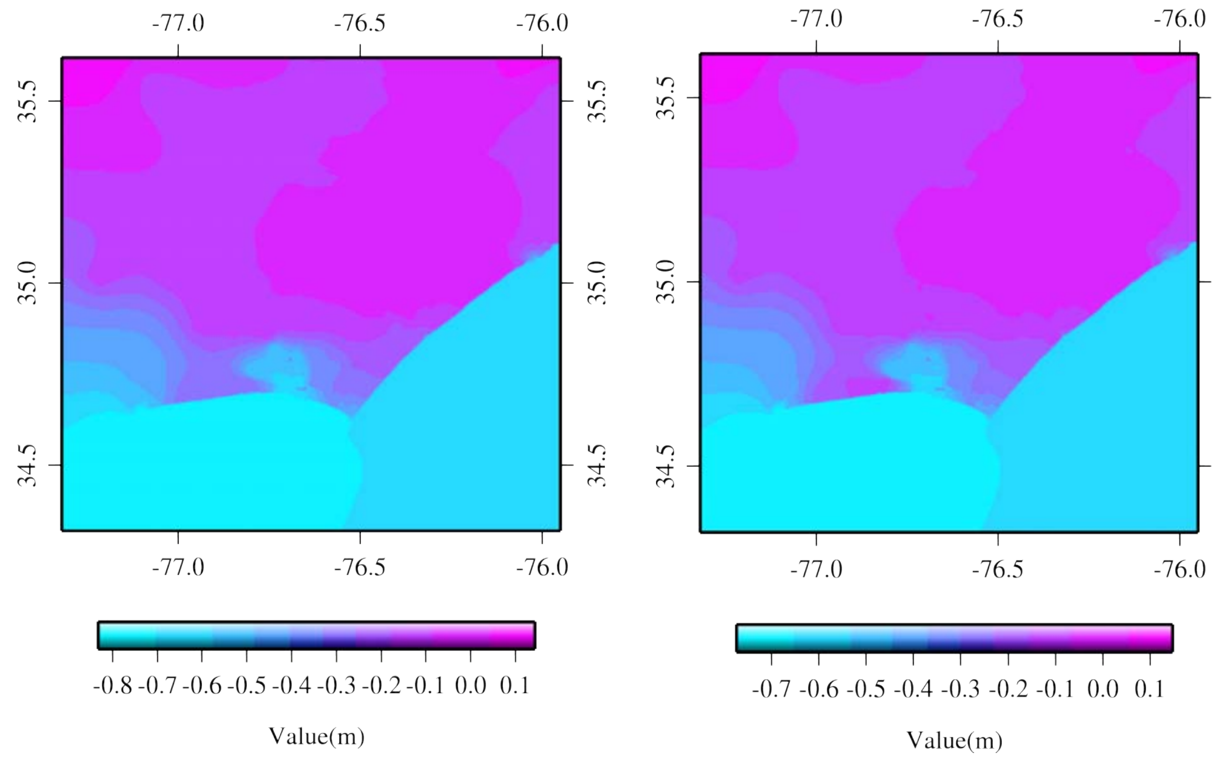

Figure B1. Elevation conversion values of the a) 'MLLW to NAVD 88' conversion grid and b) "MLW to NAVD 88" derived from VDatum. Values equal difference between MLLW and NAVD 88. These grids were used to convert source bathymetric data to NAVD 88.

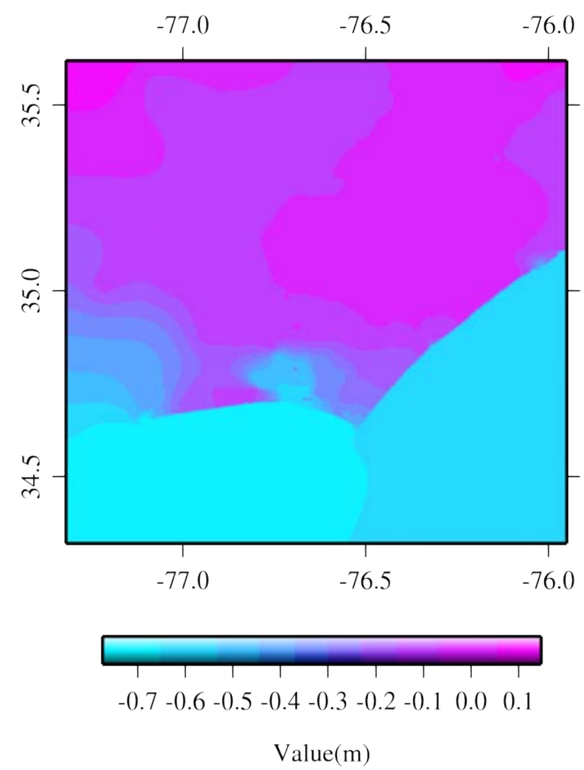

Figure B2. Elevation conversion values of the 'NAVD 88 to MHW' conversion grid derived from VDatum. Values equal difference between NAVD and 88 and MHW. This grid was used to convert the NAVD 88 grid to MHW.

[Page left intentionally blank]

[Page left intentionally blank]