NOAA Technical Memorandum NESDIS NGDC-2

DIGITAL ELEVATION MODEL OF CAPE HATTERAS, NORTH CAROLINA: PROCEDURES, DATA SOURCES AND ANALYSIS

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Digital Elevation Model of Cape Hatteras, North Carolina: Procedures, Data Sources and Analysis

1. Introduction

In July 2006, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a bathymetric/topographic digital elevation model (DEM) of Cape Hatteras, North Carolina (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). A 1/3 arc-second (~10 meter) elevation grid was generated from numerous, diverse digital datasets in the region (grid boundary and sources shown in Fig. 2). The grid will be used as input for the Method of Splitting Tsunami (MOST) Model (http://www.pmel.noaa.gov/pubs/PDF/tito1927/tito1927.pdf) developed by PMEL to simulate tsunami generation, propagation and inundation. An intermediate 9 arc-second bathymetric grid of the East Coast previously developed by NGDC, will also be used as input to the MOST Model. This report provides a summary of the data sources and methodology used in developing the Cape Hatteras DEM.

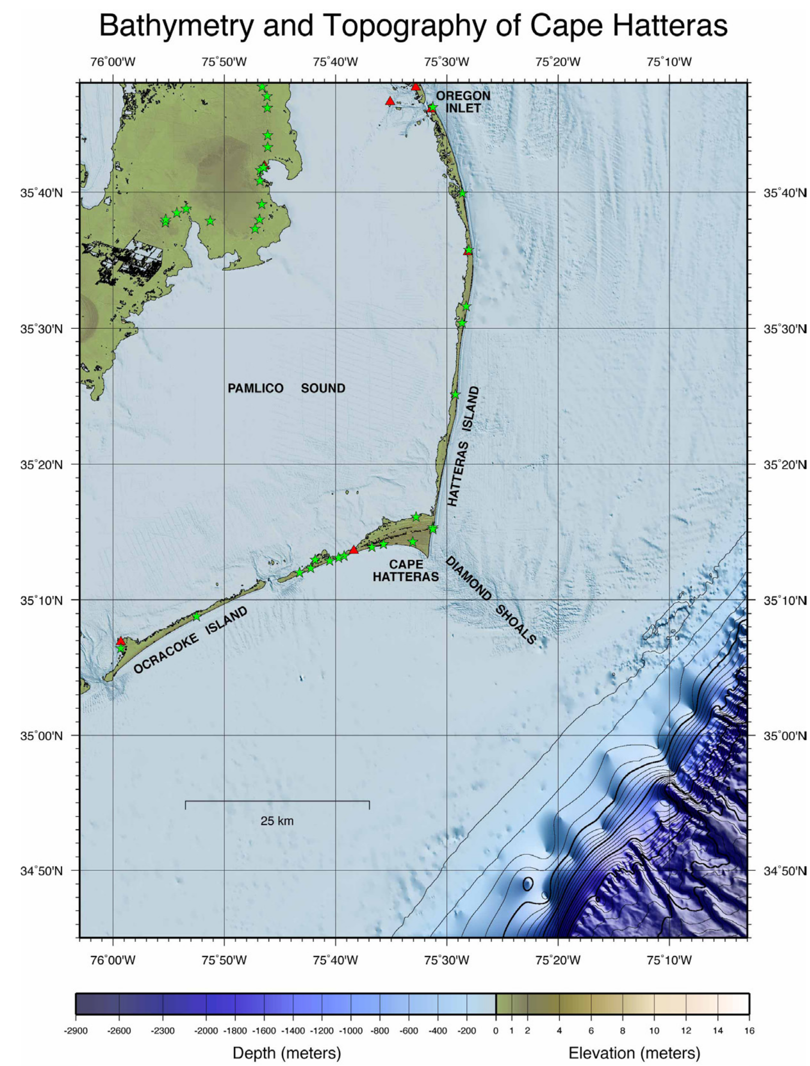

Figure 1. *Shaded-relief image, derived from the DEM, of the Cape Hatteras, North Carolina area. Red triangles locate tidal bench marks listed in Table 7; green stars locate USGS bench marks listed in Table 8. Contour interval (referenced to MHW): 5 meters subaerial, 500 meters submarine.*

2. Study Area

The study area covers the coastal community of Cape Hatteras, North Carolina, located on Hatteras Island, a low, sandy, barrier bar between the Atlantic Ocean and Pamlico Sound. The Cape Hatteras National Seashore spans 30,319 acres, and includes Hatteras, Bodie, and Ocracoke islands. It is one of the largest stretches of undeveloped seashore on the U.S. Atlantic coast. Diamond Shoals, on the seaward side of Cape Hatteras, is referred to as the 'Graveyard of the Atlantic', as the cape experiences frequent storms that drive ships landward toward dangerous shallow depths. National Ocean Service (NOS) nautical charts designate this area as hazardous to all watercraft and therefore is not thoroughly surveyed. Cape Hatteras Lighthouse, built in 1870, was removed in 1936 due to heavy beach erosion. A new lighthouse structure stands farther inland.

3. Methodology

The Cape Hatteras DEM was developed to meet PMEL required specifications (Table 1), based on input requirements for the MOST inundation model. The best available data were obtained by NGDC and used to produce the grid. Data processing, grid assembly, and quality assessment are described in the following subsections.

Table 1: PMEL specifications for the Cape Hatteras, North Carolina grid.

Grid Area	Cape Hatteras, North Carolina
Coverage Area	75.05º to 76.05º W; 34.75º to 35.80º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System (WGS84)
Vertical Datum	Mean High Water
Vertical Units	Meters
Grid Spacing	1/3 arc-seconds
Grid Format	ASCII raster grid

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic data (Fig. 2) were obtained from numerous federal and state government agencies, and universities, including: the NOAA National Ocean Service (NOS) and Office of Coast Survey (OCS); the U.S. Army Corps of Engineers (USACE); the University of New Hampshire's Center for Coastal and Ocean Mapping/Joint Hydrographic Center (CCOM/JHC); and the North Carolina Division of Emergency Management, Floodplain Mapping Program (NCDEM-FPMP). ESRI ArcGIS v. 9.1 (http://www.esri.com/) was used to display and assess data quality. Datasets were converted into ESRI shape files and transformed to Mean High Water (MHW) and WGS84 geographic coordinates. Vertical datum transformations were largely achieved using *VDatum* model software (http://vdatum.noaa.gov) developed jointly by OCS and NOAA's National Geodetic Survey.

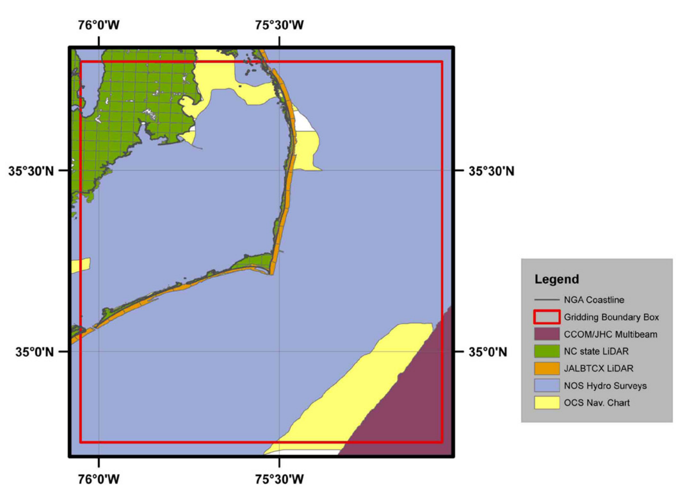

Figure 2. *Coverage of data sources used to compile the Cape Hatteras, North Carolina DEM.*

3.1.1 Shoreline

The National Geospatial-Intelligence Agency (NGA) 'Global Shoreline Data' digital shoreline was used for evaluating the North Carolina Floodplain Mapping topographic LiDAR data (see Section 3.1.3). The NGA Global Shoreline Data is an unclassified vector dataset generated by Earth Satellite Corporation (http://www.earthsat.com/) of Rockville, Maryland for NGA, under contract to Boeing in 2004. The shoreline is referenced to MHW and constructed from consistently orthorectified Landsat TM satellite imagery (GeoCover Ortho), acquired between 1998-2002 for NASA under the Global Land Mapping Program (GLMP). NDVI and SWIR models were used to define the landward extent of inundation (i.e., MHW). Independently verified positional accuracy for the source product (GeoCover Ortho) is consistently better than 50 meter root mean square (RMS) error. The NGA coastline does not match the topographic LiDAR data along the open ocean–land boundary due primarily to its lower resolution (e.g., Fig. 3). Nor does it match satellite imagery viewable with *Google Earth* (http://earth.google.com/). It does, however, provide a useful check of the LiDAR data, but was not used in compiling the Cape Hatteras DEM.

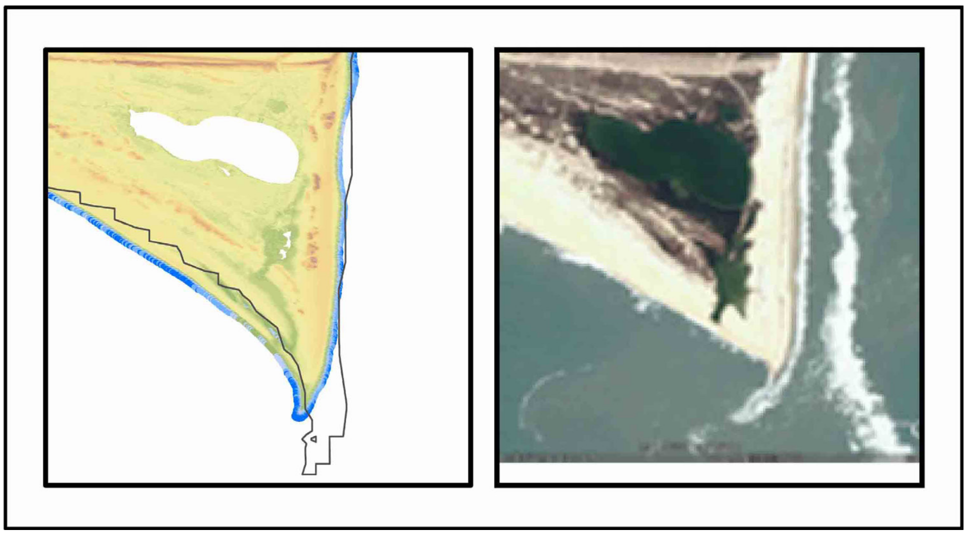

Figure 3. *NGA coastline in the area of Cape Hatteras. Left panel illustrates the mismatch between the NGA MHW coastline (black line) and topographic LiDAR, which is of higher resolution (blue colors are values below MHW). A Google Earth view of same area (right) more closely matches the LiDAR data.*

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Cape Hatteras DEM include 46 NOS hydrographic surveys, three OCS electronic nautical charts, and deep-water multibeam surveys of the U.S. Atlantic margin conducted by CCOM/JHC.

Table 2. Bathymetric data sources used in gridding.

Source	Year	Data Type	Spatial Resolution	Original Horizontal Datum/Coordinate System	Original Vertical Datum	URL
NOS	1850 to 2001	Hydrographic survey soundings	Ranges from 10 meters to 1 kilometer (varies with scale of survey, depth, traffic and probability of obstructions)	NAD27, NAD1913, NAD83	MLLW, MLW, LLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
OCS	2006	Soundings from nautical charts	200 meters to 5 kilometers	WGS84	MLLW	http://vdatum.noaa.gov
CCOM/JHC	2004	Multibeam bathymetry grid	100-meter grid spacing	WGS84, geographic coordinates	MSL	http://ccom.unh.edu/

1) **NOS hydrographic survey data**

A total of 46 NOS hydrographic surveys conducted between 1870 and 2001 were included in the grid compilation (Fig. 4). The survey data were originally vertically referenced to either Mean Lower Low Water (MLLW), Mean Low Water (MLW) or Local Low Water (LLW), and horizontally referenced to either NAD1913, NAD27 or NAD83 (Table 3). Data point spacing for the surveys ranged from about 10 meters in shallow water to 1 kilometer in deep water. All surveys were extracted from NGDC's online database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) in NAD83 and MLLW, MLW and LLW datums. The data were then converted to WGS84 using FME software, an integrated collection of spatial extract, transform, and load tools for data transformation (http://www.safe.com). The surveys were subsequently clipped to a polygon 5% larger than the final gridding area to support data interpolation along grid edges.

After converting all NOS survey data to MHW (see Section 3.2.1), the data were displayed in ESRI ArcMap and reviewed for digitizing errors against scanned original survey smooth sheets and compared to current topographic LiDAR data, the NGA coastline, and *Google Earth* satellite imagery. Geomorphologic and anthropogenic modification of the barrier-bar coastline has resulted in inconsistencies between the NOS survey data and recent topographic LiDAR data, necessitating modification of the NOS bathymetric data—this is especially true for the oldest NOS surveys.

13 NOS surveys were not available in digital format, resulting in some bathymetric coverage gaps (see Fig. 2 and 4), which were filled with OCS electronic nautical charts.

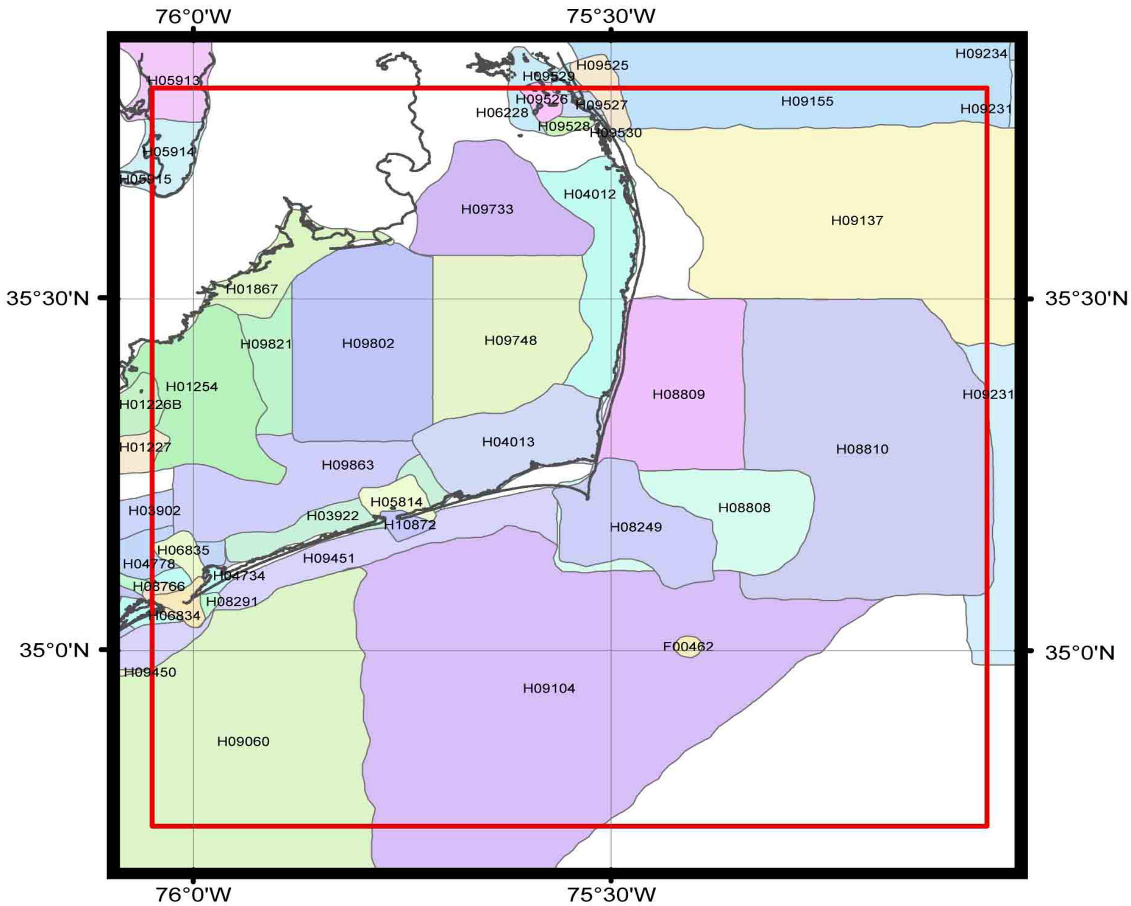

Figure 4. *Digital NOS hydrographic survey coverage in the Cape Hatteras region. Red line denotes DEM boundary; NGA coastline in black.*

Table 3. Digital NOS hydrographic surveys included in the Cape Hatteras, North Carolina DEM.

Survey ID	*Year*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*	*VDatum Transform Tool*[+]
F00462	2000	10,000	NAD83	MLLW	central
H01083	1870	40,000	undetermined - NAD27	MLW	pamlico
H01226B	1874	20,000	NAD1913	Local LW	FME
H01227	1874	40,000	undetermined	Local LW	FME
H01254	1875	20,000	undetermined	Local LW	FME
H01867	1887	20,000	undetermined	MLW	pamlico
H03902	1916	20,000	NAD1913	Local LW	FME
H03922	1916	20,000	NAD1913	Local LW	FME
H04012	1917	40,000	NAD1913	Local LW	FME
H04013	1917	20,000	NAD1913	Local LW	FME
H04734	1927	20,000	NAD1913	MLW	pamlico/central
H04778	1927	20,000	NAD1913	Local LW	FME
H05814	1935	10,000	NAD27	MLW	pamlico/central
H05913	1935	20,000	NAD27	MLW	FME
H05914	1935	10,000	NAD27	MLW	FME
H05915	1935	10,000	NAD27	Local LW	FME
H06228	1937	10,000	NAD27	MLW	pamlico/north
H06834	1943	10,000	NAD27	MLW	pamlico/central
H06835	1943	20,000	NAD27	MLW	pamlico
H06836	1943	10,000	NAD27	MLW	pamlico
H08249	1955	20,000	NAD27	MLW	central
H08291	1956	10,000	NAD27	MLW	pamlico/central
H08766	1962	10,000	NAD27	MLW	pamlico/central
H08808	1964	20,000	NAD27	MLW	central
H08809	1964	20,000	NAD27	MLW	north/central
H08810	1965	40,000	NAD27	MLW	north/central
H09060	1970	80,000	NAD27	MLW	central
H09104	1970	80,000	NAD27	MLW	central
H09137	1970	40,000	NAD27	MLW	north
H09155	1970	40,000	NAD27	MLW	north
H09231	1971	80,000	NAD27	MLW	north/central
H09243	1971	80,000	NAD27	MLW	north
H09450	1974	40,000	NAD27	MLW	central
H09451	1974	40,000	NAD27	MLW	central
H09525	1975	10,000	NAD27	MLW	north
H09526	1975	5,000	NAD27	MLW	pamlico
H09527	1975	5,000	NAD27	MLW	pamlico/north
H09528	1975	5,000	NAD27	MLW	pamlico
H09529	1975	5,000	NAD27	MLW	pamlico/north
H09530	1975	5,000	NAD27	MLW	north
H09733	1977/78	20,000	NAD27	Low water (.5 ft. below Mean Water Level	FME
H09748	1978	20,000	NAD27	Local LW	FME
H09802	1978/79	20,000	NAD27	Local LW	FME
H09821	1979/80	20,000	NAD27	Local LW	FME
H09863	1980	20,000	NAD27	Low water (.5 ft. below Mean Water Level	FME
H10872	2001	10,000	NAD83	MLLW	pamlico/central

[+] 'FME' transformations using -0.15 meter vertical shift—Local Low Water to MHW in Pamlico Sound.

2) OCS electronic nautical charts

Three electronic nautical charts in the Cape Hatteras region (#11520, #11555, and #12205; Fig. 5) were downloaded from NOAA's Office of Coast Survey (OSC) website (http://www.nauticalcharts.noaa.gov/). Chart sounding data were originally in WGS84 geographic and MLLW (units of meters) datums. Chart #12205, in Albemarle Sound, has point spacings between roughly 200 meters and one kilometer in the vicinity of Oregon Inlet, a region without digital NOS hydrographic survey data. Chart #11555, Pamlico Sound, also has point spacings between 200 meters and one kilometer, while Chart #11520, deep-water soundings from Cape Hatteras to Charleston, has point spacings between 2 and 5 kilometers. Though the soundings on these three nautical charts are sparse, they provided the only digital values in some areas (see Fig. 2). Soundings were clipped to a polygon 5% larger than the gridding area, converted to MHW, then used in the gridding process.

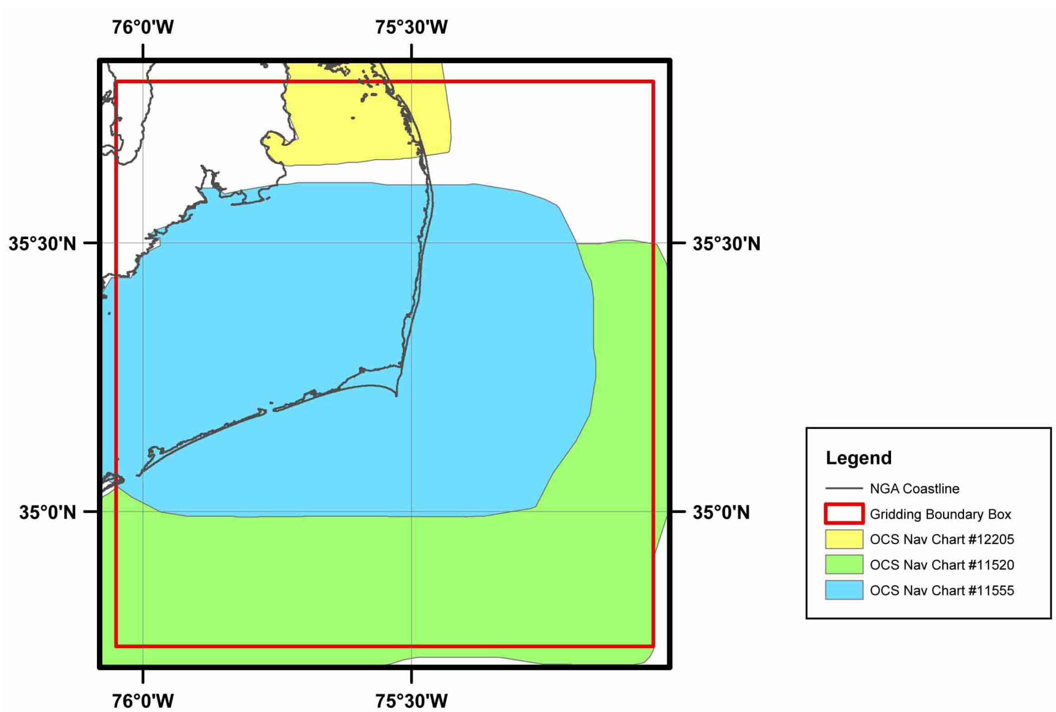

Figure 5. *Spatial coverage of OCS electronic nautical charts in gridding area.*

3) Gridded multibeam bathymetric surveys

The University of New Hampshire's Center for Coastal and Ocean Mapping/Joint Hydrographic Center (CCOM/JHC; http://ccom.unh.edu/) has conducted deep-water multibeam sonar surveys of the U.S. Atlantic margin in support of the United Nations Convention on the Law of the Sea (Gardner, 2004). A small portion of one CCOM/JHC gridding region ("South", Fig. 6) overlaps the southeastern corner of the Cape Hatteras gridding region (see Fig. 2). Data from this 100-meter grid was extracted, clipped to a polygon 5% larger than the Cape Hatteras gridding region, converted to MHW and then used in the gridding process.

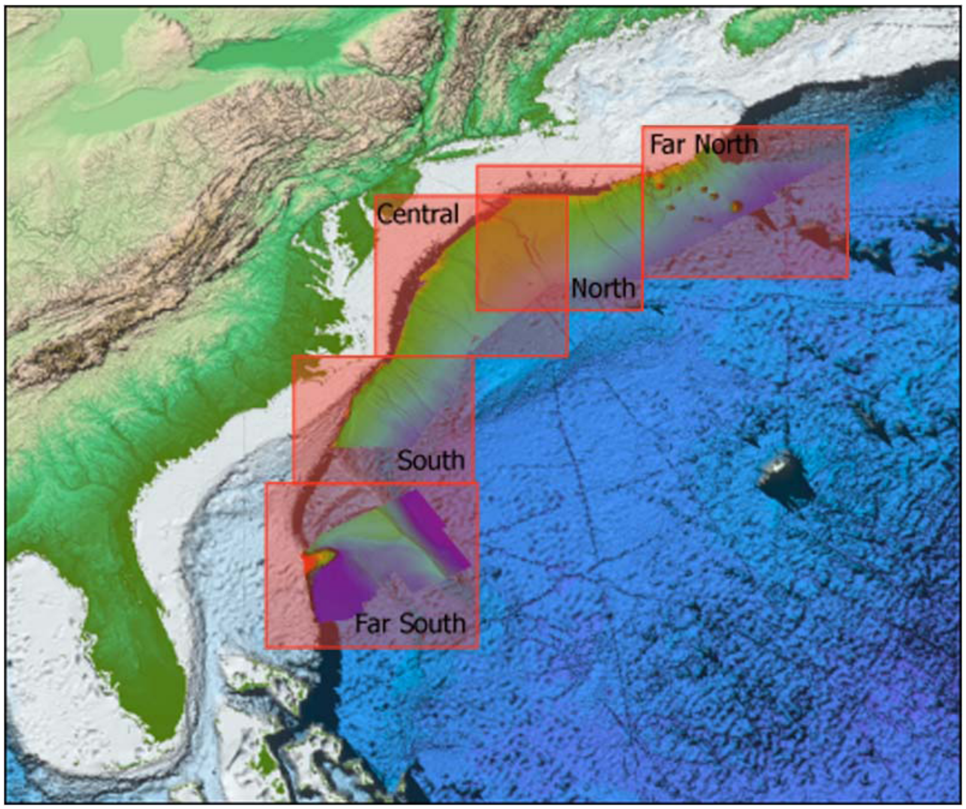

Figure 6. *Spatial coverage of CCOM/JHC multibeam surveys along the U.S. Atlantic margin.*

3.1.3 Topography

High-resolution topographic LiDAR data collected and processed in 2001 by the North Carolina Division of Emergency Management, Floodplain Mapping Program (NCDEM-FPMP) were used for subaerial regions in the compilation of the grid (Fig. 6). The NCDEM-FPMP was established in response to the extensive damage caused by Hurricane Floyd in 1999, and these data were collected as part of its effort to modernize FEMA Flood Insurance Rate Maps (FIRM) statewide. The data were received in ASCII xyz format organized in 10,000 ft x 10,000 ft tiles using the North Carolina Bureau of Land Records Management standards. The data were collected at 5-meter nominal post spacing and referenced to NAD83 North Carolina State Plane and NAVD88 horizontal and vertical datums, units of feet.

Although not used in the compilation of the Cape Hatteras DEM, ultra-high-resolution topographic LiDAR data (1/3 meter postings) were collected along the North Carolina coastline by the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX; http://shoals.sam.usace.army.mil/) following the 2004 hurricane season, and provided to NGDC. The NCDEM-FPMP topographic data matched well with this very dense JALBTCX topographic data, and was of sufficient density as to make the JALBTCX data redundant; the NCDEM-FPMP data also provided complete coverage of subaerial regions within the Cape Hatteras gridding region.

Table 4. Topographic data sources used in gridding.

Source	Year	Data Type	Spatial Resolution	Original Horizontal Datum/Coordinate System	Original Vertical Datum	URL
NCDEM-FPMP	2001	Topographic LiDAR	5-meter nominal post spacing	NAD83, North Carolina State Plane (feet)	NAVD88 (feet)	http://www.ncfloodmaps.com/

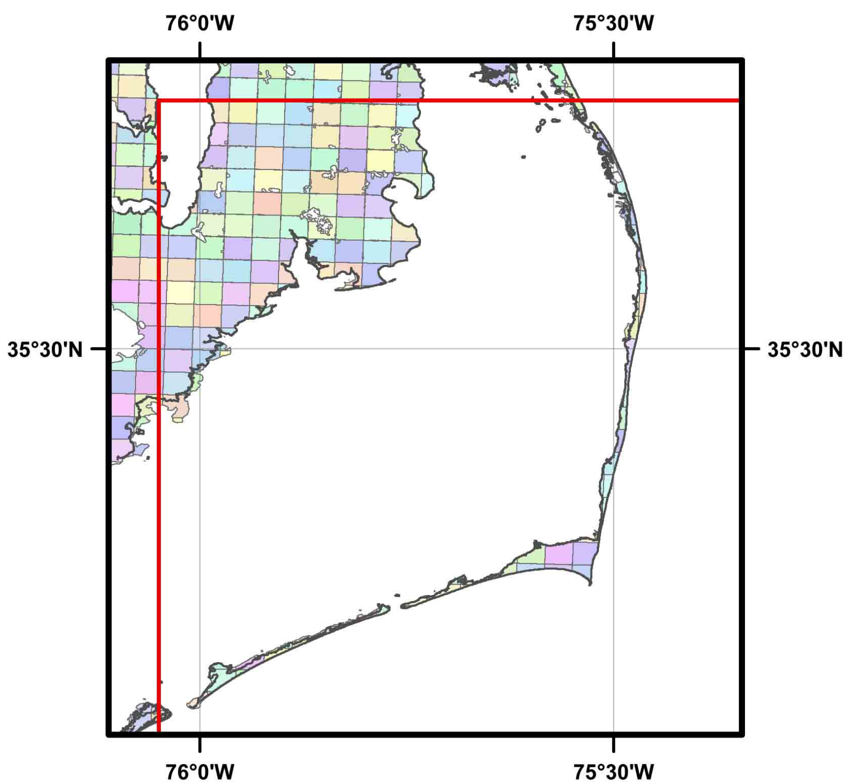

Figure 7. *Topographic LiDAR coverage tiles in the Cape Hatteras region. Red line denotes DEM boundary; NGA coastline in gray.*

3.1.4 *Topography/Bathymetry*

High-resolution combined topographic/bathymetric LiDAR surveys of the North Carolina open-ocean coastline were conducted by Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX; http://shoals.sam.usace.army.mil/), providing a dense dataset in the shallowest bathymetric zone. JALBTCX performs operations, research, and development in airborne LiDAR bathymetry and complementary technologies to support the coastal mapping and charting requirements of the U.S. Army Corps of Engineers (USACE) National Coastal Mapping Program, the U.S. Naval Meteorology and Oceanography Command, and NOAA.

The JALBTCX LiDAR data used in gridding was collected in 2004 along the North Carolina coast using the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system. The CHARTS system includes an Optech, Inc., SHOALS-3000 LiDAR instrument integrated with an Itres CASI-1500 hyperspectral imager and collects either 20 kHz topographic LiDAR data or 3 kHz bathymetric LiDAR data, each concurrent with digital RGB and hyperspectral imagery.

Bathymetric data were collected from the shoreline to ~1 km offshore at 5-meter spacing; topographic data were collected from the shoreline to 0.5 km onshore at 1-meter spacing. The topographic data were collected in opposing flight directions, resulting in 200% coverage of the land portion of the survey. All data were positioned using post-processed kinematic GPS and National Geodetic Survey monumentation.

The bathymetric data from the JALBTCX combined topographic/bathymetric LiDAR surveys were of significantly higher resolution than the sparser NOS hydrographic surveys—they were also consistent with those NOS soundings. The topographic data, however, did not overlap well with the subaerially complete NCDEM-FHMP topographic data or with the 1/3-meter postings from the entirely topographic surveys performed by JALBTCX (see Section 3.1.3): shifting topographic features horizontally by tens of meters in some cases. Thus, NGDC chose to use only the bathymetric data from the JALBTCX combined topographic/bathymetric surveys.

Table 5. Topographic/ Bathymetric LiDAR data source used in gridding.

Source	Year	Data Type	Spatial Resolution	Original Horizontal Datum/Coordinate System	Original Vertical Datum	URL
JALBTCX	2004	Topographic/ bathymetric LiDAR	0.5 to 5 meter point spacing	NAD83, geographic coordinates	NAVD88	http://www.sac.usace.army.mil/

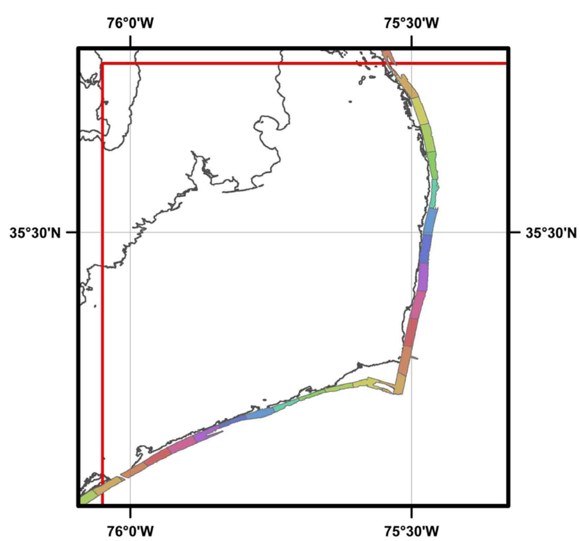

Figure 8. *JALBTCX topographic/bathymetric LiDAR coverage in the Cape Hatteras region. Red line denotes DEM boundary; NGA coastline in gray.*

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation of the Cape Hatteras DEM were originally referenced to a number of vertical datums including: Mean Low Water (MLW), Local Low Water (LLW), Mean Lower Low Water (MLLW), and North American Vertical Datum of 1988 (NAVD88). All datasets were transformed to MHW to provide the worst case scenario for inundation modeling.

1) Bathymetric data

The OCS electronic nautical charts and most of the NOS surveys were transformed to MHW using VDatum (http://vdatum.noaa.gov) model software developed jointly by OSC and NOAA's National Geodetic Survey. For the Cape Hatteras gridding area, the VDatum Transformation Tool consists of three Java based programs applicable to three specific North Carolina coastal regions (Fig. 8).

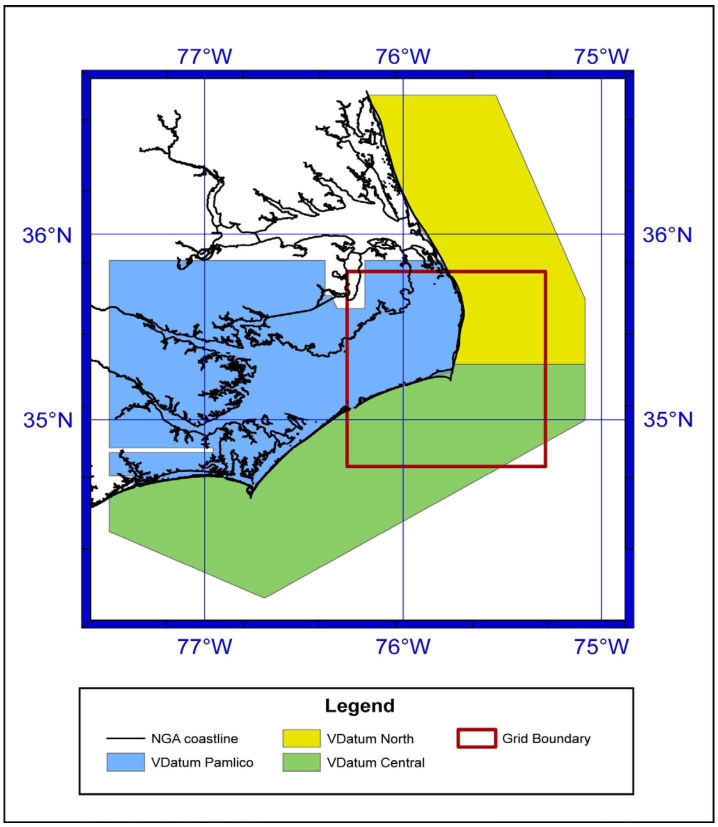

Figure 9. *Three VDatum regions for coastal North Carolina.*

NOS surveys were grouped by reference to original vertical datum (see Table 3) and input to VDatum using the batch mode utility (Fig. 9). Surveys that spanned two VDatum regions were input to both transform tools, which only transform soundings within the specified region. Some surveys in Pamlico Sound were originally referenced to LLW, a vertical datum not supported by VDatum. These survey depths were brought to MHW by adding a constant of -0.15 meters (Dr. Kurt Hess, NOAA Office of Coastal Survey, Kurt.Hess@noaa.gov, personal communication).

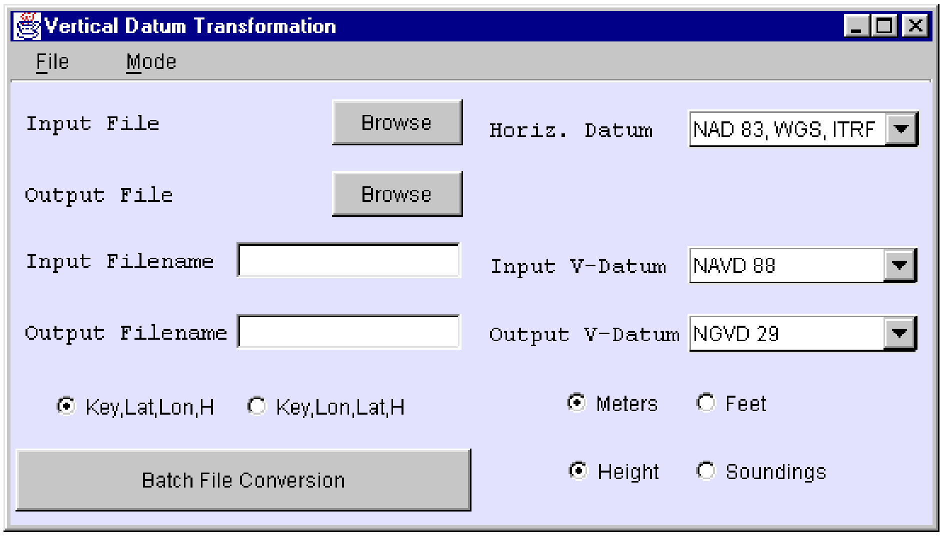

Figure 10. *VDatum model software Java input window.*

Other bathymetric datasets, in Mean Sea Level (MSL) vertical datum, were converted to MHW using FME software by adding a constant offset of -0.179 (Table 6), which was derived by averaging the difference between MSL and MHW at tidal stations along the Cape Hatteras coastline (http://tidesandcurrents.noaa.gov/).

2) Topographic and topographic/bathymetric LiDAR data

Topographic and topographic/bathymetric LiDAR data were converted from NAVD88 to MHW using FME software by adding a constant value of -0.126 meters (Table 6).

Table 6. Relationship between Mean High Water and other vertical datums in the Cape Hatteras region.*

Vertical datum	*Difference to MHW*
NAVD88	-0.126
MSL	-0.179
MLW	-0.405
NGVD29	-0.449
LLW	-0.15

* Datum relationships derived from averaging tidal range values at up to 7 tidal stations within the Cape Hatteras region—vertical datums are not necessarily benchmarked at all stations.

3.2.2 Horizontal datum transformations

Datasets used to compile the grid were originally horizontally referenced to NAD83, WGS84, NAD27, or North Carolina State Plane horizontal datums; the relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of WGS84 using FME software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shape files were checked in ESRI ArcMap for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps; the quality-assessed ESRI shape files were then converted to xyz files in preparation for gridding. Problems included:

- Mismatch between the topographic data of the combined topographic/bathymetric LiDAR surveys conducted by JALBTCX with the exclusively topographic LiDAR surveys conducted by JALBTCX and NCDEM-FPMP. The topographic part of the JALBTCX combined LiDAR surveys was excluded from the gridding process.

3.3.2 Gridding the data with GMT

As there was very little overlap between the various data sets—with the exception of the NOS surveys and OCS chart soundings, which were highly consistent—all processed xyz files were gridded with GMT (http://gmt.soest.hawaii.edu/). GMT is an NSF-funded share-ware software application designed to manipulate data for mapping purposes. The GMT tool 'surface' was used to create the 1/3 arc-second Cape Hatteras grid—a modeled surface draping the point data—of combined sounding and topographic point data. These point data were first combined into an individual file, then smoothed using the GMT tool 'blockmedian' onto a 1/3 arc-second grid 5% larger than the gridding region. 'Surface' then applied a tight spline tension to interpolate cells without data values; 'surface' does not support a data hierarchy. The GMT grid created by 'surface' was converted into an Arc ASCII file using the MB-System tool 'mbm_grd2arc'; MB-System is also an NSF-funded share-ware application that has numerous data processing and conversion tools (http://www.ldeo.columbia.edu/res/pi/MB-System/).

3.4 Quality Assessment of the Grids

3.4.1. Horizontal accuracy

The digital elevation grids have an estimated horizontal accuracy of about 10 meters for topographic features; the LiDAR data has an accuracy of ~2 meters for individual postings. Bathymetric features are resolved only to within a few hundred meters in deep water areas; shallow, near-coastal regions have an accuracy approaching the subaerial topographic features. Positional accuracy is limited by: transformation of multiple datasets from various datums; sparseness of deep-water soundings; potentially large positional accuracy of pre-satellite navigated (GPS) hydrographic surveys; and natural and artificial morphologic change that has occurred since the hydrographic surveys were conducted.

3.4.2 Vertical accuracy

The grids have an estimated vertical accuracy of 0.1 to 1 meters for topographic areas and 0.1 meters to 5% of water depth for bathymetric areas. Topographic values are derived from NCDEM-FPMP and JALBTCX LiDAR surveys, which have an estimated vertical accuracy of 0.1 to 0.15 meters. Bathymetric values were derived from the wide range of input data single and multibeam sounding measurements from the late 19th and early 20th centuries to recent. Gridding interpolation to determine values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Comparison with North Carolina NOAA tidal bench marks

Four tidal bench marks within the Cape Hatteras study area were compared with values taken at the same locales from the 1/3 arc-second (~10 meter) DEM (see Fig. 1 and Table 7 for station locations). Each bench mark has a geographic position recorded to within 1 arc-second, with an accuracy of +/-6 arc-seconds (http://tidesandcurrents.noaa.gov/). Most bench marks are level with the ground surface; the rest are within a few centimeters. The National Geodetic Survey (NGS) data sheets for the tidal stations also document benchmark elevation above MHW, in meters, allowing for direct comparison with grid values at those locations. Most grid values compare favorably with the known bench mark elevations. The Oregon Inlet bench mark has the largest discrepancy, 2.6 m, which is due partly to its being located at the north end of Bonner Bridge, elevated 0.3 m above the highway.

Table 7. Comparison of NOAA tidal benchmark elevations, in meters above MHW, with the Cape Hatteras DEM.

STATION NUMBER	STATION NAME	YEAR	LONGITUDE	LATITUDE	BENCH MARK	GRID VALUE	DIFFERENCE
8654400	CAPE HATTERAS FISHING PIER	1980	075°38'23"W	35°13'37"N	0.231	0.616	-0.385
8652587	OREGON INLET	1974	075°32'49"W	35°47'40"N	4.100	1.473	2.627
8652587	USCG LIFEBOAT STATION	1974	075°31'25"W	35°46'04"N	1.259	1.539	-0.280
8653215	RODANTHE, PAMLICO SOUND	1977	075°28'07"W	35°35'35"N	1.072	0.710	0.362
						Standard Deviation:	*1.403*

3.4.4 *Comparison with North Carolina USGS bench marks*

Benchmark elevations were extracted from online digital USGS topographic quadrangles (http://www.topozone.com), which give benchmark position and elevation in WGS84 and NVGD29 vertical datum (in feet). Elevations were converted to meters and shifted to MHW vertical datum (see Table 6) for comparison with the Cape Hatteras DEM. The four USGS bench marks with discrepancies greater than 2 m are all located along the open-ocean edge of Hatteras Island. In each case, the grid value for the location of the corresponding bench mark accurately reflects the values of the surrounding NCDEM-FPMP topographic LiDAR data. The origin of the mismatch between the topographic LiDAR data and the USGS benchmark elevations is unknown.

Table 8. Comparison of USGS topographic quadrangle benchmark elevations, in meters above MHW, with the Cape Hatteras DEM.

LONGITUDE	LATITUDE	BENCH MARK	GRID VALUE	DIFFERENCE
-75.9882	35.1069	0.16	0.78	-0.62
-75.6974	35.2161	0.16	0.17	0.00
-75.9045	35.6411	0.16	0.35	-0.19
-75.5462	35.2683	0.47	0.46	0.01
-75.9217	35.6293	0.47	0.37	0.10
-75.7795	35.693	0.47	0.93	-0.46
-75.7731	35.6965	0.47	0.16	0.31
-75.9211	35.633	0.78	0.15	0.63
-75.7885	35.808	0.78	0.41	0.37
-75.8061	35.8273	0.78	0.37	0.41
-75.8749	35.1461	1.09	1.31	-0.22
-75.4672	35.5955	1.09	1.24	-0.16
-75.8547	35.6313	1.09	0.65	0.43
-75.8903	35.6459	1.09	0.44	0.64
-75.7683	35.7215	1.09	0.32	0.76
-75.7685	35.736	1.09	0.60	0.49
-75.769	35.7694	1.09	1.09	-0.01
-75.7767	35.7951	1.09	0.53	0.56
-75.7952	35.8152	1.09	0.55	0.53
-75.7203	35.2	1.39	0.74	0.65
-75.6758	35.2147	1.39	1.04	0.35
-75.6625	35.2183	1.39	1.79	-0.40
-75.4872	35.4187	1.39	1.51	-0.12
-75.7807	35.6328	1.39	0.86	0.54
-75.7773	35.6513	1.39	1.07	0.32
-75.78	35.6802	1.39	1.57	-0.18
-75.7694	35.7835	1.39	0.27	1.12
-75.6121	35.2316	1.70	5.24	-3.54
-75.4771	35.5064	1.70	1.40	0.30
-75.4766	35.6651	1.70	2.95	-1.25
-75.7749	35.6966	1.70	0.47	1.23
-75.5212	35.7701	1.70	0.20	1.50
-75.7037	35.2055	2.01	2.30	-0.29

-75.5212	35.2555	2.01	1.79	0.21
-75.6541	35.2206	2.31	-0.15	2.46
-75.5211	35.2533	2.31	-0.26	2.57
-75.6624	35.2183	2.62	1.79	0.83
-75.5951	35.235	2.62	2.36	0.26
-75.5511	35.238	2.62	1.65	0.97
-75.471	35.5265	2.62	4.91	-2.30
-75.7873	35.6215	1.39	0.48	0.91
			Standard Deviation:	*1.54*

3.4.5 Slope map and 3-D perspectives

ESRI ArcCatalog was used to generate a slope map from the Cape Hatteras DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 11). The grid was transformed to UTM Zone 18 coordinates (horizontal units in meters) in ArcCatalog for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope-map derivation. Analysis of preliminary slope maps revealed suspect data points, which were corrected before regridding the data. Three-dimensional viewing of the UTM-transformed grid (e.g., Fig. 12) was accomplished using ESRI ArcScene. The sparseness of the OCS electronic nautical chart data in the southeast (deep-water) corner of the DEM created smooth "tent poles" that are apparent in the southeast corner of Figure 11; these artifacts could not be excised from the DEM.

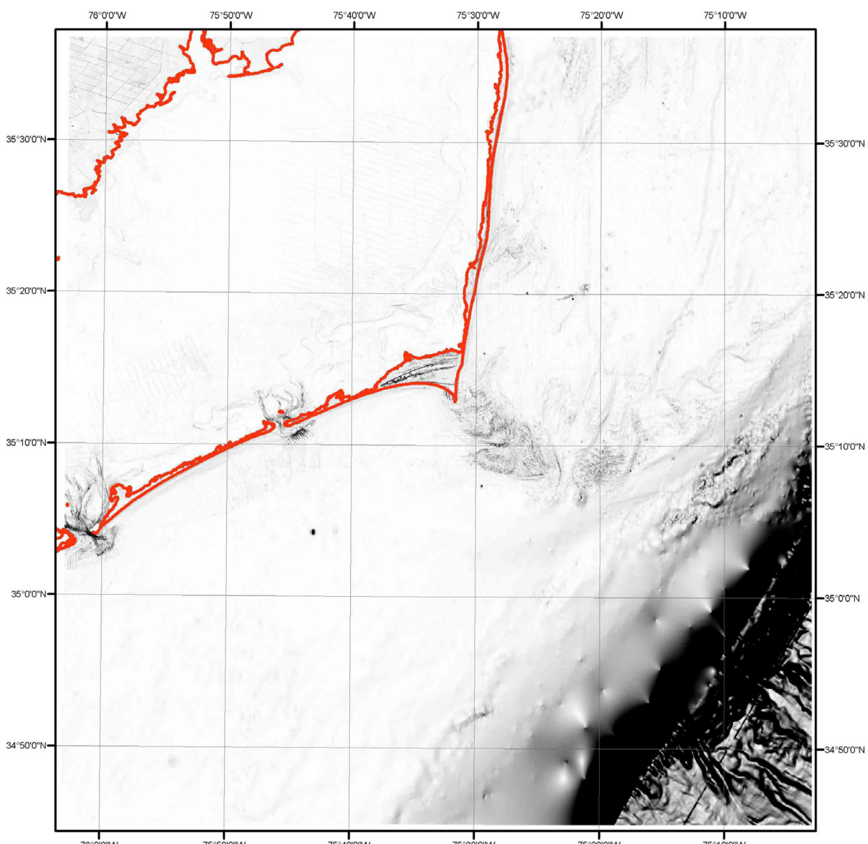

Figure 11. *Slope map of the 1/3 arc-second Cape Hatteras DEM. Flat-lying slopes are white; dark shading denotes steep slopes; NGA coastline in red. Prominent dark feature at 35°04'N, 075°43'W is from real NOS sounding on chart H09104.*

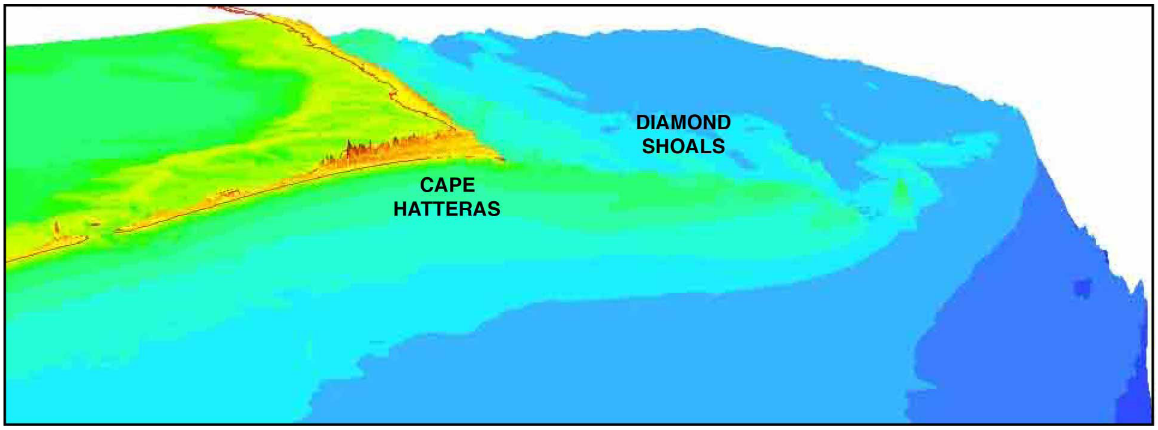

Figure 12. *Perspective view from the southwest of part of the Cape Hatteras DEM. Diamond Shoals is a prominent shallow region extending southeast from Cape Hatteras. NGA coastline in red; vertical exaggeration–times 100.*

A region of prominent patterned lineations in the Cape Hatteras DEM lies on the landward side of Pamlico Sound (see northwest corner of Fig. 1 where some land topography lies below the MHW zero level). The lineations are clearly resolvable within the NCDEM-FPMP topographic LiDAR data, and in *Google Earth* satellite imagery (Fig. 13) and are not gridding-related artifacts. As such, they are interpreted as large-scale manmade structures, perhaps related to local farming endeavours.

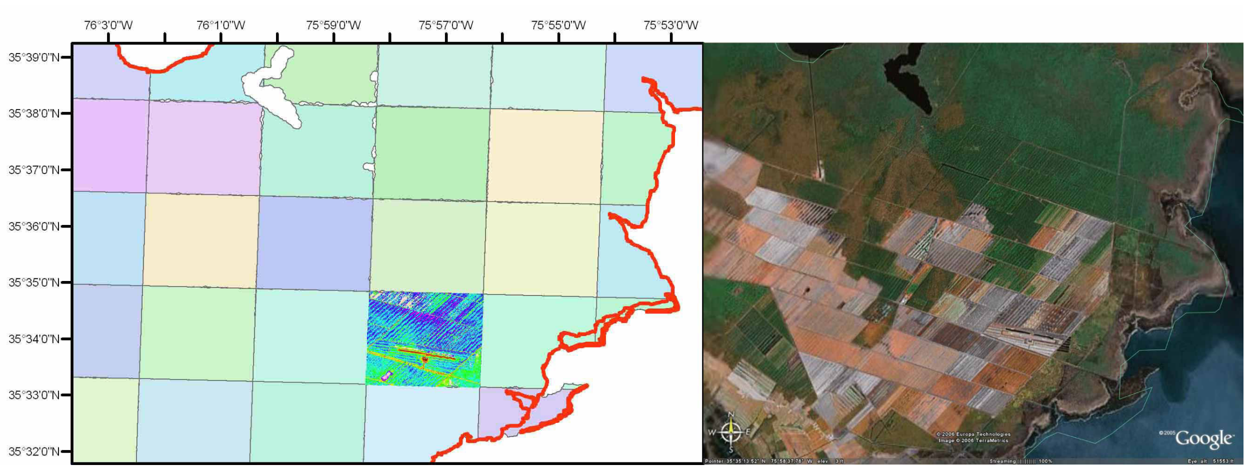

Figure 13. *Prominent manmade features visible in topographic LiDAR data. Left panel shows an example of linear features resolvable in a tile of the NCDEM_FPMP topographic LiDAR data; NGA coastline is in red. Right panel shows a Google Earth satellite image of the same region. This patchwork of lineated features is also present in the Cape Hatteras DEM, some of which lie below the MHW zero level.*

4. Summary and Conclusions

A topographic/bathymetric digital elevation model with cell spacing of 1/3 arc-second (~10 meters) of the Cape Hatteras, North Carolina area was developed for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Inundation Mapping Efforts (TIME). The best available data from U.S. federal and state agencies, and universities were obtained for grid compilation. The data were quality checked, processed and gridded using ESRI ArcGIS, FME, GMT and MB-System software.

Recommendations to improve the DEMs based on NGDC's research and analysis are listed below:

- Resurvey bathymetric regions without digital data, or digitize analog NOS sounding sheets for these areas.

5. Acknowledgments

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