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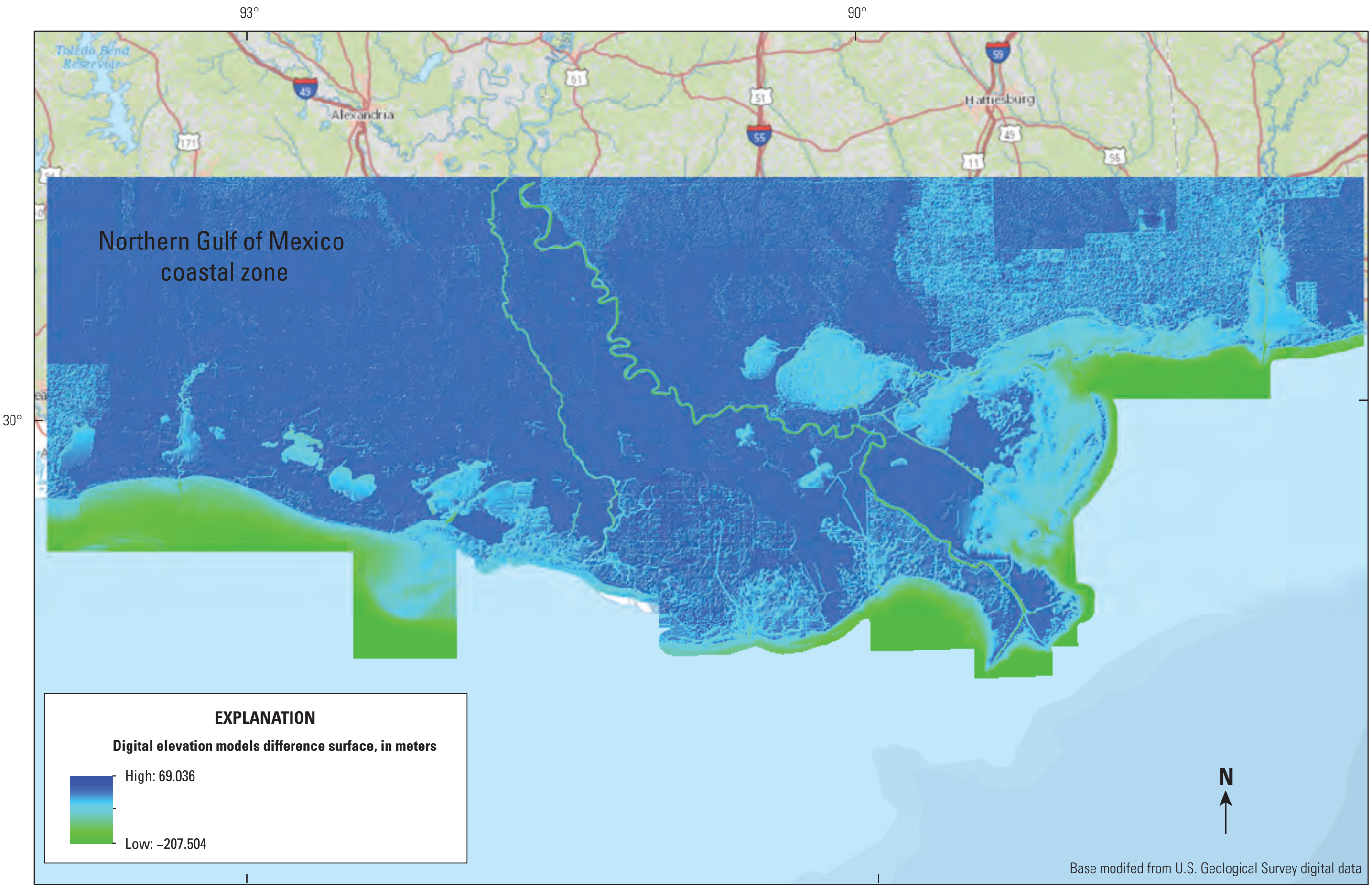
Analysis for Agreement of the Northern Gulf of Mexico Topobathymetric Digital Elevation Model with 3-Dimensional Elevation Program 1/3 Arc-Second Digital Elevation Models



Open-File Report 2019–1016

U.S. Department of the Interior
U.S. Geological Survey

Cover. Map showing Northern Gulf of Mexico topobathymetric model and 3D Elevation Program digital elevation models difference surface.

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By Cynthia Miller-Corbett

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
meter (m)	.281	foot (ft)
kilometer (km)	.6214	mile (mi)
meter (m)	1.094	yard (yd)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinavte information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations

ASPRS	American Society for Photogrammetry and Remote Sensing
CoNED	Coastal National Elevation Database Applications Project
DEM	digital elevation model
EAARL	Experimental Advanced Airborne Research Lidar
HR NHD	High Resolution National Hydrography Dataset
IHO	Internal Hydrographic Organization
lidar	light detection and ranging
NAIP	National Agricultural Imagery Program
NED	National Elevation Dataset
NOAA	National Oceanic and Atmospheric Administration
NVA	nonvegetated vertical accuracy
RMSE	root mean square error
sonar	sound navigation and ranging
TBDEM	topobathymetric digital elevation model
3D	three-dimensional
3DEP	3-Dimensional Elevation Program
TNM	The National Map
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VDatum	vertical datum transformation
VVA	vegetated vertical accuracy

Analysis for Agreement of the Northern Gulf of Mexico Topobathymetric Digital Elevation Model with 3-Dimensional Elevation Program 1/3 Arc-Second Digital Elevation Models

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Abstract

Topographical differencing and edge-matching analyses were used to evaluate agreement of the Coastal National Elevation Database Applications Project's Northern Gulf of Mexico topobathymetric digital elevation model (TBDEM) with The National Map 3-Dimensional Elevation Program (3DEP) 1/3 arc-second digital elevation models (DEMs). In addition to topographic map products provided through the National Geospatial Program, the model integrates bathymetric and topobathymetric datasets for three-dimensional (3D) mapping of rivers, lakes, and bays in the upland and intertidal wetlands to offshore environments in coastal zones from the border between Texas and Louisiana to east of Mobile Bay, Alabama.

Contoured elevation differences between the Northern Gulf of Mexico TBDEM and the 3DEP 1/3 arc-second DEMs indicate that 85 percent of elevation data in the Northern Gulf of Mexico TBDEM agree (no difference for contoured elevations) between 95 and 100 percent with 3DEP 1/3 arc-second DEMs. Edge matching differences between adjacent Northern Gulf of Mexico TBDEM source projects or between the TBDEM and 3DEP DEMs indicate most seams between integrated and 3DEP DEMs are smooth. Where seams did not match, most differences were in the range of tenths to hundredths of a meter. Valid differences that are greater than plus or minus 2 meters in areas of bathymetric data are found in the Mississippi River, Atchafalaya River, Lower Atchafalaya River, Wax Lake Pass channel, the Vermilion Bay bathymetric datasets, and where topobathymetric datasets are integrated in the model. Areas with positive or negative outlier difference elevations seem to be a result of site conditions that affect light detection and ranging (lidar) waveform return signals, misclassification of surface features, or possibly because of interpolation required to develop a smooth elevation surface. Results of this analysis provide information to help understand model parameters and agreement of the Northern Gulf of Mexico TBDEM developed using different data types from different sources with The National Map 3DEP DEMs.

Inclusion of bathymetric and topobathymetric data types in the 3DEP aligns with the mission to respond to growing needs for a wide range of three-dimensional representations of the Nation and supports the U.S. Geological Survey strategy for developing a National Terrain Model to provide hydrographic and elevation data that extend the elevation surface below water bodies. The 3D Nation Requirements and Benefits Study sponsored by the U.S. Geological Survey and National Oceanic and Atmospheric Administration to assess local to regional Tribal, State, and Federal technical requirements, needs, and benefits for using topographic and bathymetric 3DEP elevation data will be used to help develop and refine future program alternatives for 3D elevation data that include a category for bathymetry and topobathymetry. At the time of this report (2019), 3DEP acquisition is specific to topographic lidar that meets lidar DEM specifications and which requires surface-water feature areas to be hydroflattened. Cataloging bathymetric and topobathymetric DEMs as part of the 3DEP will require new specifications for acoustic, lidar, merged acoustic and lidar, and possibly other bathymetric and topobathymetric survey data types.

Introduction

This report presents a quantitative analysis for agreement between the Northern Gulf of Mexico topobathymetric digital elevation model (TBDEM) developed through integration of topographic, bathymetric, and topobathymetric data types, with The National Map 3-Dimensional Elevation Program (3DEP) 1/3 arc-second digital elevation models (DEMs). The analysis is based on assessing elevation differencing grids developed using ArcGIS tools to provide a measure of how well the regionally extensive TBDEM, which was developed through integration of the variable elevation data types from different sources and vintage (fig. 1), aligns with 3DEP 1/3 arc-second DEMs. Most Northern Gulf of Mexico TBDEM geospatial data are cited in metadata as derived from

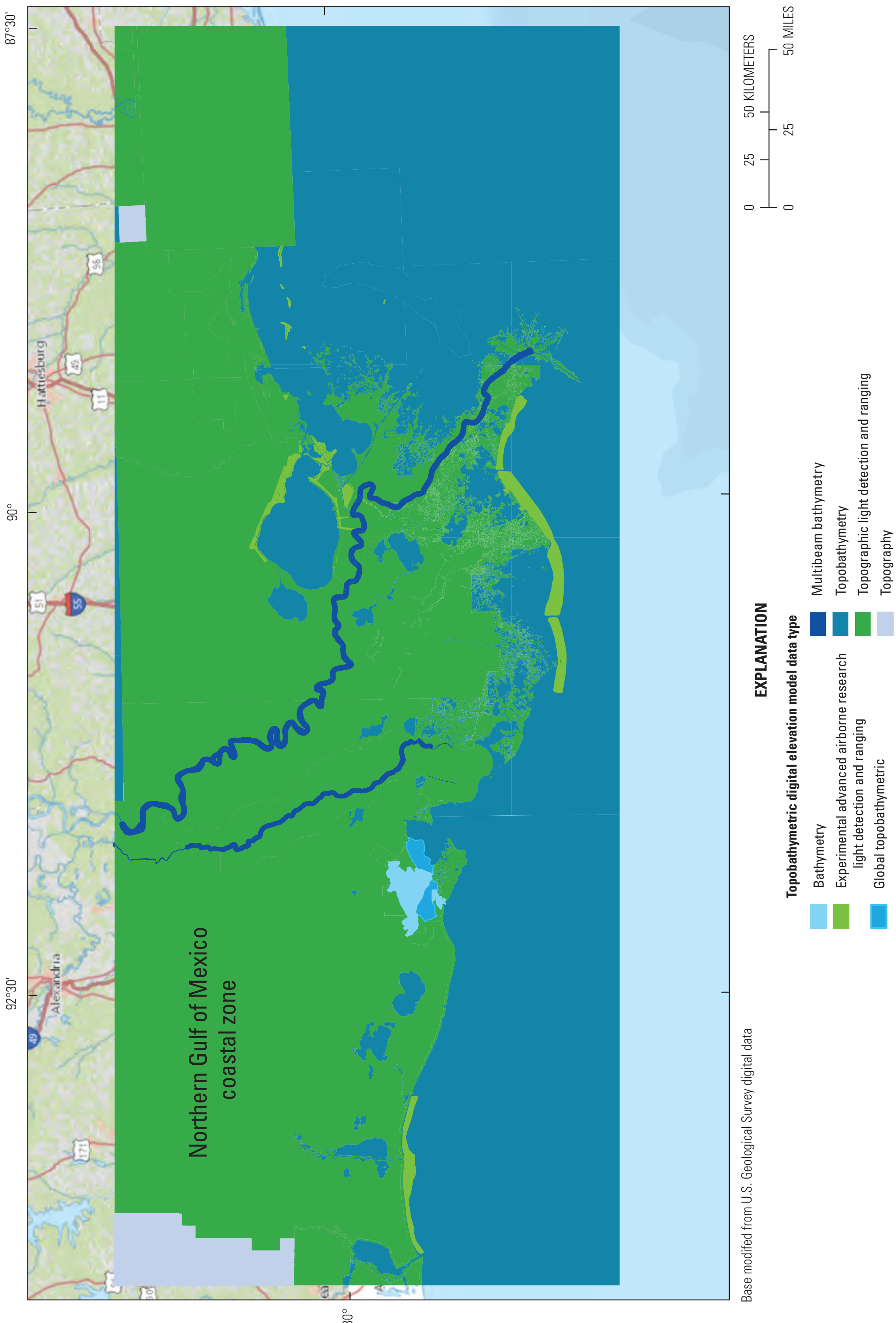


Figure 1. Northern Gulf of Mexico topobathymetric digital elevation model (modified from Danielson and others, 2016).

topographic light detection and ranging (lidar) survey projects and mosaicked topographic lidar projects, or from the topobathymetric models that map the coastal zone from upland to offshore (U.S. Geological Survey, 2014). The topobathymetric datasets covering a substantial part of the TBDEM are from National Oceanic and Atmospheric Administration (NOAA) projects; the Coastal National Elevation Database Applications Program (CoNED) also provides topobathymetric projects. Bathymetric data collected in multibeam and side-scan hydroacoustic sound navigation and ranging (sonar) surveys and historical lead-line sounding surveys provide inland to coastal zone subsurface bottom depths for the Mississippi River and Atchafalaya River, two other river courses, or the Vermilion and Wicks Bay area west of the Mississippi River. Topobathymetric lidar survey datasets providing the position of land/water boundaries, and geographic 1/3 arc-second DEMs as well as DEMs that may be derived from interpolated elevation field observations, photogrammetry, or aerial photographic interpretation (Usery and others, 2009) also are integrated in the Northern Gulf of Mexico TBDEM.

Results for contouring elevation difference grids were used to identify smooth to rough elevation transitions at the boundary of TBDEM source projects with the 3DEP DEMs as an indication of the agreement or magnitude of differences between these. Results of the differencing also indicate some areas of notable elevation differences within or between integrated TBDEM source projects. Differences between the TBDEM and 3DEP 1/3 arc-second DEMs within tiled survey areas and at seams between integrated source projects and 3DEP 1/3 arc-second DEMs may represent variation in the integrated source project data types, dataset vintage, collection protocols, processing, interpolation, or production methods. Nonuniform elevation differences within source project datasets also may be a result of these variations. Understanding the extent and possible causes for differences between the Northern Gulf of Mexico TBDEM and 3DEP DEMs can provide insight into the level of effort that could be required to integrate bathymetric and topobathymetric data types with 3DEP DEMs produced from lidar data.

This analysis is not designed as an evaluation of the accuracy or quality of the TBDEM. However, available information for integrated dataset accuracy and survey parameters provides insight into how source project data information aligns with 3DEP product requirements or meets national hydrographic data standards. Because 3DEP DEMS are created from lidar data, new procedures and specifications would need to be implemented to develop a 3DEP category for bathymetric and topobathymetric data types. However, the Northern Gulf of Mexico TBDEM is included in the online U.S. Geological Survey inland bathymetric and topobathymetric survey dataset inventory initiated by the 3DEP to understand the geographic distribution of USGS inland bathymetric and topobathymetric surveys and to characterize survey parameters relevant to data collection, processing, and quality (U.S. Geological Survey, Community for Data Integration, Earth Science Themes Working Group, 2018).

A description of the study area, which includes a summary of the landscape that transitions from uplands in the northern and western model regions to rivers and wetlands, and from the intertidal zone to deeper offshore coastal zones is described first. Then, an overview of the TBDEM source project datasets and methods used to create the Northern Gulf of Mexico TBDEM is presented. Next, methods to evaluate overall agreement and edge matching among and within individual source project types are described, followed by a discussion of the results of the comparison of the Northern Gulf of Mexico TBDEM with the 3DEP DEMs.

Study Area

The Northern Gulf of Mexico TBDEM includes more than 150,000 square kilometers (km^2) of coastal zone elevation data from topographic, bathymetric, or topobathymetric survey projects for the Northern Gulf of Mexico coastal zone (table 1). Regional coverage of the Northern Gulf of Mexico TBDEM is from 29 degrees (º) N to 32 ºN latitude and −88 ºW to −94 ºW longitude, spanning the coastal zone from the Louisiana and Texas border at Sabine Lake to east of Mobile Bay, Alabama, including upland, intertidal, and offshore environments. More than 50 percent of the TBDEM is classified as estuarine and marine deepwater (U.S. Fish and Wildlife Service, 2017). About 40 percent of the landscape is classified as a wetlands type, where water saturation is the dominant land attribute (table 2), and lakes or rivers comprise the remaining landscape.

Flowing from northern Louisiana to the coast, the Atchafalaya and Mississippi Rivers drain 41 percent of the United States (Fleury, 2000) and dominate the landscape. The Atchafalaya River Basin is the largest wetland and swamp area in the United States (Hupp and others, 2008). More than one-third of southern Louisiana is part of the Mississippi River delta plain, where the river discharges into the Gulf of Mexico (Georgiou and others, 2010). Other major rivers within the regional model are the Sabine River, Ouachita River, Pearl River, Pascagoula River, and Mobile River. The Pascagoula River and Pearl River account for more than 90 percent of the freshwater discharge into the Mississippi Sound (Moncreiff, 2006; Eleuterius, 1978).

Almost one-half of the Gulf of Mexico Basin is a shallow water environment where 31 major estuarine watersheds drain and estuarine landform types shape 65 to 75 percent of the Gulf of Mexico coast (Harte Research Institute for Gulf of Mexico Studies, 2015). Roughly one-half of the estuarine landforms are salt marsh and mixed subtypes present in bays, deltaic environments, and other intertidal zones protected by barrier coast landforms (Miller-Corbett and Simley, 2014).

The TBDEM was acquired from the CoNED as a tiled matrix of four west-to-east trending rows, each including nine tiles across. Gridded data were provided at 3-meter (m) resolution. Most TBDEM tiles are 72 kilometers (km)

Table 1. Northern Gulf of Mexico topobathymetric digital elevation model source projects.

[topo, topographic; km², square kilometer; bathy, bathymetric; topobathy, topobathymetric; m, meter; USGS, U.S. Geological Survey; NED, National Elevation Dataset; --, no data; <, less than; CoNED, Coastal National Elevation Database Applications Project; BICM, Barrier Island Comprehensive Monitoring program; lidar, light detection and ranging; USACE, U.S. Army Corps of Engineers; CPRA, Coastal Protection and Restoration Authority; EAARL, Experimental Advanced Airborne Research Lidar; NOAA, National Oceanic and Atmospheric Administration; HFIP, Hurricane Forecast Improvement Project; OCS, Office of Coast Survey; N/A, not applicable designation in metadata; VDatum, vertical datum transformation; DEM, digital elevation model]

Source project	Source project area					Percent of model for data type resolutions					
	Topo (km²)	Topo lidar (km²)	Bathy acoustic (km²)	Topobathy acoustic/ lidar (km²)	Topobathy lidar (km²)	1 m	2 m	3 m	10 m	30 m	100 m
USGS NED	--	14,038	--	--	--	<1	1.7	4.5		--	--
USGS NED	2,653	--	--	--	--	--	--	--	1.7	--	--
USGS CoNED	--	27	--	--	--	--	--	<1	--	--	--
USGS CoNED	--	--	--	8,932	--	--	--	5.8	--	--	--
USGS BICM	--	--	--	--	0.13	--	--	--	<1	--	--
USGS BICM	--	945	--	--	--	<1	--	--	--	--	--
Stoker and others, 2009	--	17,636	--	--	--	--	--	11.5	--	--	--
USGS Louisiana Lidar Mosaic	--	34,767	--	--	--	--	--	22.5	--	--	--
USACE, CPRA	--	--	7	--	--	(0.6–1.5) <1	--	--	--	--	--
USGS EAARL	--	277	--	--	--	--	--	<1	--	--	--
NOAA HFIP	--	--	--	18,448	--	--	--	--	12	--	--
NOAA Global Topo	--	--	--	278	--	--	(1.5) <1	--	--	--	--
NOAA OCS	--	--	436	--	--	N/A	--	--	--	--	--
NOAA Tsunami Inundation	--	--	--	5,578	--	--	--	--	3.6	--	--
NOAA VDatum DEM	--	--	--	21,002	--	--	--	--	2.6	11	--
NOAA Coastal Relief	--	--	--	23,153	--	--	--	--	--	--	15
USACE Multi-beam	--	--	499	--	--	--	--	<1	--	--	--
USACE Topo lidar	--	5,374	--	--	--	--	--	3.5	--	--	--
USACE National Mapping Program	--	--	--	--	88	--	--	<1	--	--	--
Total area 154,138 km²	2,653	73,064	942	77,391	88	--	--	--	--	--	--
Percent of model	<1	66	1–2	28	<1	<1	<1	44	20	11	15

Table 2. Wetlands type for Louisiana, Mississippi, and Alabama coastal zones (from U.S. Fish and Wildlife Service, 2017).

[--, no data; N/A, not applicable]

Northern Gulf of Mexico model section	State	Estuarine and marine deepwater	Estuarine and marine wetland	Freshwater emergent wetland	Freshwater forested/ shrub wetland	Freshwater pond	Lake	Riverine
North	Louisiana	--	--	<1	80	2	2	15
North	Mississippi	--	--	<1	44	<1	2	53
North	Alabama	1	6	2	75	2	2	12
Midnorthern	Louisiana	46	2	2	41	<1	2	6
Midnorthern	Mississippi	81	2	<1	15	<1	<1	<1
Midnorthern	Alabama	80	3	1	15	<1	<1	<1
South and midsouthern	Louisiana	52	18	10	13	<1	3	3
South and midsouthern	Mississippi	N/A	N/A	N/A	N/A	N/A	N/A	N/A
South and midsouthern	Alabama	N/A	N/A	N/A	N/A	N/A	N/A	N/A

on a side, but for the northern and southern border tiles the north-south length is about 33 km. To make it easier to locate descriptions in the analysis, the four rows in the TBDEM are named the north, midnorth, midsouth, and south groups in this report (fig. 2).

From inland to offshore, where the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEMs overlay, the change in wetlands types from predominantly forested and shrub landscapes to estuarine and marine wetlands (deltaic) or estuarine and deepwater marine wetlands can be associated with an increase in differences between the TBDEM and 3DEP 1/3 arc-second DEMs. Differences also are pronounced in river systems classified as riverine and freshwater forested/shrub wetlands.

In the north group of the TBDEM, Louisiana and Alabama are predominately (80 percent) classified as freshwater forested/shrub wetlands (U.S. Fish and Wildlife Service, 2017); Mississippi wetlands are predominately riverine where freshwater forested/shrub wetlands make up most of the other wetlands type. Differences between the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEMs seem to be because datasets are from different periods, different sources, or both (Danielson and others, 2013).

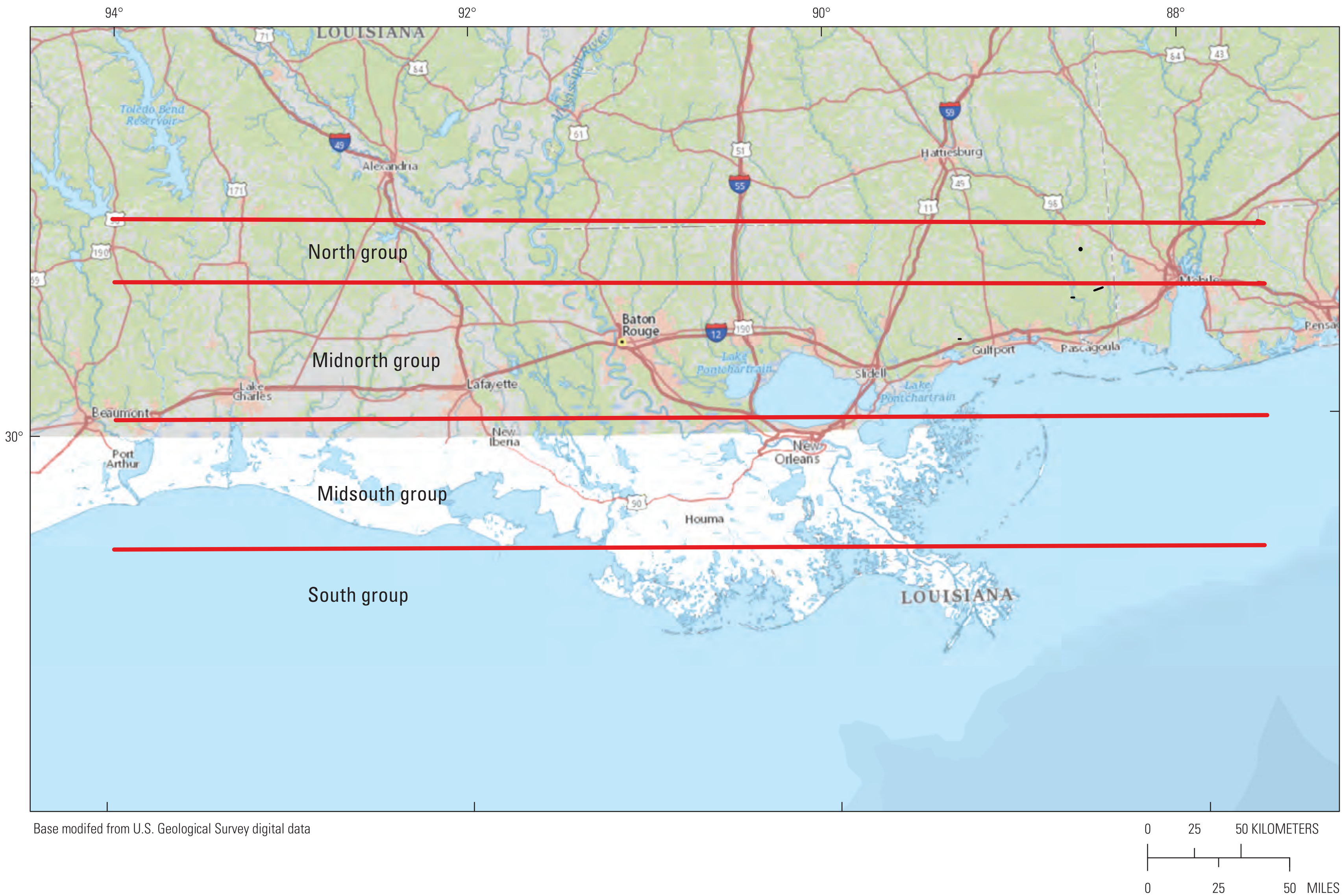
Beginning with the midnorth group, inland surface-water features, and estuarine or marine wetlands dominate the landscape. Louisiana wetlands are classified as 46 percent estuarine and marine deepwater wetlands types, and 41 percent of the landscape retains the freshwater forested/shrub wetland classification (table 2). East of onshore Louisiana and offshore of the Mississippi Delta Birdfoot, the TBDEM for Mississippi and Alabama maps the region across the land-water interface into the Mississippi Sound and oceanward of mean high water, transitioning from the estuarine and marine wetlands to barrier islands and the shallow to marine deepwater continental shelf. A total of 80 percent or more of Mississippi and Alabama that are within the study area where the largest percentage of differences was calculated are classified as the estuarine and marine deepwater wetlands type (table 2).

In the midsouth group, Louisiana transitions to predominately estuarine and marine deepwater environments (table 2). West of the Mississippi River, the Northern Gulf of Mexico TBDEM maps reaches of the Mississippi River, Atchafalaya River, Lower Atchafalaya River, the Wax Lake Pass channel, and large bays including Timbalier, Terrebonne, West Bays, and other smaller bays. Wetlands are classified as freshwater emergent or freshwater forested/shrub wetlands, or estuarine and marine intertidal wetlands that include saltwater marsh, beaches, shrubs, bays, shoals, open water estuarine, and deep marine (U.S. Fish and Wildlife, 2017). Land subsidence attributed to peat compaction or other physical processes in the Louisiana/Mississippi Delta is thought to account for ongoing changes in land surface elevations (Törnqvist and others, 2008), indicating temporal changes as a possible source for differences in elevation datasets. Wetlands classifications do not extend into the TBDEM south group (table 2).

Topobathymetric Digital Elevation Model Datasets

Source Project Data Types

Northern Gulf of Mexico TBDEM data are referenced to the Universal Transverse Mercator coordinate reference system. The horizontal datum is the North American Datum



Base modifed from U.S. Geological Survey digital data

Figure 2. Topobathymetric digital elevation model study area group.

of 1983. The vertical datum is the North American Vertical Datum of 1988. Topographic, bathymetric, and topobathymetric digital data available from the U.S. Geological Survey (USGS) The National Map 3DEP and USGS CoNED Applications Project, NOAA, the U.S. Army Corps of Engineers (USACE), and the State of Louisiana Coastal Protection and Restoration Project are provided as 67 source projects. Some of these resources contain multiple datasets (U.S. Geological Survey, 2017a; appendix). Spatially referenced metadata that conform to the Content Standard for Digital Geospatial Metadata (Federal Geographic Data Committee, 2014) are provided as Esri shapefiles.

Almost one-half of the Northern Gulf of Mexico TBDEM is constructed from topographic lidar projects covering more than 73,000 km^2 (47 percent) of the model region (table 1; fig. 3). These include the Katrina Regional Lidar Mosaic, covering 17,636 km^2, and the Louisiana Statewide Lidar Project, covering almost 35,000 km^2 of the TBDEM, which is a mosaicked topographic lidar project (Stoker and others, 2009; U.S. Geological Survey, 2009), and other USGS or USACE topographic lidar survey project datasets.

The Northern Gulf of Mexico metadata shapefile tags several Experimental Advanced Airborne Lidar (EAARL) surveys as bathymetric lidar datasets with a total coverage of 227 km^2. However, metadata for the EAARL projects indicate the datasets provide topographic maps but do not describe bathymetric data collection or integration. For Louisiana, these include topographic surveys for the north shore of Lake Pontchartrain (Bonisteel-Cormier and others, 2012), wetlands between Lake Pontchartrain and Lake Borgne (Nayegandhi and others, 2012a, 2009), and wetlands north and south of New Orleans, La., (Nayegandhi and others, 2012b, 2008). There also is an EAARL survey project for barrier islands in the Mississippi Sound (Smith and others, 2008; not shown). The Jean Lafitte National Historical Park lidar survey metadata indicate that “no data areas may include targets where an optical water depth is greater than 1.5 Secchi disc depths” that are used as an indicator of water clarity, but there is no description of bathymetric survey data collection or results (Nayegandhi and others, 2008). There are several EAARL surveys reported for the USGS Barrier Island Comprehensive Monitoring project (Hanson and Howd, 2008). However, the cited report for these surveys only describes different topobathymetric survey systems and neither descriptions of data collection surveys nor products could be found.

Geographic topographic 1/3 arc-second DEMs that include older elevation data, which were acquired between 1942 and 2006, account for about 2 percent of the Northern Gulf of Mexico TBDEM (table 1). These older elevation data predate lidar survey projects and depict elevation contours that may be derived from interpolated elevation field observations, photogrammetry, or aerial photography interpretation (Usery and others, 2009).

Topobathymetry developed from merged bathymetric sonar and topographic lidar-derived topobathymetry provide elevation datasets for more than 94,000 km^2 (55 percent) of the Northern Gulf of Mexico TBDEM (table 1; fig. 4). Of the six integrated topobathymetric models, four originate from NOAA projects using the Vertical Datum Transformation (VDatum) tool to transform input source data into common vertical and horizontal source units (Parker and others, 2008). These models are created to map coastal zones from the landward, navigable reaches of estuaries and charted embayments out to 25 nautical miles offshore (National Ocean and Atmospheric Administration, National Geodetic Survey, 2012). The CoNED Mobile Bay, Ala., topobathymetric model, created by merging 71 topographic lidar and acoustic bathymetric datasets, also used the VDatum tool to develop a common reference frame (Danielson and others, 2013). The CoNED topobathymetric model for the Chandeleur Islands is unpublished.

South of the Louisiana and Mississippi shoreline, the depths depicted in NOAA VDatum DEMs range from 91 m in the area west of the Mississippi Delta Birdfoot (hereafter referred to as the Birdfoot) to more than 700 m in the area southeast of the Birdfoot. East of Mississippi and oceanward of the Alabama barrier coast, the NOAA VDatum DEM depicts bathymetry 1,760 m below sea level.

Hydroacoustic data collected in sonar bathymetric surveys using side-scan, single-beam, or multibeam sonar systems to map riverbeds cover 943 km^2 of the Northern Gulf of Mexico TBDEM (fig. 5). Historical bathymetric data collected in 1888 used lead-line depth soundings to measure the depths to the bottom surface of Wicks Bay and Vermilion Bay, La. (National Oceanic and Atmospheric Administration, Department of Commerce, 1888a, b, c). Two integrated hydroacoustic survey projects used multibeam sonar and side-scan sonar systems to map the approach to Vermilion Bay, La. (National Oceanic and Atmospheric Administration, Department of Commerce, 2008; appendix). Hydroacoustic data were collected in multibeam sonar surveys to map bathymetry for the Atchafalaya River, Mississippi River, Lower Atchafalaya River, and Wax Lake Pass channel (U.S. Army Corps of Engineers, 2010, 2013; Coastal Planning and Engineering, Inc., 2012).

The USACE provides topobathymetric lidar data collected using the Scanning Hydrographic Operational Airborne Lidar Survey system for about 88 km^2 along Alabama, Florida, Louisiana and Mississippi coastal zones (U.S. Army Corps of Engineers, 2005).

Topobathymetric Digital Elevation Model Source Project Accuracy

The TBDEM metadata indicate the integrated topographic lidar datasets account for 47 percent of the Northern Gulf of Mexico TBDEM (table 1) and delineate most onshore elevations. Most of the these datasets are 3-m resolution DEMs (U.S. Geological Survey, 2017a). Vertical accuracies for the lidar source projects were not provided. However, original reports for the integrated projects and information from other sources were used as a basis for describing probable

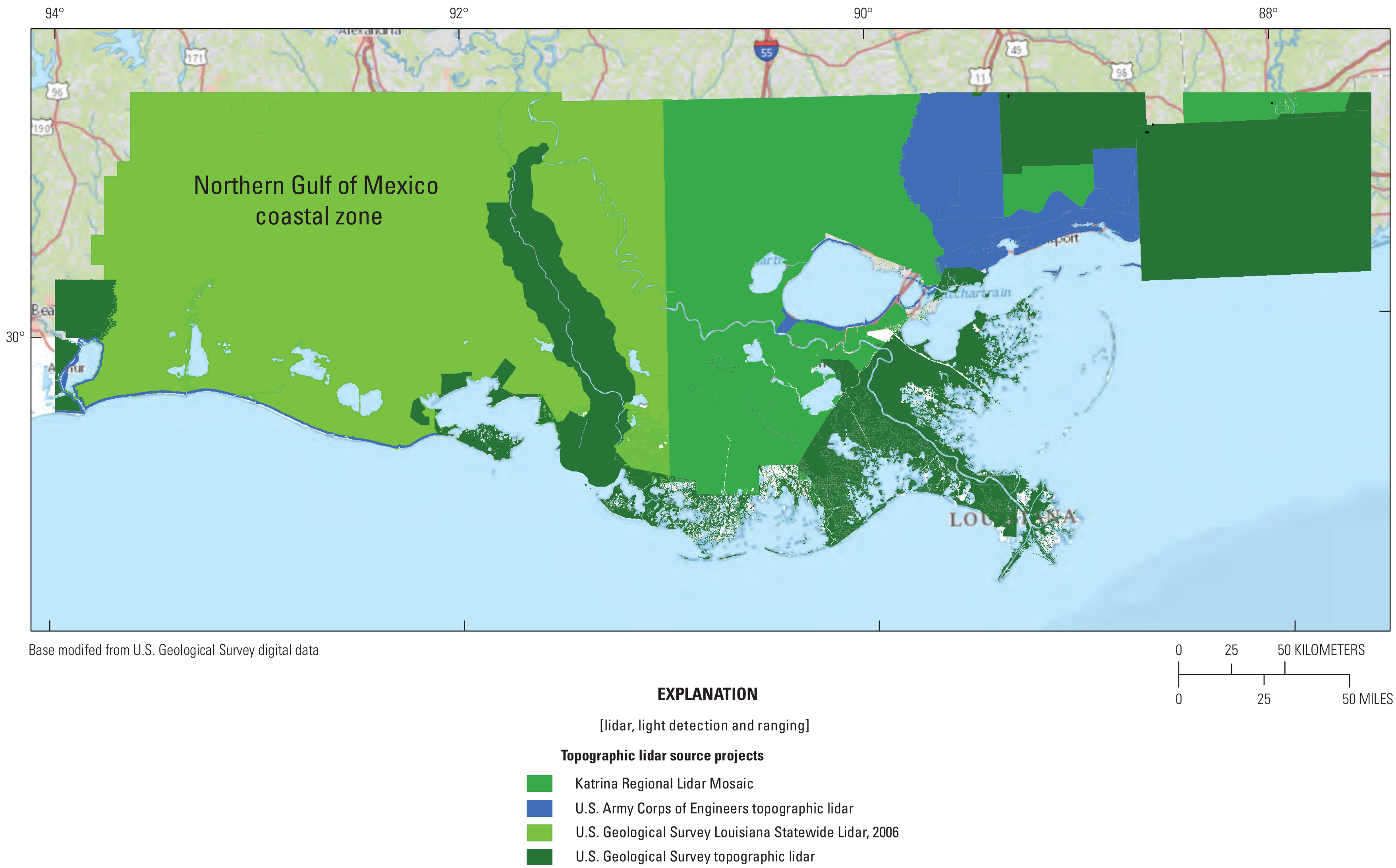


Figure 3. Topographic light detection and ranging project coverage.

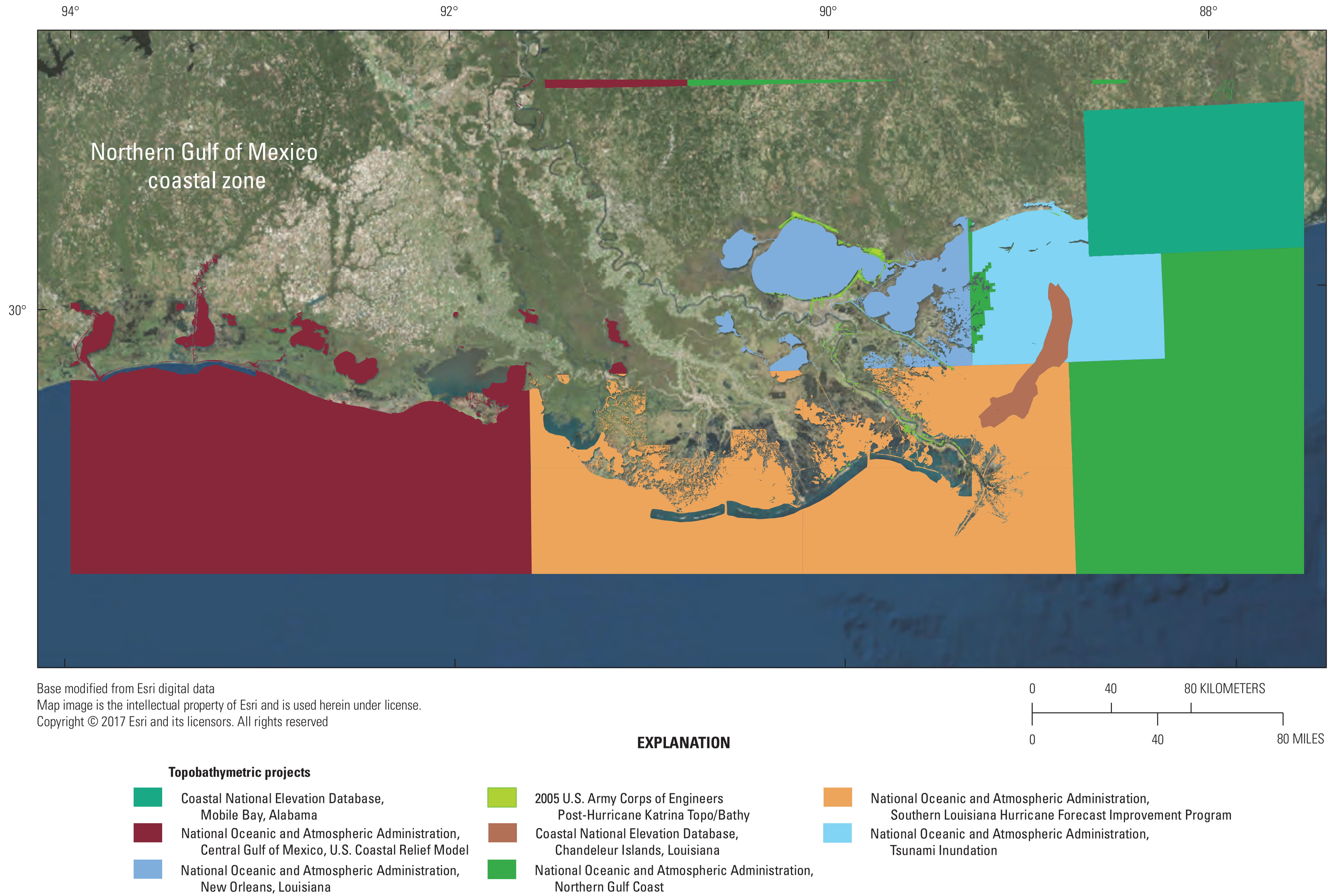


Figure 4. Topobathymetric survey projects coverage.

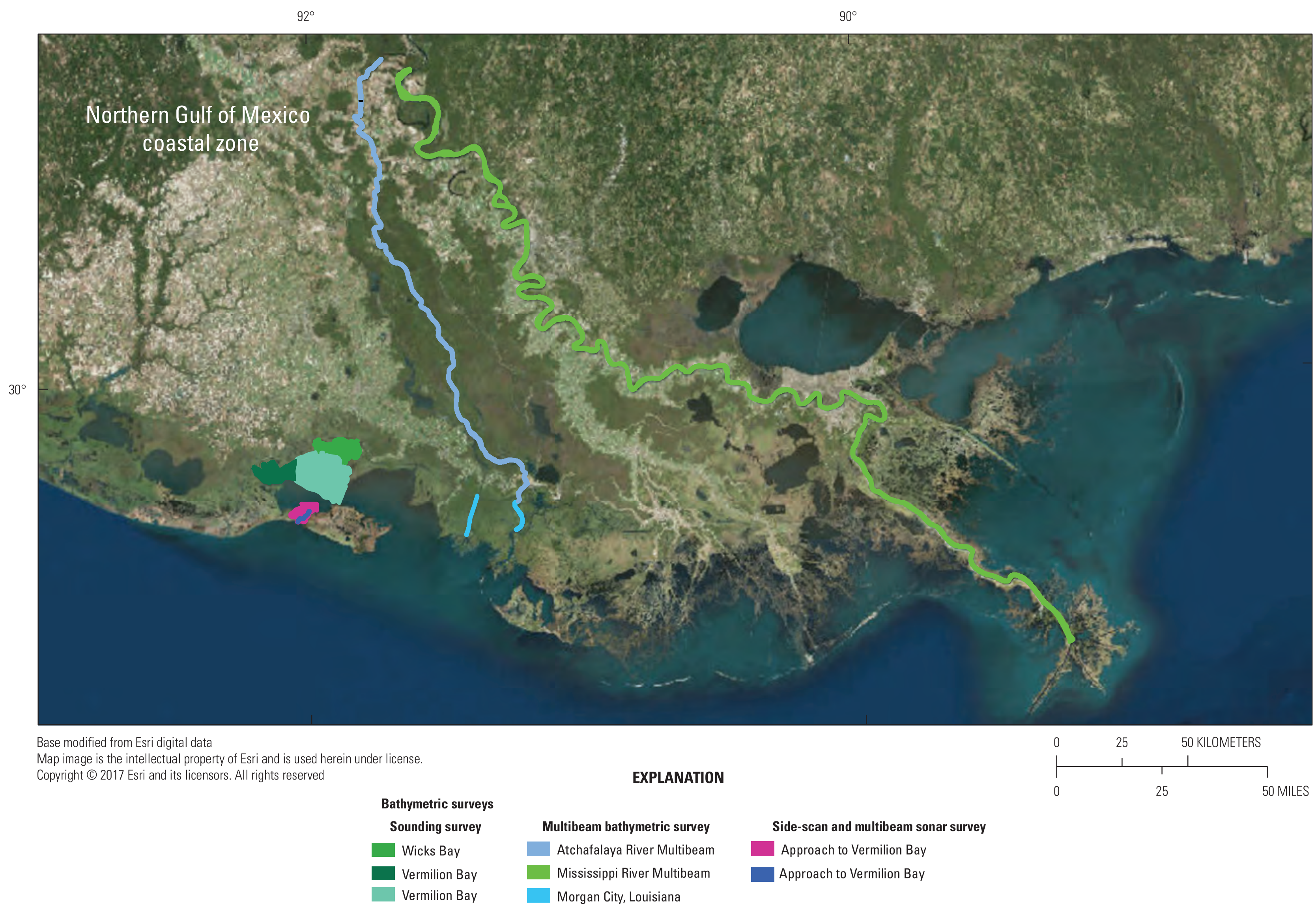


Figure 5. Bathymetric survey projects coverage.

vertical accuracies for datasets integrated in the TBDEM and assessing agreement with 3DEP lidar base specifications (version 1.3). These specifications identify four vertical accuracy quality levels for vegetated and for nonvegetated survey targets (Heidemann, 2018). Although almost all the Northern Gulf of Mexico topographic datasets are from 3DEP 1/3 arc-second DEMs produced from lidar (U.S. Geological Survey, 2018b), the probable TBDEM vertical accuracies are not reported in terms of vegetated or nonvegetated survey targets. Therefore, agreement between probable vertical accuracies for TBDEM lidar datasets and 3DEP lidar base specifications for vertical accuracy is qualitative and does not mean the TBDEM lidar datasets meet the specifications for quality levels.

3DEP lidar base specifications describe four quality levels, QL0 through QL4, each of which includes a value for nonvegetated vertical accuracy (NVA), calculated at a 95-percent confidence interval, and vegetated vertical accuracy (VVA) calculated at a 95th percentile (Heidemann, 2018). Quality levels are based on meeting lidar DEM absolute vertical accuracy and vertical root mean square error (RMSE) specifications for the vertical direction, $RMSE_z$, which is used to calculate the vertical accuracies (table 3). Absolute vertical accuracy is a measure that accounts for all systematic and random errors in a dataset (American Society for Photogrammetry and Remote Sensing, 2014); in 3DEP lidar base specifications it is stated with respect to a defined datum or reference system (Heidemann, 2018).

Applying National Standard for Spatial Data Accuracy methods, the $RMSE_z$ at the 95-percent confidence interval are calculated as (Federal Geographic Data Committee, 1998):

$$RMSE_z = \sqrt{\left(\sum_{i=0}^{n}\left(Z_{data\,i} - Z_{check\,i}\right)^2 / n\right)} \qquad (1)$$

where

$Z_{data\,i}$ is the vertical coordinate of the ith check point in the dataset,

$Z_{check\,i}$ is the vertical coordinate of the ith check point in the independent source of higher accuracy,

n is the number of points being checked, and

i is an integer from 1 to n.

The vertical accuracy, $Accuracy_z$, at the 95-percent confidence interval is estimated as:

$$Accuracy_z = 1.96 \times RMSE_z \qquad (2)$$

About 17 percent of the topographic DEMs integrated in the TBDEM were published in 2013 or 2014 (U.S. Geological Survey, 2017a). Gesch and others (2014, table 3) have estimated an absolute vertical accuracy RMSE of 0.87 m for the National Elevation Dataset (3DEP) 2013 version of 1/3 arc-second lidar DEMs. Assuming the 2013 topographic lidar datasets integrated in the TBDEM were included in this analysis, even if survey target vertical accuracies were designated as VVA or NVA, this set of TBDEM topographic lidar would not meet lidar base specifications for nonvegetated vertical accuracy (NVA) or vegetated vertical accuracy (VVA) quality levels QL0 through QL3 (table 3). The 2014 1/3 arc-second lidar DEMs are not evaluated.

A total of 83 percent of the Northern Gulf of Mexico TBDEM 1/3 arc-second topographic DEMs were published before 2013 (U.S. Geological Survey, 2017a). An example of accuracies for this vintage of 1/3 arc-second lidar DEMs is provided in a different analysis by Gesch (2013), which estimated vertical uncertainties for seven topographic 1/3 arc-second lidar DEMs ranging in age from 2005 to 2011 that were integrated in the Mobile Bay, Ala., topobathymetric source project (Danielson and others, 2013) included in the Northern Gulf of Mexico TBDEM. Results for the Gesch (2013) analysis indicate absolute vertical uncertainties estimated as the vertical $RMSE_z$ for lidar DEMs range from 0.06 m $RMSE_z$ to 0.20 m $RMSE_z$. If the RMSEz values were for nonvegetated targets, the QLs for the different DEMs range between lidar base specification QL0 to QL3 (table 3). These survey datasets were from either the USGS, USACE, or NOAA and can provide a good representation of the quality of 1/3 arc-second lidar DEMs for other source projects integrated in the TBDEM.

The source for unacceptable absolute vertical uncertainty for the 2013 lidar DEMs estimated by Gesch and others (2014) is of interest because the 2013 lidar DEMs were created from survey projects newer than those in the Gesch (2013) study group that were estimated to have vertical accuracies that align with lidar DEM standards. However, Gesch and others (2014)

Table 3. Absolute vertical accuracy for light detection and ranging data and digital elevation models (modified from Heidemann, 2018).

[$RMSE_z$, root mean error in the z direction; m, meter; NVA, nonvegetated vertical accuracy; VVA, vegetated vertical accuracy; QL, quality level; ≤, less than or equal to]

Quality level	$RMSE_z$, nonvegetated (m)	NVA at the 95-percent confidence level (m)	VVA at the 95-percent confidence level (m)
QL0	≤0.05	≤0.098	≤0.15
QL1	≤0.100	≤0.196	≤0.30
QL2	≤0.100	≤0.196	≤0.30
QL3	≤0.200	≤0.392	≤0.60

point out that the estimated accuracy of the 2013 lidar DEMs may because the analysis is based on comparing the lidar DEMs with the National Elevation Dataset DEMs, for which accuracy varies spatially because of the variable quality of the source data.

Other integrated topographic lidar surveys are from EAARL projects flown between 2007 and 2012 (Bonistell-Cormier and others, 2012; Nayegandhi and others, 2012a; Nayegandhi and others, 2008; Nayegandhi and others, 2009; Nayegandhi and others, 2012b; Smith and others, 2009). Each of the surveys report a 0.15-m vertical accuracy for the survey system. Though survey targets are not identified as vegetated or nonvegetated, the reported vertical accuracies could indicate the EAARL-derived data would meet quality level QL1 for NVA and VVA standards (table 3).

Topobathymetry datasets created using the NOAA VDatum tool provide 50 percent of the TBDEM (table 1), with 88 percent of those originating as NOAA VDatum topobathymetry projects. In the coastal to offshore zone, the VDatum tool merges topographic DEMs covering intertidal zones with bathymetric survey data extending out into the Northern Gulf of Mexico and delineating the ocean floor. Like topographic lidar survey errors, VDatum RMSE vertical errors (uncertainties) are calculated based on random and systematic errors (American Society for Photogrammetry and Remote Sensing, 2014; National Oceanic and Atmospheric Administration, National Ocean Services, 2016). The maximum vertical uncertainties at a 95-percent confidence reported by NOAA for VDatum topobathymetric projects in the northern Gulf of Mexico (Texas, Louisiana, Mississippi, and Alabama) range from 0.08 to 0.17 m (National Oceanic and Atmospheric Administration, National Ocean Service, 2016). Although the topobathymetric DEMs are largely a bathymetric data type, comparing these values with lidar DEM specifications indicate vertical uncertainties for the topobathymetric DEMs are in the range of the National Geospatial Program lidar base vertical accuracy specifications for quality level QL1 NVA and VVA.

Bathymetric source projects provide less than 1 percent of the TBDEM (table 1). For these survey data, standards for hydrographic surveys established by the International Hydrographic Organization (IHO; 2008) and adopted by the NOAA National Ocean Service (National Oceanic and Atmospheric Administration, National Ocean Service, 2017) are referenced for evaluating vertical accuracies. The IHO Order 1 total propagated uncertainty standard for multibeam bathymetry survey depths less than 100 m with a 95-percent confidence interval is 0.5 m (International Hydrographic Organization, 2008). None of the TBDEM bathymetric source projects mapped depths greater than 100 m; however, the IHO Order 2 total propagated uncertainty standard is 1.0 m with a 95-percent confidence interval for depths greater than 100 m (International Hydrographic Organization, 2008).

The NOAA report for the multibeam survey at the approaches to Vermilion Bay provided total (cumulative) vertical propagated uncertainties ranging from plus or minus (±) 0.297 to ± 0.300 m for two survey points (National Oceanic and Atmospheric Administration, Department of Commerce, 2008), which means these data meet the IHO Order 1 standard. Uncertainties were not found for the Wicks Bay and Vermilion Bay lead-line surveys that were done in 1888 and are available through NOAA.

Vertical accuracy values were not available for the USACE Atchafalaya River survey using the Teledyne Reson Seabat 8101 multibeam echosounder, or for the Mississippi River survey that used the Teledyne Reson Seabat 7101 survey systems. However, the manufacturer for both systems reports survey system specifications that meet International Hydrographic Survey standards (Reson, 2001, 2010).

Methods

Topobathymetric Digital Elevation Model

The CoNED Northern Gulf of Mexico TBDEM was created to integrate topographic, topographic lidar, acoustic sonar bathymetric, and topobathymetric, and topobathymetric lidar DEMs. The software uses systematic gridding techniques for handling spatial data having varying point and spacing densities and invokes a sequence of functionalities that support the topographic, bathymetric, or interpolation model components (Danielson and others, 2016). Interpolation for elevations is done using an empirical Bayesian kriging algorithm method to account for modeling elevations where data from different sources overlap and to retain accuracy of original bathymetric single-beam, multibeam, and hydrographic survey source data (Danielson and others, 2016). Statistical methods to evaluate model accuracy are also part of the process. The three-part process to integrate the disparate datasets is shown in figure 6. A complete description of the methods and process used to develop the TBDEM is provided in Danielson and others (2016). Although reported to provide vertical accuracy values expressed as an RMSE calculated at a 95-percent confidence interval (Danielson and others, 2016), these values were not included with the datasets or information provided to the USGS National Geospatial Technical Operations Center.

Digital Elevation Model Differences and Edge Matching

The TBDEM was provided as a set of tiles at 1-m resolution and resampled at three spatial resolutions to evaluate agreement with 3DEP 1/3 arc-second DEMs primarily produced from lidar. For more than 15 years, USGS elevation bare earth DEMs were maintained in the National Elevation Dataset (NED; Gesch, 2007). NED DEMs now are stored and distributed as 3DEP DEMs available in The National Map (U.S. Geological Survey, 2017f). Results for elevation differencing and edge-matching TBDEM and 3DEP 1/3 arc-second

DEMs provide examples of how well datasets for bathymetric, topobathymetric, and topographic lidar DEMS that are from different vintages can be merged and how well disparate data types from different sources agree with 3DEP DEMs. The results also can help to understand the level of effort that could be needed to develop hydrographic and elevation-hydrography dataset specifications and integrate bathymetric and topobathymetric data types with 3DEP DEMs to extend elevations beneath waterbodies.

Approach

The differences between the tiled Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEMs were calculated for all tiles at 10-m and 30-m grid spacing and for half the tiles at 100-m grid spacing. The map document for gridded elevation differences displays the geographic distribution of the magnitude of differences (fig. 7). Difference grids then were contoured at 2-m contour intervals to delineate the elevation differences. The high and low values for the range of absolute elevation difference values estimated for the 10-m and 30-m grid spacing varied by an average of 0.5 m and 4.6 m, respectively. For the same set of tiles, the high and low values for the range of absolute elevation difference values estimated for the 10-m and 100-m grid spacing varied by an average of 1.7 m and 6.3 m, respectively. The analysis described is for the comparison of the 10-m gridded TBDEM with the 3DEP 1/3 arc-second DEMs. The contoured results for differencing identify abrupt elevation changes in isolated or dense contour-difference patterns that stand out from adjacent areas. Summing the total length of contour lines in each difference contour interval and taking the ratio of that value to the total length for all difference contours provides an estimation of the percent agreement and differences between the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEMs.

Contoured differences between adjacent source projects were checked to evaluate project integration within the TBDEM. Potential elevation disparities were assessed by overlaying National Agricultural Imagery Program (NAIP) orthoimagery to evaluate the possible source for differences and outlier contour patterns. NAIP provides 1-m ground sample distance orthoimagery with a horizontal accuracy that matches within 6 m of photo-identifiable ground control points (U.S. Department of Agriculture, 2016), and in this analysis, the imagery is used as a higher accuracy dataset to derive accuracy information for the TBDEM.

Sites with exaggerated lidar-derived surface elevation highs are identified as positive outliers, and sites with exaggerated elevation depressions are negative outliers (Kobler and others, 2006; Matkan and others, 2014). Positive outliers have been interpreted as the result of multipath waveform reflections that can develop in lidar surveys for steep and forested areas that have dense to sparse canopy cover and forest openings. Steep angles between the top of a building and the immediately surrounding ground elevations also can result in positive outliers if lidar is misclassified or aboveground structures are not removed from the lidar-derived digital surface model. Negative outliers can happen where multiple reflections are at spots beside tall buildings and represent laser beams reflected several times among the glasses of buildings before being detected, where the increased travel time results in lower elevation calculations during lidar point cloud processing (Kobler and others, 2006; Matkan and others, 2014).

Overlaying results for differencing with gray-scale 3DEP 1/3 arc-second DEMs sometimes clarified where contoured difference patterns represent hydroflattened river system channels. Results also are overlain by High Resolution National Hydrography Dataset (HR NHD) Flowline networks to identify where contour patterns overlay artificial paths (stream/river features greater than 15.2-m wide) and streams/rivers (creeks and tributaries) or other flowline feature types. For example, an area of square to rectangular geometric patterns along the Louisiana coastal area turned out to be HR NHDFlowline network pipeline feature types (U.S. Geological Survey, 2017c, d, e).

Results—Digital Elevation Model Matches and Differences

Results for evaluating elevation differences between the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEMs generally corroborate successful integration of disparate datasets to create the regional elevation-hydrography TBDEM. Steep elevation differences, areas of isolated clusters of contoured differences, or dissimilar difference contours at adjacent source project boundaries account for a small part of the TBDEM that can be and are planned for updating with new elevation data to develop the Northern Gulf of Mexico TBDEM, version 2 (Jeffrey Danielson, U.S. Geological Survey, oral commun., 2019).

Overlaying areas of steep elevation transitions displayed in the contoured-difference results with 3DEP 1/3 arc-second DEM elevation profiles, U.S. Topo topographic maps, and NAIP imagery helped to clarify the validity of the steep gradients. In many areas, linear patterns of clustered difference contours follow dendritic flowline networks seen in gray-scale 3DEP 1/3 arc-second DEM imagery and reflect bathymetric and topobathymetric geodata integrated in the TBDEM. Overlaying these patterns and the HR NHDFlowline network often affirmed linear difference patterns that correlate in position with artificial paths, named or unnamed streams/rivers, and other feature types in NHDFlowline networks (U.S. Geological Survey, 2017c, d, e). In some places, difference patterns within source projects seem inherent to originally integrated datasets and were not caused by dataset preprocessing or interpolation techniques used to develop the Northern Gulf of Mexico TBDEM. However, areas of poor topographic elevation edge-matching at or within some integrated TBDEM projects need to be resolved for the TBDEM to meet 3DEP

Process component	Steps
Topographic component	Quality control check
	Lidar point classification
	Introduction of available breaklines
	Development of RMSE calculations using a random spatial subset of 5 percent of the total points to compute the interpolation accuracy; creating the land/water boundary mask using the MCH method; hydrologic enforcement (if required)
	Use of the MCH algorithm to constrain the terrain model
	Computation of the interpolation accuracy in RMSE by comparing elevation values in the random subset of points to values extracted from the derived gridded elevation surface
Bathymetric component	Checking of vertical and horizontal datums for bathymetry and, if required, transformation of datums to be referenced in NAVD88 and the NAD83 and projected in the appropriate UTM
	Tasks to prioritize and spatially sort bathymetric survey points based on accuracy, acquisition date, spatial distribution, and point density
	Selection of a random spatial subset of 5 percent of the bathymetric data as accuracy control points to compute the interpolation accuracy (RMSE)
	Interpolation of the remaining (95 percent) of the spatially sorted bathymetric data using the empirical Bayesian kriging algorithm to create a geostatistical model and use of these data along with associated spatial masks to develop a smooth, gridded bathymetric surface; cross-validation of the geostatistical model data against the control point data subset, with differences reported as RMSE; computation of the interpolation accuracy (as RMSE) by comparing the 5-percent random subset elevation values with values extracted from the derived kriging predictive surface.
Integration component	Tasks to create a mosaicked dataset model to load individual raster files from the topography and bathymetry components and create spatial seamlines using the MCH land/water boundary or associated breaklines from each raster layer
	Generalization of seamlines and splitting complex raster datasets to develop smooth layer transition boundaries; development of an integrated shoreline transition zone
	Sorting and sequencing of topographic and bathymetric raster layers based on accuracy and acquisition dates
	Output of the final integrated TBDEM based on prioritization of raster layers, and generation of spatially referenced metadata for each unique data set
Model revisions	After the Northern Gulf of Mexico TBDEM has been created and published, implement process steps as needed to revise layers for areas within the TBDEM to allow updates to incorporate newly acquired source data.

EXPLANATION

lidar	light detection and ranging
RMSE	root mean square error
MCH	Minimum Convex Hull
NAVD88	North American Vertical Datum of 1988
NAD83	North American Datum of 1983
UTM	Universal Transverse Mercator
TBDEM	topobathymetric digital elevation model

Figure 6. Topobathymetric digital elevation model development process (modified from Danielson and others, 2016).

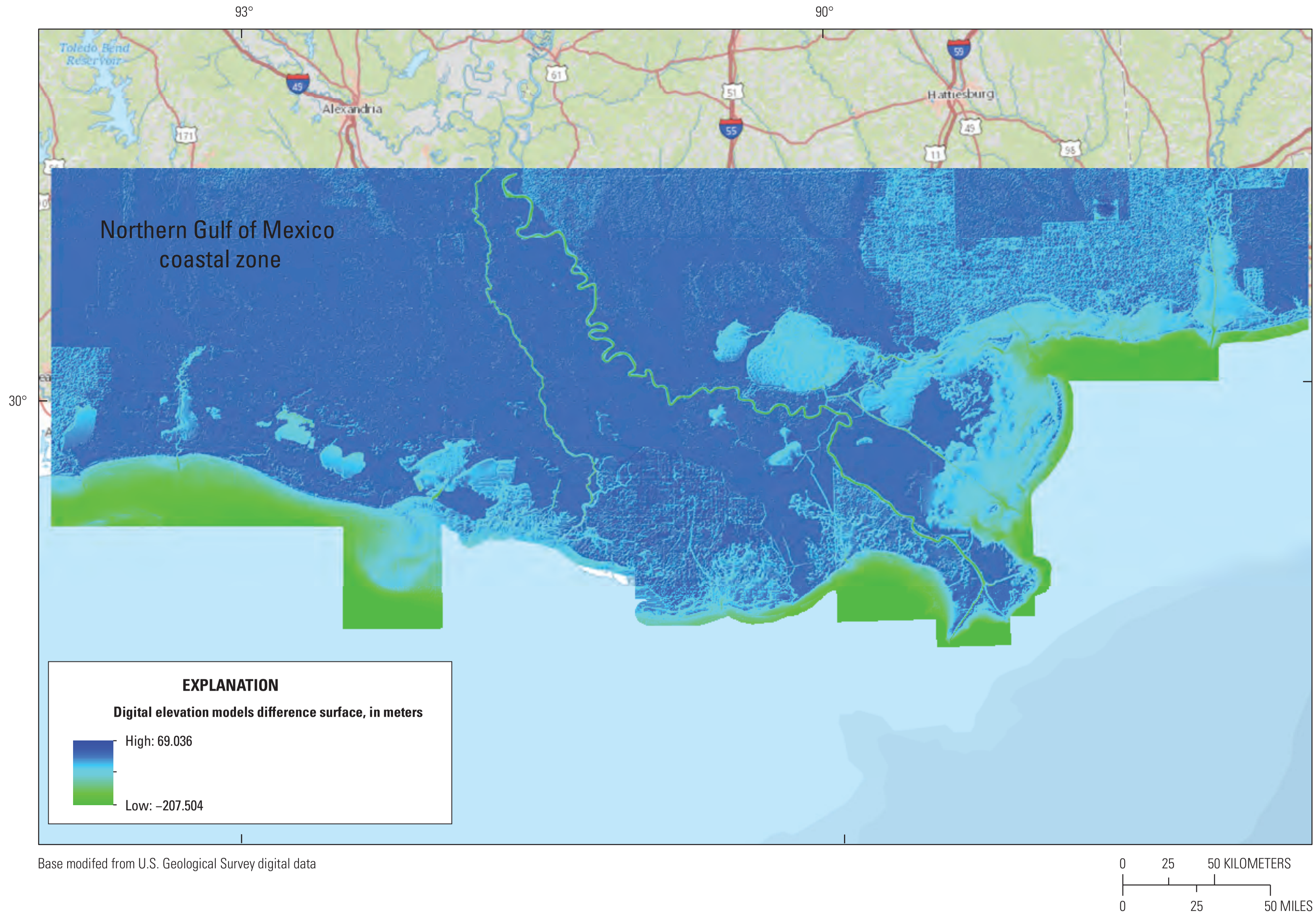


Figure 7. Northern Gulf of Mexico topobathymetric model and 3D Elevation Program digital elevation models difference surface.

specifications for seamless edge-matching described in Heidemann (2018).

Existing 3DEP specifications are for topographic lidar DEMs and preclude incorporating the bathymetric and topobathymetric datasets integrated in the Northern Gulf of Mexico TBDEM as a 3DEP product. Acquisition of the TBDEM for distribution through the 3DEP would require new specifications to address variable survey systems, data collection protocols, and reporting data or product quality.

Agreement for Topobathymetric and 3DEP Digital Elevation Models

The comparison of Northern Gulf of Mexico TBDEM with 3DEP 1/3 arc-second lidar DEMs affirms that at 10-m, 30-m, and some 100-m resolutions, the range of differences is similar, often within 2 m. Based on the similarity of initial results for differencing, the analysis using 1/3 arc-second DEMs also can provide a valid premise for characterizing agreement and the range or geographic distribution of differences between the two DEM types at 30-m and 100-m resolutions.

Comparison of the Northern Gulf of Mexico TBDEM north group and 3DEP 1/3 arc-second DEMs indicates elevations for five of the nine tiles display 99- to 100-percent agreement with 3DEP 1/3 arc-second DEM geodata (fig. 8). Two tiles display 93- to 95-percent agreement, and the remaining two tiles had 89-percent and 75-percent agreement, respectively. Most differences are within the ±2-m range and are associated with surface-water features identified in other referenced sources. Differences identified at the seams between or within integrated source projects indicate the TBDEM would not meet The National Map (Archuleta and others, 2017) requirements for a single nonoverlapping project tiling scheme, but this requirement for consistency might not be applicable to the TBDEM.

In the westernmost section of the north group, integrated topographic lidar is from the Louisiana Statewide Lidar Project (U.S. Geological Survey, 2009). Differences in this area of the TBDEM correlate with hydrographic features visible in gray-scale 3DEP 1/3 arc-second DEMs and in the HR NHDFlowline network (U.S. Geological Survey, 2017d). Difference contours also exist along apparent linear seams within the Louisiana Statewide Lidar Project and seem to reflect differences within the source project dataset.

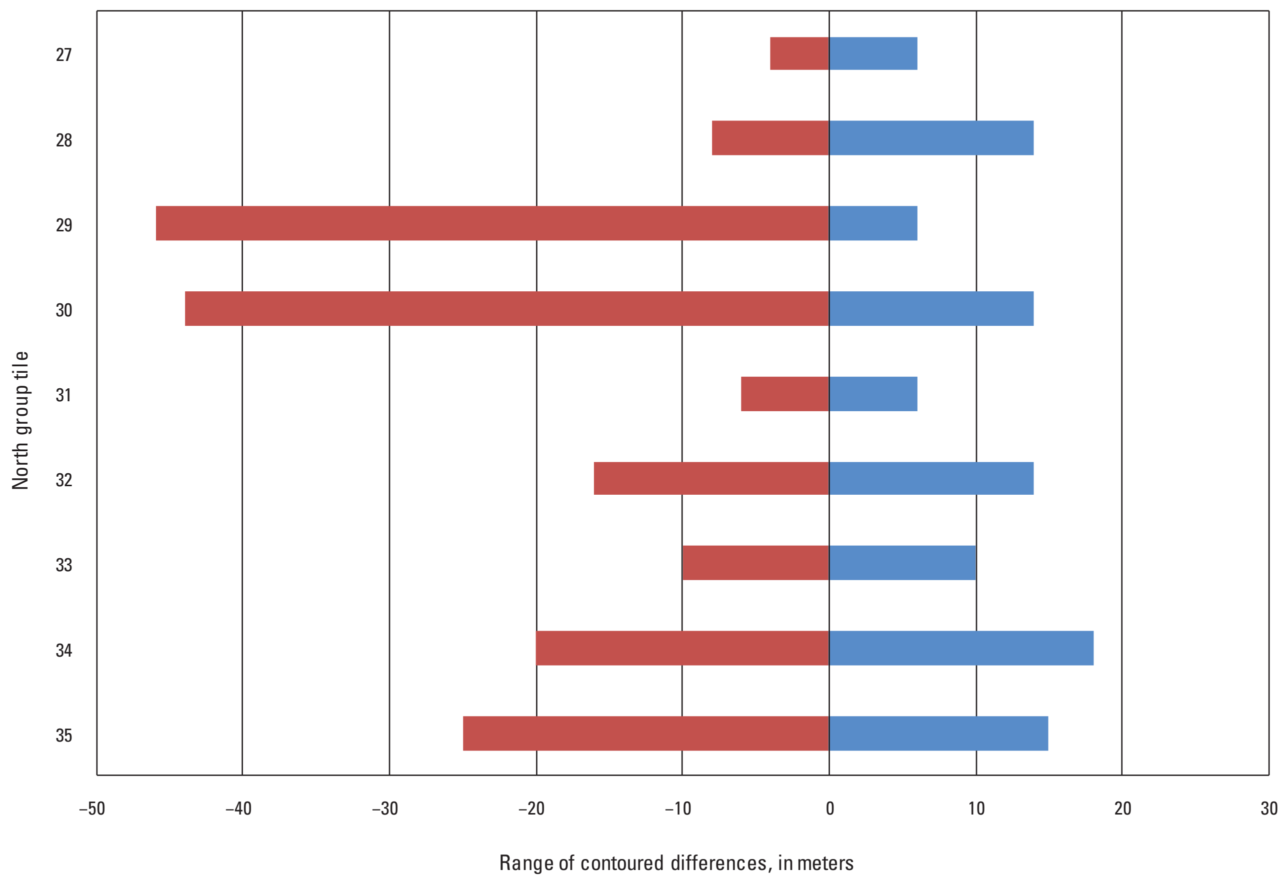
Continuing east and still within the Louisiana Statewide Lidar Project, there generally is good agreement between the TBDEM and 3DEP 1/3 arc-second DEMs, except where multibeam bathymetric surveys that map the Atchafalaya River and Mississippi River channels (U.S. Army Corps of Engineers, 2010, 2013b) are integrated in the TBDEM. Other differences between the TBDEM and 3DEP 1/3 arc-second DEMs are associated with surface-water features often identified as artificial path feature types representing the assumed and generalized flow through a two-dimensional feature, such as a lake or a wide double-banked stream in the HR NHDFlowline network (U.S. Geological Survey, 2017d).

For the northern part of the TBDEM covering Mississippi, a dense pattern of contour differences developed between the Pascagoula River and Escatawpa River. Overlaying the HR NHDFlowline network showed that constructed artificial paths and stream/river features coincide with the pattern of difference contours (U.S. Geological Survey, 2017e). This area is part of a square-shaped cluster of difference contours and seems to represent differences for a bathymetric or topobathymetric dataset that was integrated in the Mobile Bay, Ala., topobathymetric project.

The region north of Mobile Bay, Ala., includes seamlessly integrated topobathymetry for the Tensaw River, Mobile River, and a network of braided creeks mapped in the integrated NOAA Northern Gulf Coast VDatum project (Love and others, 2012). Topographic lidar data surrounding the topobathymetric project are integrated from the Mobile Bay, Ala., and Baldwin County, Ala., topographic lidar projects (Danielson and others, 2013), and the Katrina Regional Lidar Mosaic project (Stoker and others, 2009). Comparing east-west trending elevation profiles created for the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEM covering northern Mobile Bay, Ala., indicated the water body is hydroflattened in the 3DEP 1/3 arc-second DEM (not shown) where the Northern Gulf of Mexico TBDEM delineates channel bottom morphology (fig. 9).

In the Northern Gulf of Mexico TBDEM midnorth group, elevations depicted for four out of the nine TBDEM tiles (tiles 18, 19, 20, and 22) agree well with 3DEP 1/3 arc-second DEMs with minor differences account for much less than 1 percent of the results (fig. 10). Comparisons for three other tiles indicate 95- to 97-percent agreement. The other two group tiles cover intertidal to offshore environments where the TBDEM elevation data are integrated from several topobathymetric and topographic lidar projects. In this region, model elevations and 3DEP 1/3 arc-second DEMs have only 74- to 76-percent agreement. The reason for differences, described below, is attributed to the TBDEM including numerous surface-water features integrating numerous rivers and lakes, and coverage of NOAA topobathymetric DEMs that extend offshore.

From the western limit of the midnorth group to east of the Mississippi River, differences between the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEM appear where the TBDEM integrates the topobathymetric U.S. Coastal Relief Model project that delineates the Calcasieu River (National Oceanic and Atmospheric Administration, National Geophysical Data Center, 2001), and the USACE multibeam bathymetry survey projects that provide bathymetry for the Atchafalaya River and Mississippi River (U.S. Army Corps of Engineers, 2010, 2013). In other areas of the midnorth group, overlaying USGS single topographic lidar projects and the Louisiana Statewide Lidar Project (U.S. Geological Survey, 2013b, 2009) with 3DEP 1/3 arc-second DEMs, orthoimagery (U.S. Department of Agriculture, 2016),



North group tile	Total length of all difference contours, in meters	0-meter difference contours		Other difference contours
		Total length of no-difference contours, in meters	Total length of all contoured differences, in percent	Contour, percent of total length of all contours
27	71,769,617	71,66,5479	99	other, 1 percent
28	64,899,086	64,745,826	99	other, 1 percent
29	112,431,142	111,123,053	99	other, 1 percent
30	93,559,607	87,017,172	93	±2 m, 5 percent; other, 2 percent
31	67,301,921	67,300,480	100	No data
32	36,673,974	32,664,389	89	±2 m, 10 percent; other, 15 percent
33	51,468,691	48,901,450	95	±-2 m, 4 percent; other, 1 percent
34	60,951,011	45,764,558	75	±2 m, 19 percent; ±4 m, 5 percent; other, 1 percent
35	42,185,165	41,747,568	99	other, 1 percent

Figure 8. Comparison of north group topobathymetric and 3D Elevation Program digital elevation models.

and HR NHDFlowline networks (U.S. Geological Survey, 2017d,) indicates that ±2-m difference contours are associated with surface-water features included in HR NHD stream/river feature types. Larger differences between 3DEP 1/3 arc-second DEMs and the Northern Gulf of Mexico TBDEM also exist where the TBDEM includes topobathymetric or bathymetric datasets.

From Lake Pontchartrain, La., to the seaway entrance at Biloxi Bay, La., the midnorth group covers the coastal zone from inland landscapes through the intertidal and estuarine zone and into marine deep water over the Mississippi-Alabama continental shelf. In addition to covering most of Lake Pontchartrain, this area includes Lake Borgne, Pearl River, Jourdan River, Wolf River, Biloxi River, other named rivers, creeks, bayous, and large bays such as Bay Saint Louis and Biloxi Bay. Roughly 40 percent of the area covered by TBDEM tile 24 is offshore. Integrated source projects covering Lake Pontchartrain to Le Petit Pass Island include the Danielson and others (2016) topobathymetric model for the northern tip of Chandeleur Islands, three NOAA acoustic-lidar topobathymetric projects, four topobathymetric lidar projects, and nine topographic lidar projects. Contours depicting elevation differences inland from the coastline often overlay reaches of the dense network of rivers and creeks in the coastal zone where topographic lidar source projects are integrated in the TBDEM.

From east of Biloxi Bay to about 88 ºW longitude (midway across Mobile Bay, Ala.), elevation data are integrated from the CoNED Mobile Bay, Ala., topobathymetric project and two NOAA topobathymetric projects (Danielson and others, 2013; Love and others, 2012; Taylor and others, 2008). In this area, the inland to offshore elevation transition is smooth. The disparity between the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEMs (25 percent) is partly because an estimated 70 percent of the TBDEM topobathymetric projects provide bathymetry for the estuarine to deepwater along the Mississippi-Alabama continental shelf. Also, bathymetry for dredged channels reaching from offshore into Mobile Bay, Ala., and Pascagoula Bay, Miss., and one or two dredged channels extending from these main channels to the western banks of each bay accounts for differences. Inland, there are concentrations of differences ranging from −14 m to +16 m along the steep western bank of the Tombigbee River in Mississippi and in the riverine and freshwater forested/shrub wetlands west and northwest of Mobile Bay, Ala.

The midsouth group begins at the west shore of Lake Sabine. The group of tiles includes Port Arthur and City of Port Neches, Texas, and the lower 12 km of the Neches River channel that empties into Lake Sabine. From here to the western shoreline of Vermilion Bay, La., the Northern Gulf of Mexico TBDEM integrates six USGS topographic lidar projects, the USACE post-Gustav and Ike topographic lidar project (U.S. Army Corps of Engineers, 2012), and the NOAA Coastal Relief topobathymetric project (National Oceanic and Atmospheric Administration, National Geophysical Data Center, 2001). The results of the TBDEM midsouth group comparison with areas covered by 3DEP 1/3 arc-second DEMs indicate that half the area is in 100-percent agreement. The other half of the area is in 97- to 98-percent agreement (fig. 11.)

Differences around the Sabine Lake area are in port cities and where a network of manmade water channels is identified as connector feature types in the HR NHDFlowline network (U.S. Geological Survey, 2017d) or appear to be wastewater holding ponds. In the Calcasieu Lake area, difference contours are present where the U.S. Coastal Relief topobathymetric model maps the Calcasieu River channel that empties into the north side of the lake and drains into the Gulf of Mexico on the south side of the lake. There also are polylines representing differences along the banks of Grand Lake and White Lake, La., which are hydroflattened in 3DEP lidar 1/3 arc-second DEMs. Offshore of mean high water, the gradual increase in differences reflects the transition to the deeper marine continental shelf.

A total of 18 different source projects are integrated in the TBDEM (U.S. Geological Survey, 2017a) for the area extending from the western margin of Vermilion Bay, La., to near Donaldsville, La., on the southern bank of the Mississippi River, and from north at a latitude about parallel with Donaldsville, La., to 29.5 ºN latitude offshore. Sonar bathymetric, NOAA topobathymetric, and topographic lidar datasets depict elevations for inland coastal to deep marine wetlands (U.S. Fish and Wildlife Service, 2017). This region includes the Lower Atchafalaya River and Vermilion River that flow through wetlands and empty into coastal bays, numerous waterways, lakes, and bayous. Comparing the TBDEM to 3DEP 1/3 arc-second DEMs showed that differences account for less than 1 percent of the area. Contours for differences greater than ±2 m are present where bathymetric data map the floor of the approach channel to Vermilion Bay or where NOAA topobathymetric data map intertidal estuarine and marine deepwater environments (National Oceanic and Atmospheric Administration, Department of Commerce, 2008; National Oceanic and Atmospheric Administration, National Geophysical Data Center, 2001; U.S. Fish and Wildlife Service, 2017).

In the next area to the east, but still to the west side of the Mississippi River, differences accounting for 3 percent of the comparison between the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEMs are predominately within the Mississippi River channel but also where contours overlay artificial paths in the HR NHDFlowline network (U.S. Geological Survey, 2017d). Continuing east from and including the area from southern Lake Pontchartrain to offshore at Chandeleur Island in Chandeleur Sound, the TBDEM midsouth group maps the Mississippi Delta and covers various coastal zone water bodies, rivers, and constructed or modified waterways. West of Chandeleur Island, La., the midsouth group is offshore in the Mississippi-Alabama continental shelf (Galloway, 2008). In this part of the midsouth group, 25 source projects including multibeam bathymetric, topobathymetric, topobathymetric lidar, and topographic lidar projects are

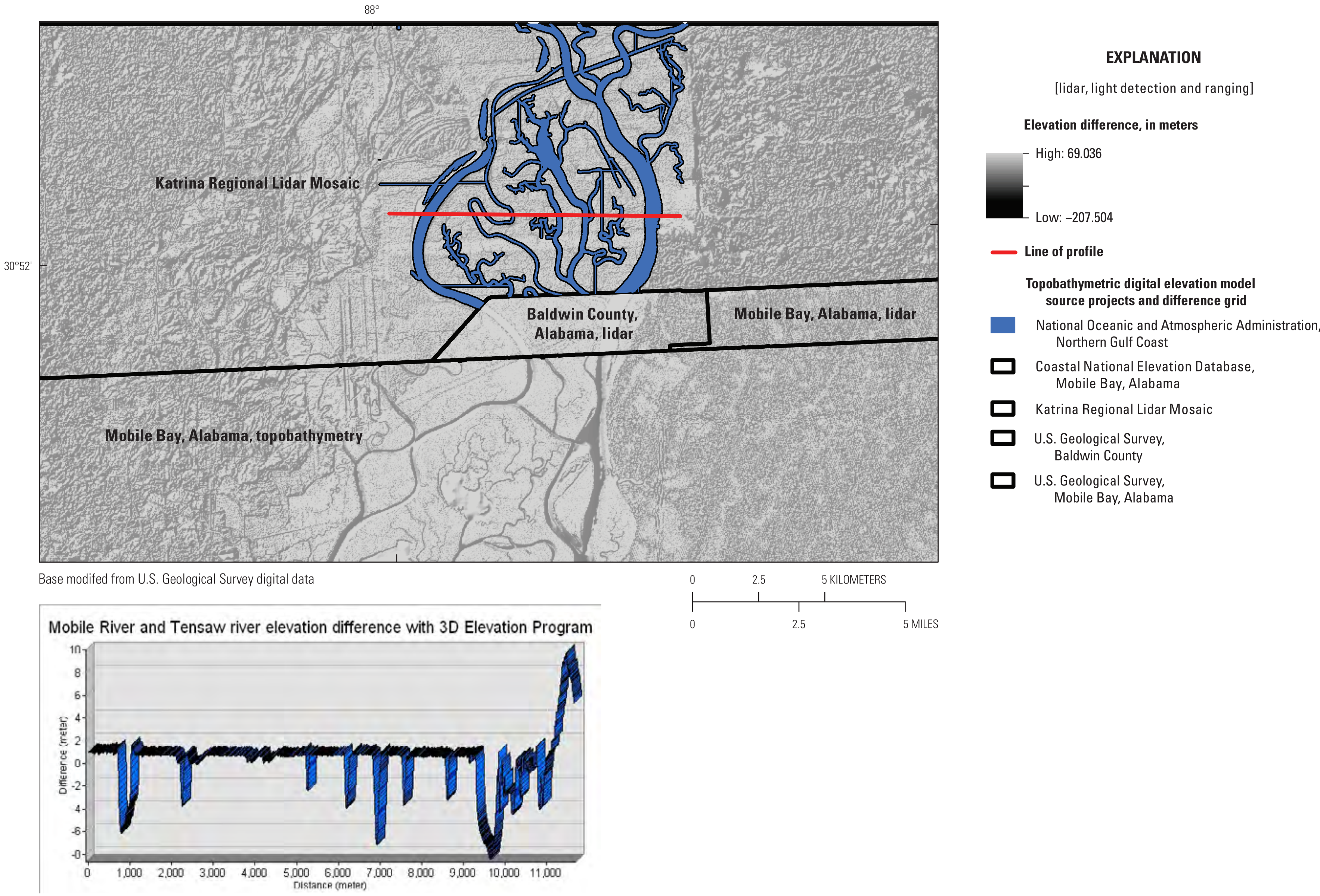
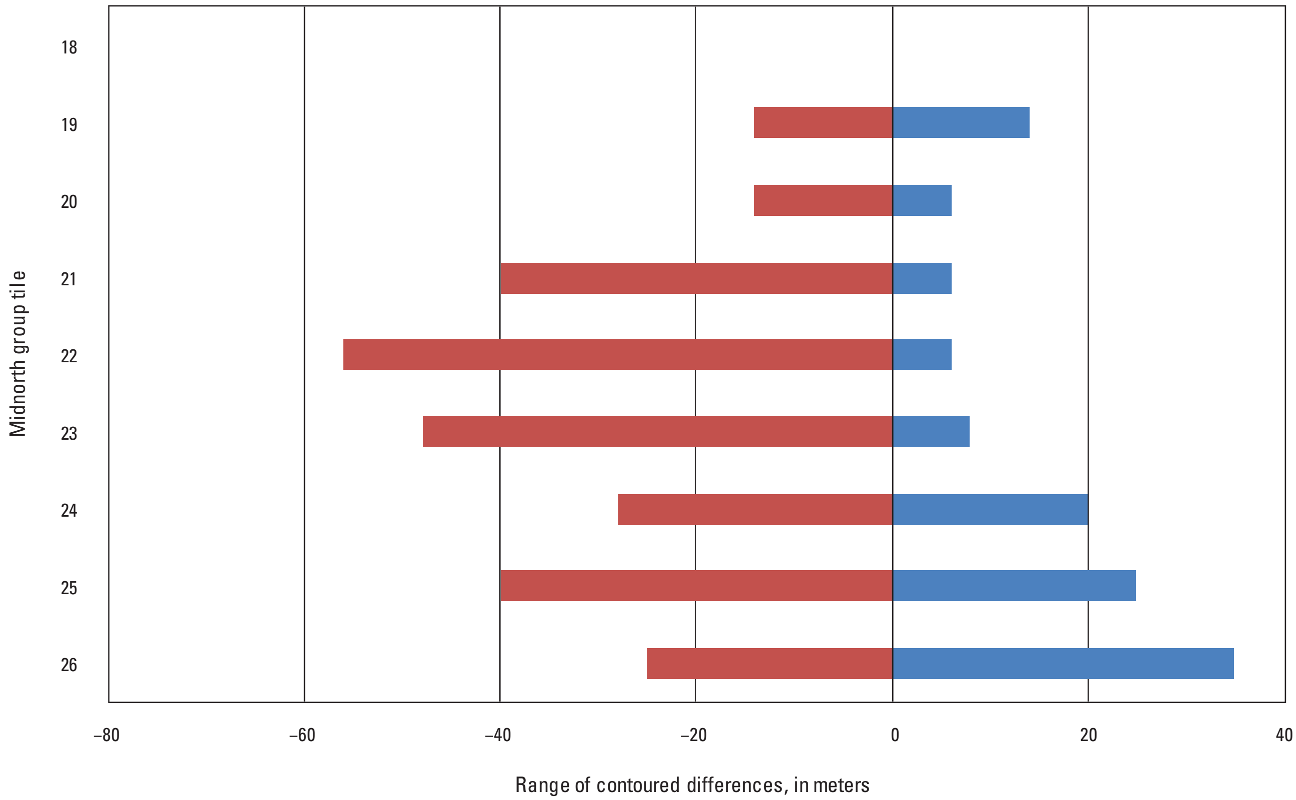
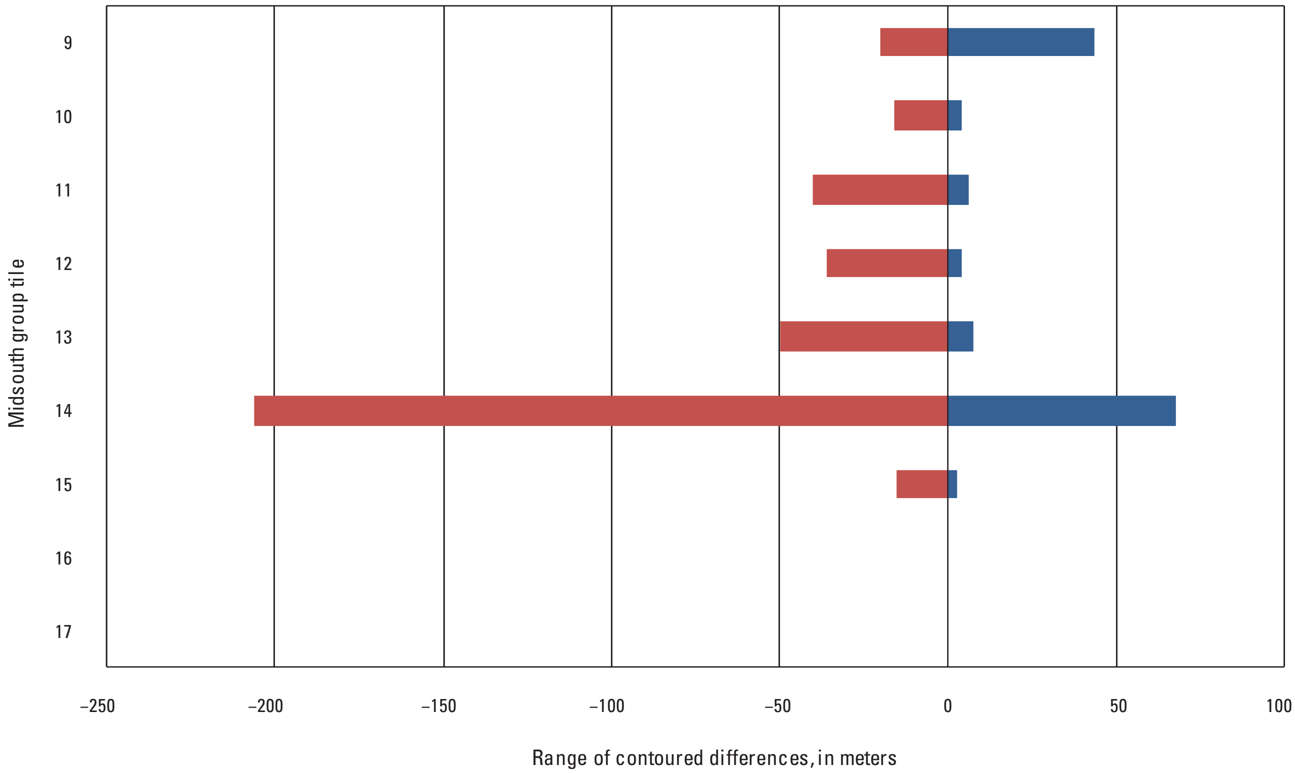


Figure 9. Elevation profile across Mobile River and Tensaw River.



Midnorth group tile	Total length of all difference contours, in meters	0-meter difference contours		Other difference contours
		Total length of no-difference contours, in meters	Total length of all contoured differences. in percent	Contour, percent of total length of all contours
18	66,925,732	66,909,697	100	other, less than 1 percent
19	61,002,603	60,991,685	100	other, less than 1 percent
20	79,027,927	78,705,951	100	other, less than 1 percent
21	76,389,311	74,573,643	97	±2 m, less than 1 percent; other, 3 percent
22	71,769,617	71,665,479	100	other, less than 1 percent
23	82,566,698	78,424,255	95	±2 m, 4 percent; other, 1 percent
24	49,451,274	37,723,564	76	+2 m, 11 percent; −2 m, 9 percent; other, 4 percent
25	39,309,954	29,082,662	74	+2 m, 6 percent; −2 m, 9 percent; other, 11 percent
26	47,270,319	45,518,967	96	±2 m, 3 percent; other, 1 percent

Figure 10. Comparison of midnorth group topobathymetric and 3D Elevation Program digital elevation models.



Midsouth group tile	Total length of all difference contours, in meters	0-meter difference contours		Other difference contours
		Total length of all difference contours, in meters	Total length of all contoured differences, in percent	Contour, percent of total length of all contours
9	90,250,639	89,108,287	99	other, 1 percent
10	67,089,849	67,046,376	100	No data
11	57,070,339	57,017,067	100	No data
12	42,410,607	42,291,474	100	No data
13	51,550,473	50,181,130	97	< −2 m, 2.5 percent; − 2 m, less than 1 percent; other, less than 1 percent
14	153,059,430	149,994,424	98	±2 m, 1.6 percent; other, less than 1 percent
15	26,580,115	25,919,901	97	±2 m, less than 1 percent; ±4 m, 2 percent; other, less than 1 percent
16	Offshore			Not applicable
17	Offshore			Not applicable

Figure 11. Comparison of midsouth group topobathymetric and 3D Elevation Program digital elevation models.

integrated (U.S. Geological Survey, 2017a). Differencing results indicate the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEM elevations are in 97- to 98-percent agreement. Contoured differences between the TBDEM and 3DEP 1/3 arc-second DEMs are as much as 60 m to 64 m for a reach of the Mississippi River in New Orleans. The difference is really the river depth, which is corroborated in other resources (Armstrong, 2008). NOAA topobathymetric projects continue offshore of 3DEP 1/3 arc-second DEMs and map the ocean bottom depth between −88 m deep and −207 m deep at the southeast corner of the Northern Gulf of Mexico TBDEM.

Except for features mapped to provide bathymetry for water areas such as the Mississippi River channel, the Gulf Outlet Canal, the Intracoastal Waterway, or the Inner Harbor Navigation Canal, absolute difference values greater than 2 m seem to represent outliers (not shown). On the south shore of Lake Pontchartrain, there are areas of multiple buildings where contours depict large positive outliers. The largest positive outlier is 68 m, and there were 24 sites that had 14-m outliers. These outlier elevation differences usually are concentrated along city streets in areas where the TBDEM integrates topobathymetric and topographic lidar source projects (Love and others, 2010; Stoker and others, 2009; U.S. Army Corps of Engineers, 2009, 2010; Nayegandhi and others, 2012a). There also are two sites depicting large negative outlier values of −22 m and −208 m for differences between topographic lidar and 3DEP 1/3 arc-second DEMs.

South group coverage extends from an area inland at 29 ºN to offshore at about 28.7 ºN latitude including southern Louisiana and the Birdfoot. More than one-half of the Northern Gulf of Mexico TBDEM south group is offshore, south of 3DEP 1/3 arc-second DEM coverage. All data integrated in the Northern Gulf of Mexico TBDEM for this offshore region are from NOAA topobathymetric projects. In the region common to the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEMs (half the width of the south group row), 3 sonar-bathymetric, 1 multibeam bathymetric, 6 NOAA topobathymetric, 1 topobathymetric lidar, and 17 topographic lidar projects were integrated to develop the TBDEM (U.S. Geological Survey, 2017a). From the southwest corner of Marshall Island, La., to the west side of the Mississippi Delta in West Bay, La., much of the TBDEM covers estuarine and marine wetland landforms or large bays and vegetation (U.S. Fish and Wildlife Service, 2017). There is 96- to 97-percent agreement for three of the four TBDEM tiles that are covered by 3DEP 1/3 arc-second DEMs, and 91-percent agreement for the other covered tiles. Most differences between the TBDEM and 3DEP 1/3 arc-second DEMs were estimated at −2 m (fig. 12). Larger differences are where the Lower Atchafalaya River empties into Atchafalaya Bay and where major manmade canals drain into Timbalier Bay or Barataria Bay.

A total of 13 source projects were integrated to map the Mississippi Delta and Birdfoot (U.S. Geological Survey, 2017a). Except for a few areas, the TBDEM elevations match 3DEP 1/3 arc-second DEMs. One area of exception is in the salt marsh along tributaries of the Mississippi River where all differences are within 0 to 2 m. Another exception is along each side of the upper Birdfoot where there are ±2-m differences. Moving away from the Birdfoot into the Norther Gulf of Mexico included in the TBDEM, the differences in depth between topobathymetric source projects and the 3DEP 1/3 arc-second DEM reflect offshore depths (fig. 13).

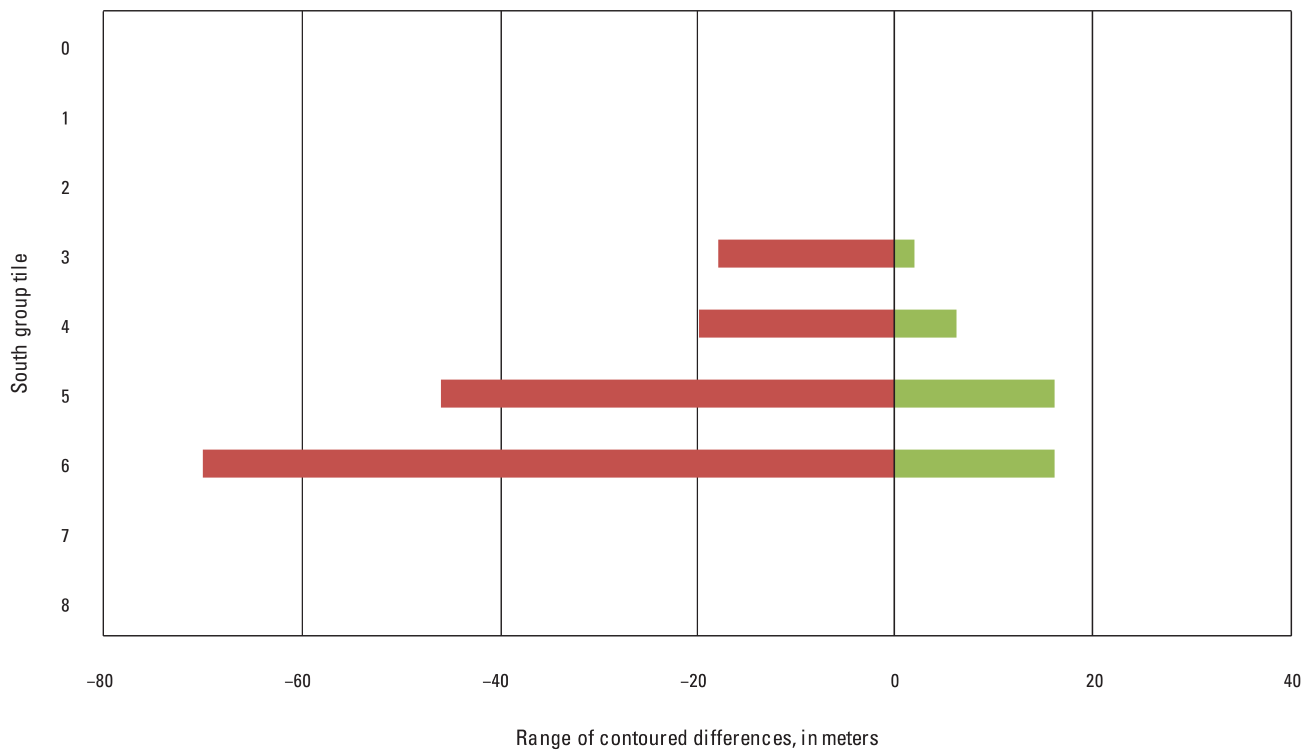
Integrated NOAA topobathymetric data (Love and others, 2010) extend the TBDEM almost 3 km seaward from the toe of the Birdfoot, covering the Northern Gulf Coast continental shelf seafloor where the elevation depth is about −26 m. The CoNED and NOAA topobathymetric elevation datasets extend the TBDEM almost 95 km oceanward of Alabama State coastal barrier islands that separate Mobile Bay from the open sea. The topobathymetric data map the seafloor at −208 m (Danielson and others, 2013; Love and others, 2012; Taylor and others, 2008). From the shoreline of the Birdfoot to the southern limit of the Northern Gulf of Mexico TBDEM, the uniform increase in bathymetric depths reflects the natural transition from shallow nearshore and intertidal zone bathymetry to the relatively deep Mississippi-Alabama continental shelf.

Source Project Edge Matching

Bathymetry

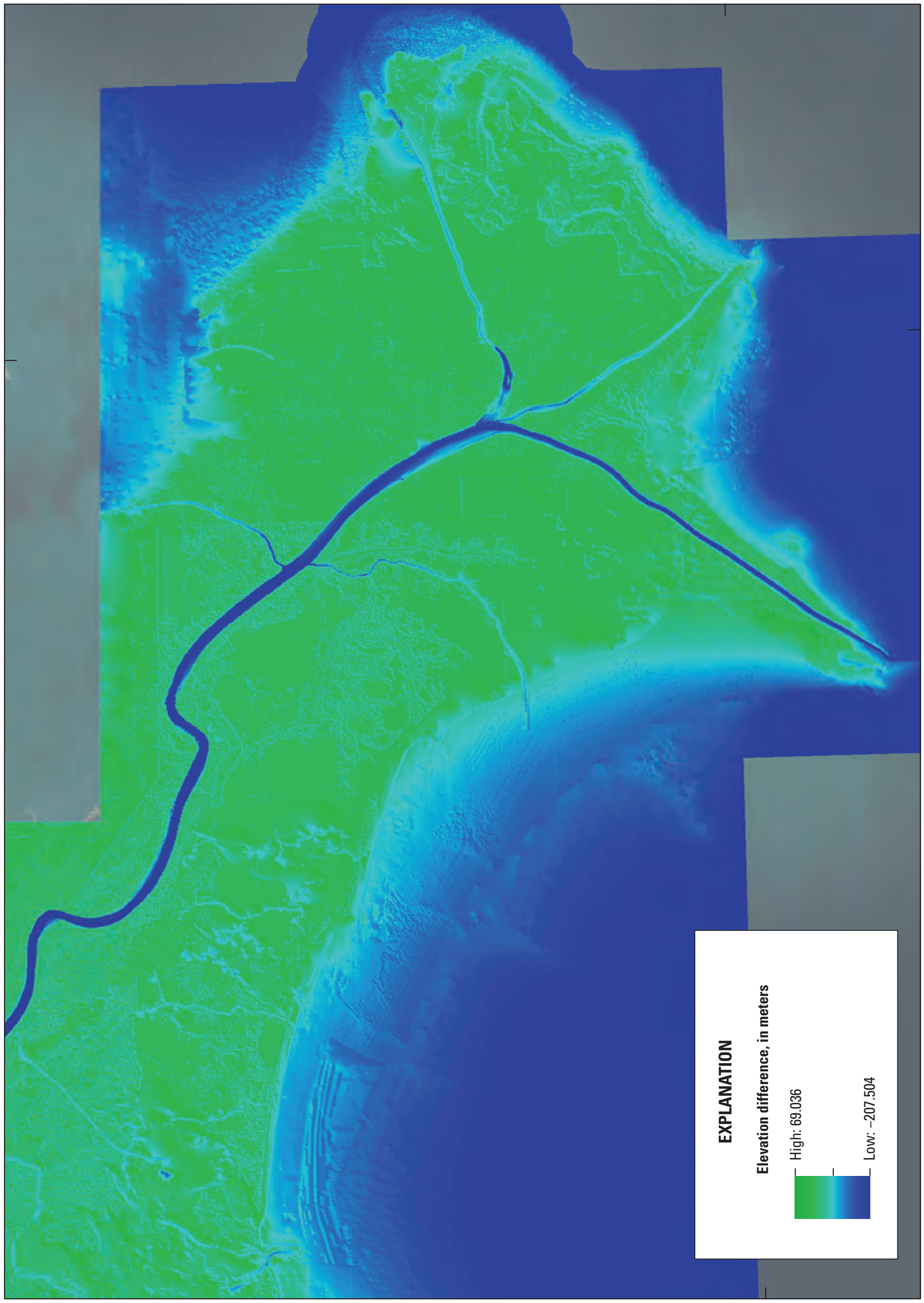
Edge matching lead-line sounding bathymetric surveys for Vermilion and Wicks Bays (National Oceanic and Atmospheric Administration, Department of Commerce, 1888a, b, c) with 3DEP 1/3 arc-second DEMs commonly showed good agreement (no difference) at the seams between the TBDEM datasets and 3DEP 1/3 arc-second DEMs. However, there were differences on the western edge of Wicks Bay that ranged between +0.99 and −4.76 m. Multibeam echo sounder and side-scan sonar survey datasets that map bathymetry for the Vermilion Bay approach channel from the Gulf of Mexico (National Oceanic and Atmospheric Administration, Department of Commerce, 2008) also merge well with 3DEP 1/3 arc-second DEMs where differences between 3DEP 1/3 arc-second DEMs and the bathymetric project edge cells on each side of the approach that runs between barrier island features are 0.1 m or less. Where the southerly boundary of the approach extends out from the barrier islands into the Gulf of Mexico, differences reflect the depth of the surveyed bathymetric surface.

Initial results for edge matching 3DEP 1/3 arc-second DEMs and TBDEM multibeam acoustic survey bathymetric projects for the Mississippi River, Atchafalaya River, and Morgan City, La., that included reaches of the Wax Lake Pass channel and Lower Atchafalaya River (U.S. Army Corps of Engineers, 2013, 2012; Coastal Planning and Engineering, Inc., 2012) indicated mostly smooth seams between the source project datasets and 3DEP 1/3 arc-second DEMs. However, elevation differences in some areas adjacent to river banks



South group tile	Total length of all difference contours, in meters	0-meter difference contours		Other difference contours
		Total length of all 0-meter contours, in meters	Total length of all contoured differences, in percent	Contour, percent of total length of all contours
0	No data	All offshore	No data	No data
1	No data	All offshore	No data	No data
2	No data	All offshore	No data	No data
3	18,356,124	17,734,178	97	−2 m, 2 percent; < −2 m, 1 percent
4	31,697,401	30,549,096	96	−2 m, 2 percent; < −2 m, 2 percent
5	26,997,560	25,856,341	96	−2 m, 1 percent; < −2 m, 3 percent
6	25,265,521	23,120,107	91.5	±2 m, 1.5 percent; < −4 m, 1 percent; 7 m, 6 percent
7	No data	All offshore	No data	No data
8	No data	All offshore	No data	No data

Figure 12. Comparison of south group topobathymetric and 3D Elevation Program digital elevation models.



Base modified from Esri digital data
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Figure 13. Northern Gulf of Mexico topobathymetric and 3D Elevation Program digital elevation model differences, Mississippi River Delta Birdfoot and offshore.

developed 2-m or greater differencing contours that abutted river banks. Overlaying the multibeam project footprint for these locations with NAIP orthoimagery showed that in these areas, the TBDEM Mississippi River polygon did not incorporate a river channel meander, all the channel banks, or side channels. Creating a 100-m buffer for the Mississippi River corridor to include these areas in the TBDEM polygon improved agreement. Isolated contours for 0-m differences adjacent to the river in results for the unbuffered polygon often were connected by adding the buffer, and between the river and the outer edge of the buffer zone almost all contours indicated there were no elevation differences between the multibeam survey; the adjacent USGS Louisiana Statewide lidar, 2006 (U.S. Geological Survey, 2009); and 3DEP 1/3 arc-second DEMs (fig. 14). Reviewing one of the multiple datasets included in the USACE suite of Mississippi River multibeam surveys for river mile data collections indicated that river bank Global Positioning System (GPS) control points and multibeam data gridded to 0.6 m by 0.6 m grids including the water's edge position (U.S. Army Corps of Engineers, 2013) would help ensure conformance with land surface elevations, which might support the idea that the TBDEM Mississippi River polygon was a little narrow and expanding the boundaries helped to include all USACE survey data.

In the few areas where there still were 2-m difference contours adjacent to the river banks, the 3DEP 1/3 arc-second DEM elevations were always greater (higher elevation) than those in the Northern Gulf of Mexico TBDEM, which might be related to hydroflattening in the 3DEP DEM. In two other areas, the river banks have heavy tree cover, and 3DEP 1/3 arc-second DEM elevations were 8 to 9 m higher than in the TBDEM, which may indicate the lidar point cloud data used to derive the 3DEP 1/3 arc-second DEM had been misclassified or that multi-reflected return laser beams caused positive outlier elevation values.

The Atchafalaya River source project also was buffered 100 m to encompass the river footprint that could be recognized in NAIP imagery of U.S. Topo maps (not shown) (U.S. Department of Agriculture, 2016; U.S. Geological Survey, The National Map, 2017). Source background information indicates a concurrent lidar survey processed to bare earth, which could provide the interface of the water level and land surface, was conducted (U.S. Army Corps of Engineers, 2010). When buffered to include possible river side channels, the only noticeable difference between the river bathymetry and 3DEP 1/3 arc-second DEMs was for an area south of Odenburg, La. In U.S. Topo maps, the area is depicted as part of the river channel (U.S. Geological Survey, The National Map, 2017).

The Morgan City multibeam survey for collecting Wax Lake Pass channel and Lower Atchafalaya River bathymetric data also was buffered 100 m. This worked well for developing 0-m difference contours for the Wax Lake Pass channel and seemed to resolve breaks in the 0-m contour formed in areas where the channel crosses other stream/river features or where it branches as it empties into the intertidal zone. The Lower Atchafalaya River required a more extensive buffer in places where the river system footprint is much wider than the shapefile polygon, particularly at the confluence with Bayou Shaffer. In this area, the river polygon was buffered 1,000 m to include Bayou Shaffer that empties into the Lower Atchafalaya River in coastal marshland, river meanders, and associated riverine features. Broadening the river system coverage also extended −2-m, −4-m, or −6-m difference contours from within the main river channel partway into Bayou Shaffer. The increased river channel polygon width could have been narrowed but this width also extended coverage to show agreement for the Avoca Island Cutoff canal that joins the Lower Atchafalaya River. This canal is included in one of the NOAA topobathymetric projects (Love and others, 2010).

Topobathymetry

The topobathymetric projects integrated in the Northern Gulf of Mexico TBDEM provide merged topographic and bathymetric data for the interface of regional land-ocean boundaries and other coastal to inland named or unnamed hydrographic features. Although these projects integrate topographic datasets that agree well with 3DEP 1/3 arc-second DEMs, hydrographic features often could be located by evaluating areas within these projects that contributed to the largest elevation differences between the TBDEM and 3DEP 1/3 arc-second DEMs in intertidal, wetlands, or uplands covered by the TBDEM (fig. 15).

The offshore Chandeleur Island, La., and the inland to offshore Mobile Bay, Ala., topobathymetric models were developed by the CoNED (Coastal National Elevation Database Applications Project, unpub. data, Danielson and others, 2013). The Chandeleur Island, La., dataset is spatially separate from all other projects except where it is seamlessly integrated to cover an area in one of the four NOAA Southern Louisiana Hurricane Forecast Improvement Projects. There are no differences with 3DEP 1/3 arc-second DEMs at the edge of the project polygon. The Mobile Bay, Ala., topobathymetric model project was developed using multiple topographic and bathymetric datasets and in the TBDEM it shares seams with several other projects. In some areas, results for differencing the Mobile Bay, Ala., topobathymetric model and 3DEP 1/3 arc-second DEMs accentuate inclusion of variant datasets within the model, and differences with adjacent TBDEM projects.

In a northwest area of the Mobile Bay, Ala., source project, results for comparing the TBDEM and 3DEP 1/3 arc-second DEMs seem to display three internal dataset boundaries (fig. 16). One area of the source project shows no difference contours, and two areas are distinguished by difference contours at different densities. The smaller of these two areas shows the greater contour density as an anomalous square-shaped pattern. As for some seams between adjacent TBDEM source projects in other areas, difference contours near the north edge and within the square pattern flatten at the apparent internal seam. At one site on the north edge, an elevation

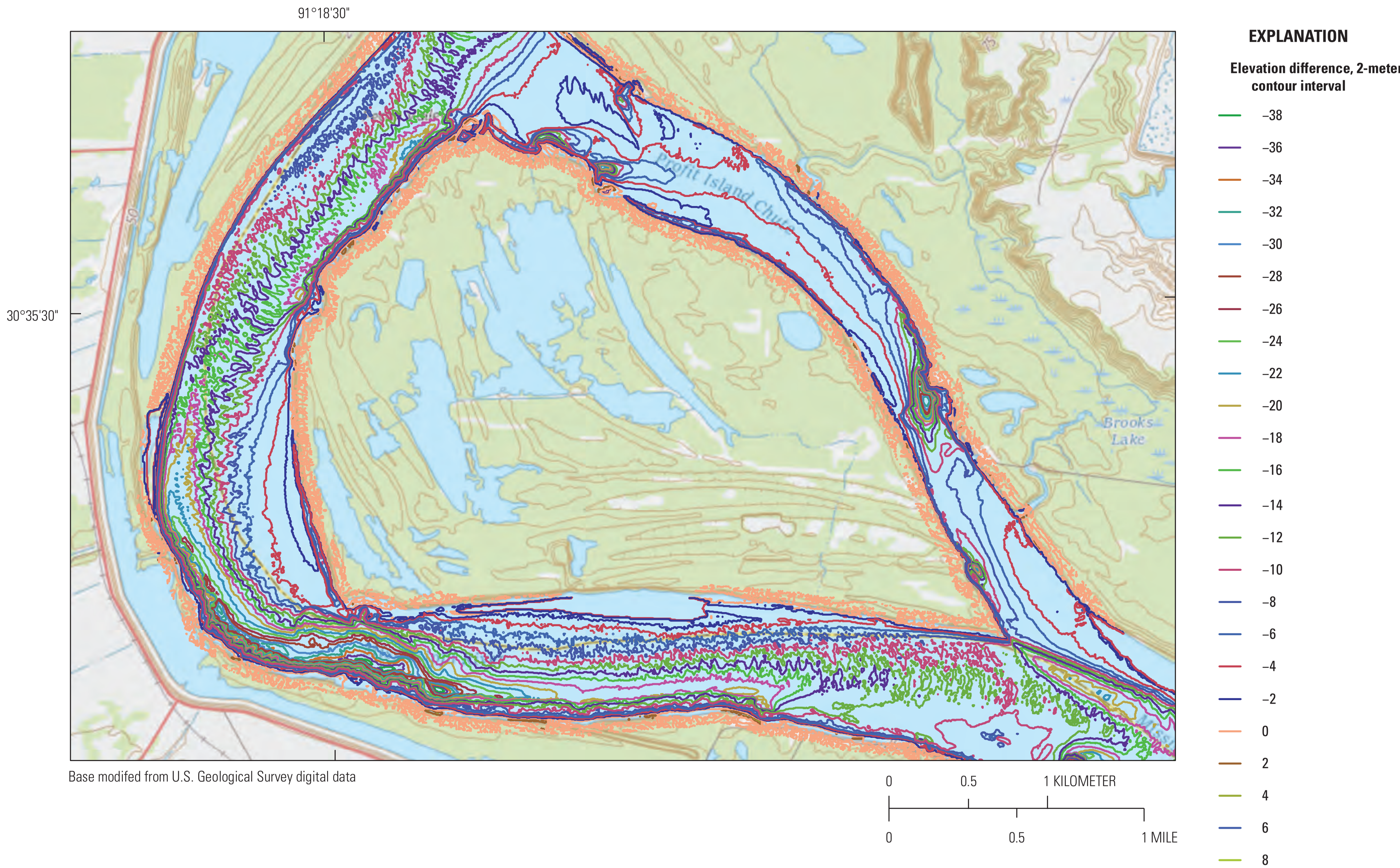

Figure 14. Edge matching Mississippi River multibeam bathymetry project buffered 100 meters.

profile that extends from within the pattern into the adjacent area where there are no elevation differences with the 3DEP 1/3 arc-second DEM indicates a steep, roughly 2-m elevation change. Similar to the larger area of contour difference patterns and in other regions of the TBDEM, overlaying HR NHDFlowline network datasets (U.S. Geological Survey, 2017c, e), and elevation difference contours for the Mobile Bay, Ala., source project often shows the contours coincide with HR NHD artificial paths or stream/river feature types (fig. 16). Here and in other TBDEM projects, overlaying the 3DEP 1/3 arc-second DEM exemplified how well 3DEP topographic lidar 1/3 arc-second DEMs display flow networks seen in NAIP orthoimagery and that are identified as artificial paths or stream/river features in the HR NHDFlowline network.

NOAA topobathymetric projects map the coastal zone transition from inland near the shoreline to offshore, and a narrow swath of the northern TBDEM (fig. 4). Four NOAA Southern Louisiana Hurricane Forecast Improvement Project datasets are integrated with all or a part of 30 other Northern Gulf of Mexico TBDEM datasets including three USACE bathymetric projects, a USACE topobathymetric lidar project, and 29 topographic lidar datasets. The only differences displayed across project boundaries are where the Houma Navigation Canal, Bayou Lafourche, and two other canals cross the coastal zone from inland to the coastline (not shown). Other NOAA topobathymetric projects include the NOAA Northern Gulf Coast project, NOAA VDatum DEM (New Orleans project), and the NOAA Tsunami Inundation datasets (Love and others, 2011; Love and others, 2012; Taylor and others, 2008) that merge well with other TBDEM projects, showing no differences at adjacent project seams. At the land-water interface, differences within the source project boundaries were between 0 and 0.7 m. Oceanward from the HR NHDFlowline network coastline (the NOAA mean high water datum), the topobathymetric projects delineate the transition to the Northern Gulf of Mexico Basin.

Although there were no differences for many edge cells, disparities for edge-matching were identified for gridded differences at edge cells located at the boundary of the ETOPO5, a 5-minute gridded global topobathymetric dataset with an original resolution ranging between 5 minutes and 1 degree (not shown) (National Oceanic and Atmospheric Administration National Centers for Environmental Information, 2004). Differences as large as −5.99 and −7.13 m were identified in the southwestern area of the ETOPO5 shapefile. For the eastern ETOPO5 shapefile, on the southern edge of Vermilion Bay near the northern tip of Marsh Island, gridded differences ranged between −1.3 and 2.29 m. At the northeast edge of the shapefile (at the upper boundary of West Cotes Bay), grid cell differences ranged between −1.51 and −2.29 m. The ETOPO5 version integrated in the TBDEM is described as a 2005 updated version of ETOPO5 that was originally generated in 1993. However, the web page dated 2017 indicates the citation of data is dated 1993. Disparities between ETOPO5 and 3DEP 1/3 arc-second DEMs may be because of the difference in resolution or vintages of some datasets.

Topographic Lidar

In a map document that displays the comparison for Northern Gulf of Mexico TBDEM topographic lidar projects and 3DEP 1/3 arc-second DEMs, the patterns for differences make a small footprint and most projects seem to be seamlessly integrated. Differences that were identified between topographic lidar source projects or within mosaicked topographic lidar projects may be because of differences in lidar survey sensor systems, or processing algorithms, or because of changes in temporal surface conditions at the time of the surveys. In some areas, overlaying the HR NHDFlowline network with the image for differencing results indicated that variation in elevation profiles for adjacent topographic lidar projects can be associated with artificial path or stream/river feature type lineaments that may be better defined in one of the projects.

In the northeast corner of the TBDEM, results for differencing 3DEP 1/3 arc-second DEMs with the Baldwin County, Miss.; Mobile Bay, Ala.; and Escambiaco County, Fla., USGS topographic lidar projects integrated in the TBDEM (Danielson and others, 2013) indicate these datasets have nearly the same level of agreement with 3DEP 1/3 arc-second DEMs, and there are no differences for elevations across shared project boundaries. To the west, the Baldwin County, Miss., project is adjacent to the Mobile Bay topobathymetric model (Danielson and others, 2013), the NOAA Northern Gulf Coast topobathymetric project (Love and others, 2012), the Katrina Regional Lidar Mosaic project (Stoker and others, 2009), and the USGS Mobile Bay, Ala., topographic lidar datasets are integrated in the TBDEM. In this area of the TBDEM, a map document shows that the elevation difference surface visually distinguishes the source projects (fig. 17).

In the same region of the TBDEM, the shapefile for the NOAA Northern Gulf Coast topobathymetric project (Love and others, 2012) is nested in the Katrina Regional Lidar Mosaic project (Stoker and others, 2009). The NOAA topobathymetry project appears only to include bathymetric data for the braided, southerly flowing Mobile Bay River and Tensaw River. The lidar mosaic DEM maps the flat surface around the braided flowpath network. An elevation profile across the topobathymetric project depicts the two-river system channels to be 3 to 8 m deep. At the southern limit of the topobathymetric project where delineation of the Mobile River and Tensaw River terminates at the project boundary with the Baldwin County, Miss., lidar dataset, the elevation differences at the seam are −4 m, reflecting the boundary between topobathymetric and topographic datasets. Differencing results within the Baldwin County, Miss., project developed difference countours correlative to channel banks for both rivers. These difference contours join with the river channels identified in the NOAA topobathymetric project to the north, and with river channel banks where bathymetry for the rivers is integrated in the Mobile Bay topobathymetric project to the south. Outside the river banks, differences at the seams between the Baldwin County, Miss., lidar project and the two topobathymetric projects were 0.8 m or less.

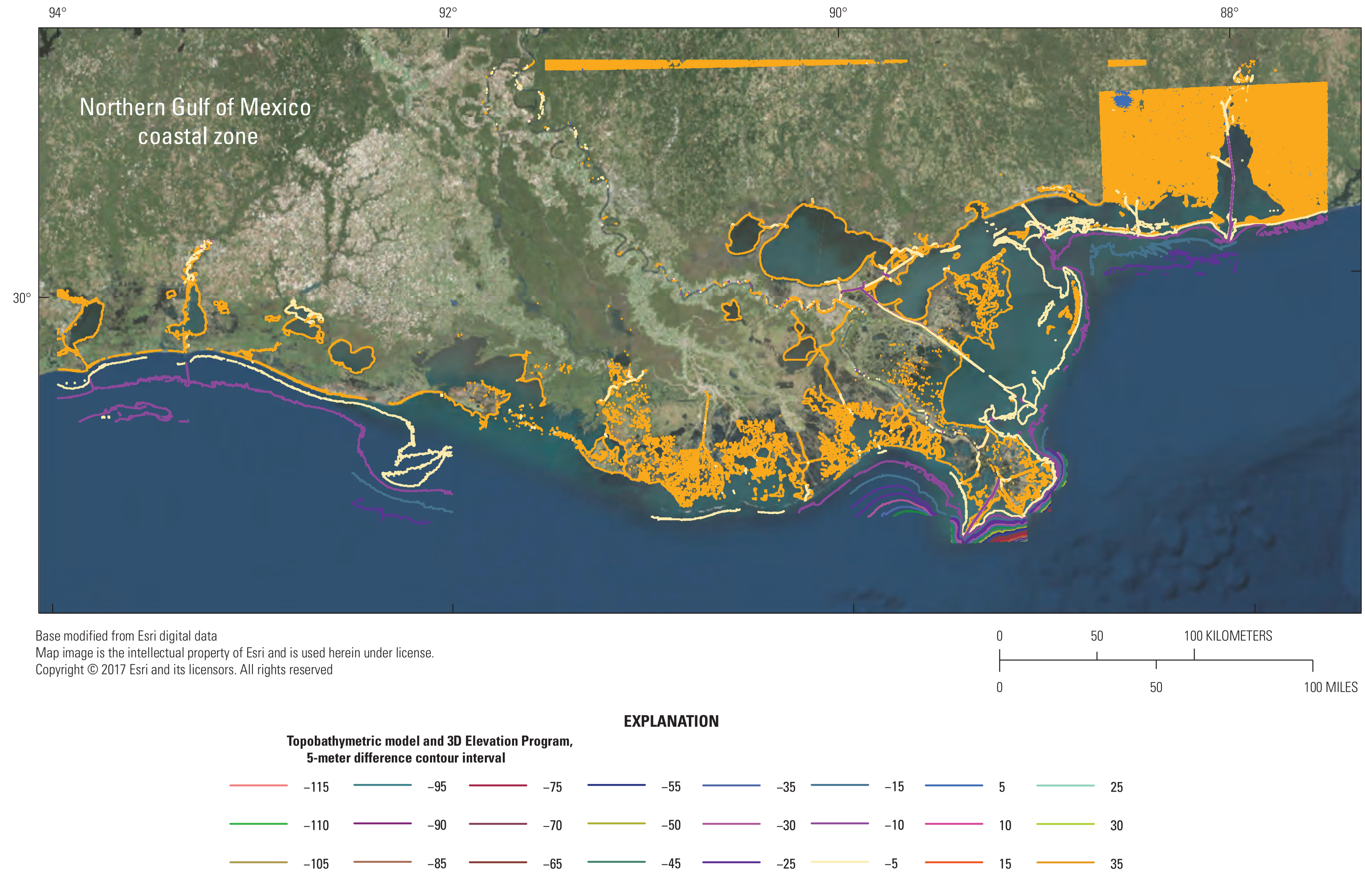

Figure 15. Topobathymetric project differencing with 3D Elevation Program digital elevation models.

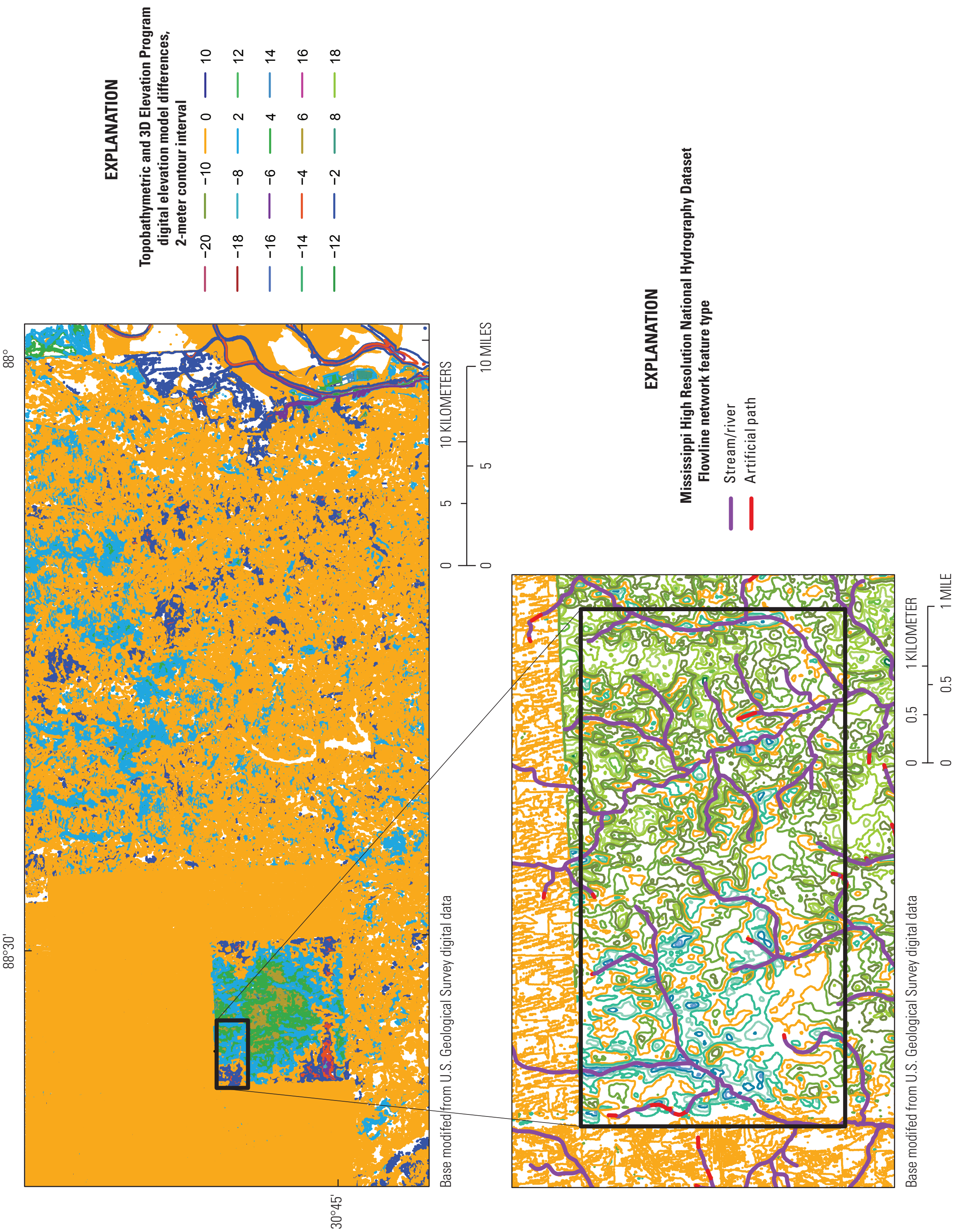

Figure 16. Elevation difference patterns in the Mobile Bay, Alabama, source project.

In the north-central TBDEM region, an elevation difference profile that is continuous from west to east across the Pearl River County, Miss., topographic lidar project, the Camp Shelby, Miss., topographic lidar project, and the Mobile Bay topobathymetric project indicates these three datasets are well merged. However, within the Pearl River County, Miss., and the Mobile Bay, Ala., projects, the comparison shows elevation differences with 3DEP 1/3 arc-second DEMs in some areas agree while in other areas differences with 3DEP 1/3 arc-second DEMs range by ±6 m or more (fig. 18). Differences between these and the Camp Shelby, Miss., projects and within the two TBDEM datasets could indicate differences in original lidar data collection or processing techniques, or site conditions. For example, although metadata for the Pearl River County Miss., lidar survey indicates vertical accuracies meet American Society for Photogrammetry and Remote Sensing Class II requirements, there also is mention that high grass areas were expected to provide discrepancies due to the density of the grasses and the inability to penetrate these areas in the Pearl River County, Miss., lidar survey (MD Atlantic Technologies, Inc., 2013; OCM Partners, 2018); this also might account for differences with the Camp Shelby, Miss., topographic lidar project and the 3DEP 1/3 arc-second DEM.

Two topographic lidar mosaic datasets, the Katrina Regional Lidar Mosaic project (Stoker and others, 2009) and the Louisiana Statewide Lidar Project (U.S. Geological Survey, 2009) provide one-third of the elevation data in the Northern Gulf of Mexico TBDEM (table 1). With a few exceptions identified in contoured differences for the TBDEM and 3DEP 1/3 arc-second DEMs, these projects look to be smoothly integrated in the TBDEM model. An example for exceptions is from the central region of the TBDEM near the northern boundary. In this area, concentric polygonal difference contours that range from +4 to −7 m flatten in an east-west direction at the north edge of the Katrina Regional Lidar Mosaic project (Stoker and others, 2009). A closer look showed the contours flatten along the edge of the 31 ºN 90 ºW 3DEP 1/3 arc-second DEM that is coincident with the edge of the lidar mosaic. Aerial imagery and an elevation profile across the area shows the land is forested and cultivated in various furrow patterns, and that the land surface is irregular, exhibiting changes in elevation with slopes as steep as 25 percent or more (not shown). North of the 31 ºN 90 ºW 3DEP 1/3 arc-second DEM, the NOAA Northern Gulf Coast topobathymetric project elevations agree well with 3DEP 1/3 arc-second DEMs. The contrast between the two TBDEM projects could mean that in this area, the Katrina Regional Lidar Mosaic project integrated a lidar dataset where the steep terrain and cultivated fields made it difficult for the laser returns to map the land surface or that the collected data were not processed to provide bare earth surface elevations.

Almost all the western half of the TBDEM includes elevation data from the Louisiana Statewide Lidar Project (U.S. Geological Survey, 2009). This integrated lidar dataset displays a linear seam along the northern boundary coincident with the 31 ºN 91 ºW 3DEP 1/3 arc-second DEM, which is similar to the seam at the northern boundary of the Katrina Regional Lidar Mosaic project. As for the Katrina Regional Lidar Mosaic project, the terrain is densely forested and gently to steeply sloping. In a different area, near Lake Sabine at the Texas and Louisiana State border, a 5–6 m elevation difference between the Louisiana Statewide Lidar Project and a 3DEP 1/3 arc-second DEM was depicted just inside the Louisiana Statewide Lidar Project at the seam of the project and USGS topographic maps that may include prelidar-derived elevation data (appendix; fig. 19).

Two USGS topographic lidar projects supported under the American Recovery and Reinvestment Act map elevations for the east side of the Mississippi River Delta and 10 topographic lidar datasets titled as Barataria Basin, La., projects map the west side. Projects on both sides of the Mississippi River Delta are seamlessly integrated in the TBDEM; there are no elevation differences between these lidar projects and the Mississippi River bathymetry from the USACE multibeam acoustic survey. Also, all EAARL projects that provide topographic elevations are seamlessly integrated in the Northern Gulf of Mexico TBDEM.

The results for differences between the 3DEP 1/3 arc-second DEM and USACE topographic lidar data collected and processed for Pearl River County, La., show 96-percent agreement. Although there are a few areas with larger elevation differences, most differences are in the ±2-m range. The largest disparity, 20 m, seems to be part of a positive outlier pattern that forms concentric polygons around a spot near a road trending through wooded terrain. At another site, difference contours encircle a bare earth surface surrounded by trees. At yet another site, concentric contour difference rings seem to develop as outliers around an unnamed water body. These disparities could be because integrated lidar data include outlier data or because the data were misclassified.

Summary

The Northern Gulf of Mexico topobathymetric digital elevation model (TBDEM) covers the coastal zone from inland, through the intertidal zone, and into the offshore. Topography, acoustic and lidar bathymetry, and acoustic and lidar topobathymetry are integrated to create a digital elevation model (DEM) that is generally consistent with 3D Elevation Program (3DEP) 1/3 arc-second DEMs. Results for elevation differences with 3DEP 1/3 arc-second DEMs highlight challenges for integrating elevation data collected over a span of years and using different data collection or processing techniques. From the border between Texas and Louisiana to the east side of Mobile Bay, Alabama, the upland-directed curve of the coastline is reflected in the change from marine to predominantly wetland types. Differences between Northern Gulf of Mexico TBDEM bathymetric or topobathymetric datasets and 3DEP 1/3 arc-second DEMs often are associated with rivers, riverine wetlands, and the freshwater forested/shrub

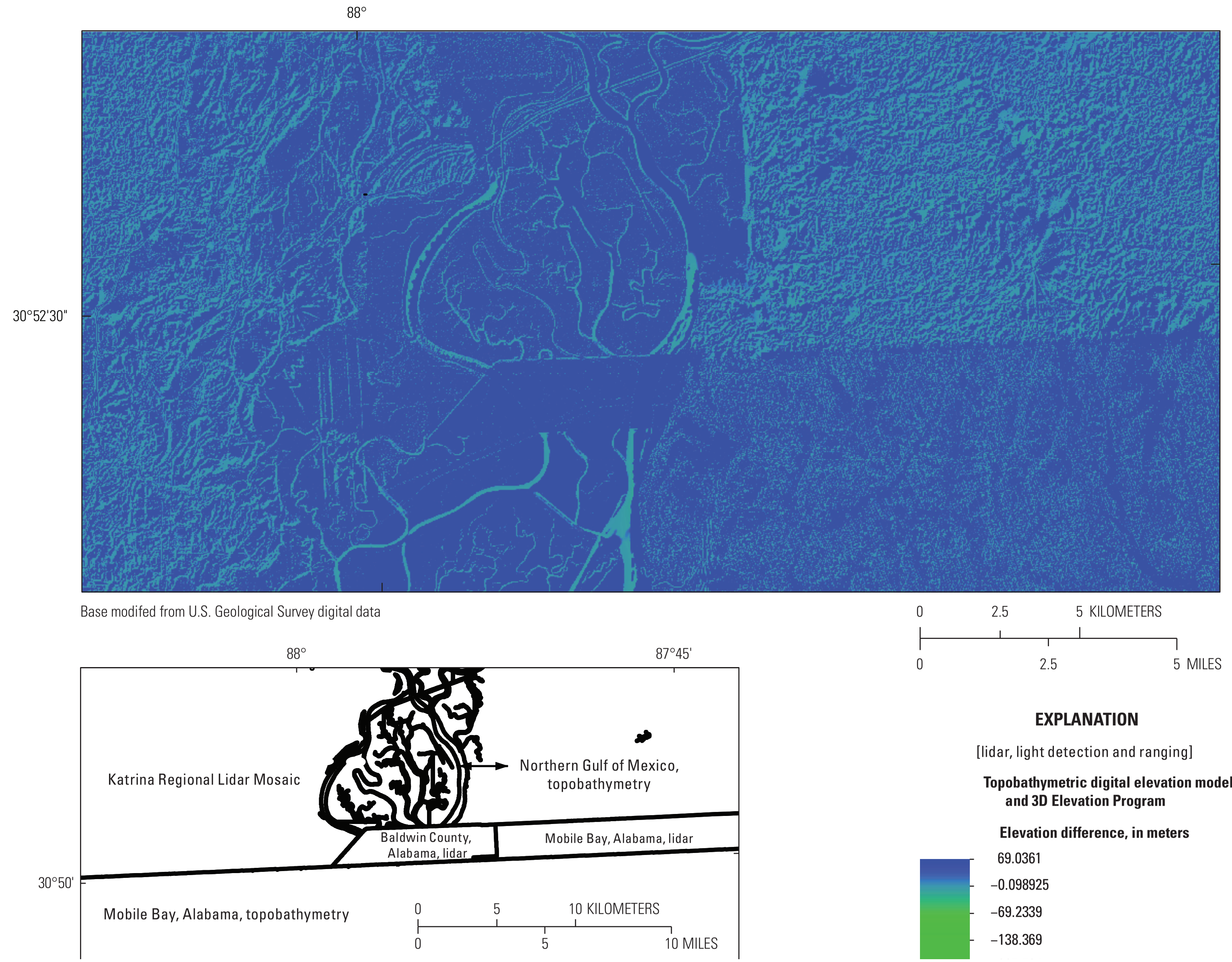

Figure 17. Elevation difference surface within adjacent projects.

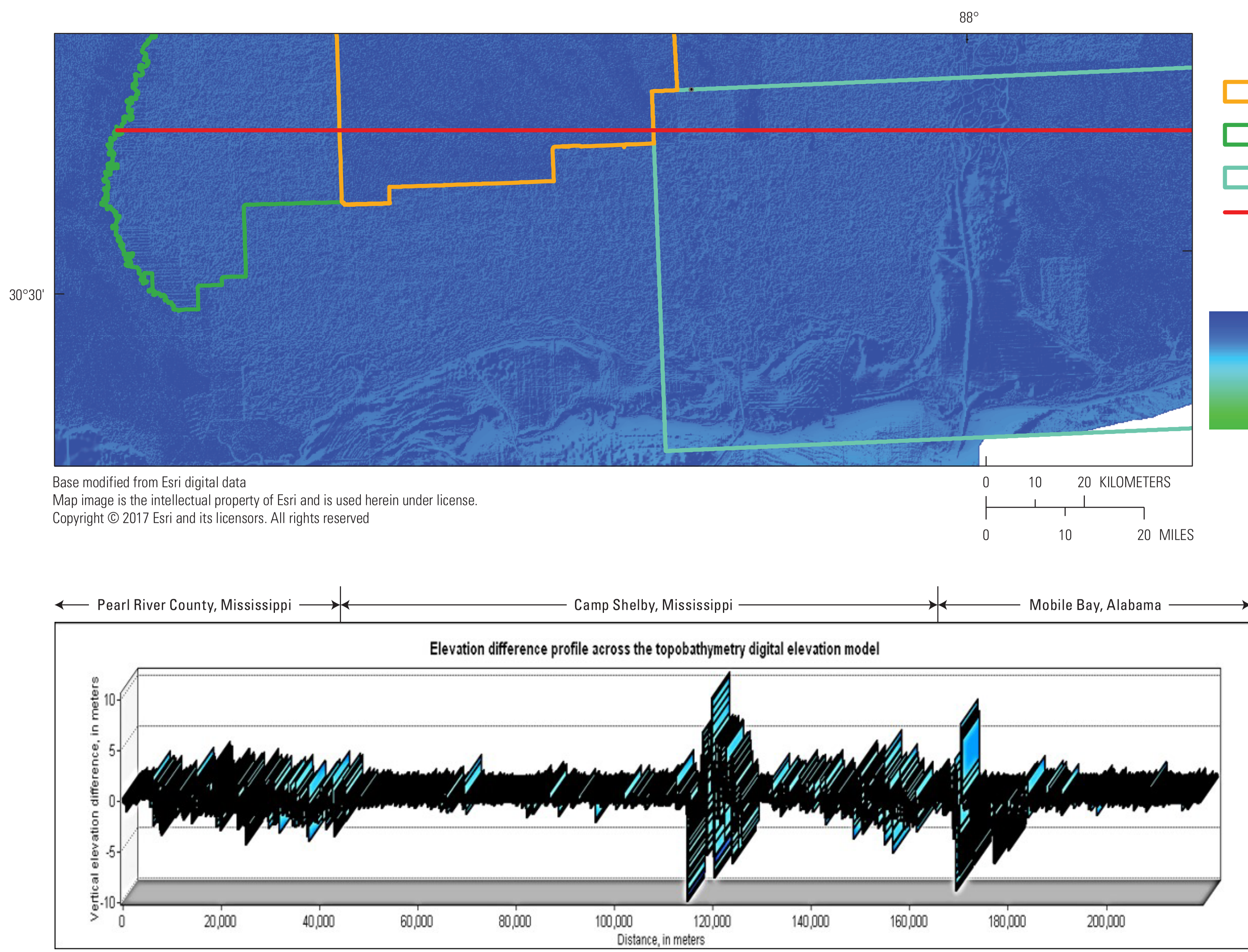

Figure 18. Profile of elevation differences between 3D Elevation Program digital elevation models and merged Northern Gulf of Mexico topobathymetric model projects.

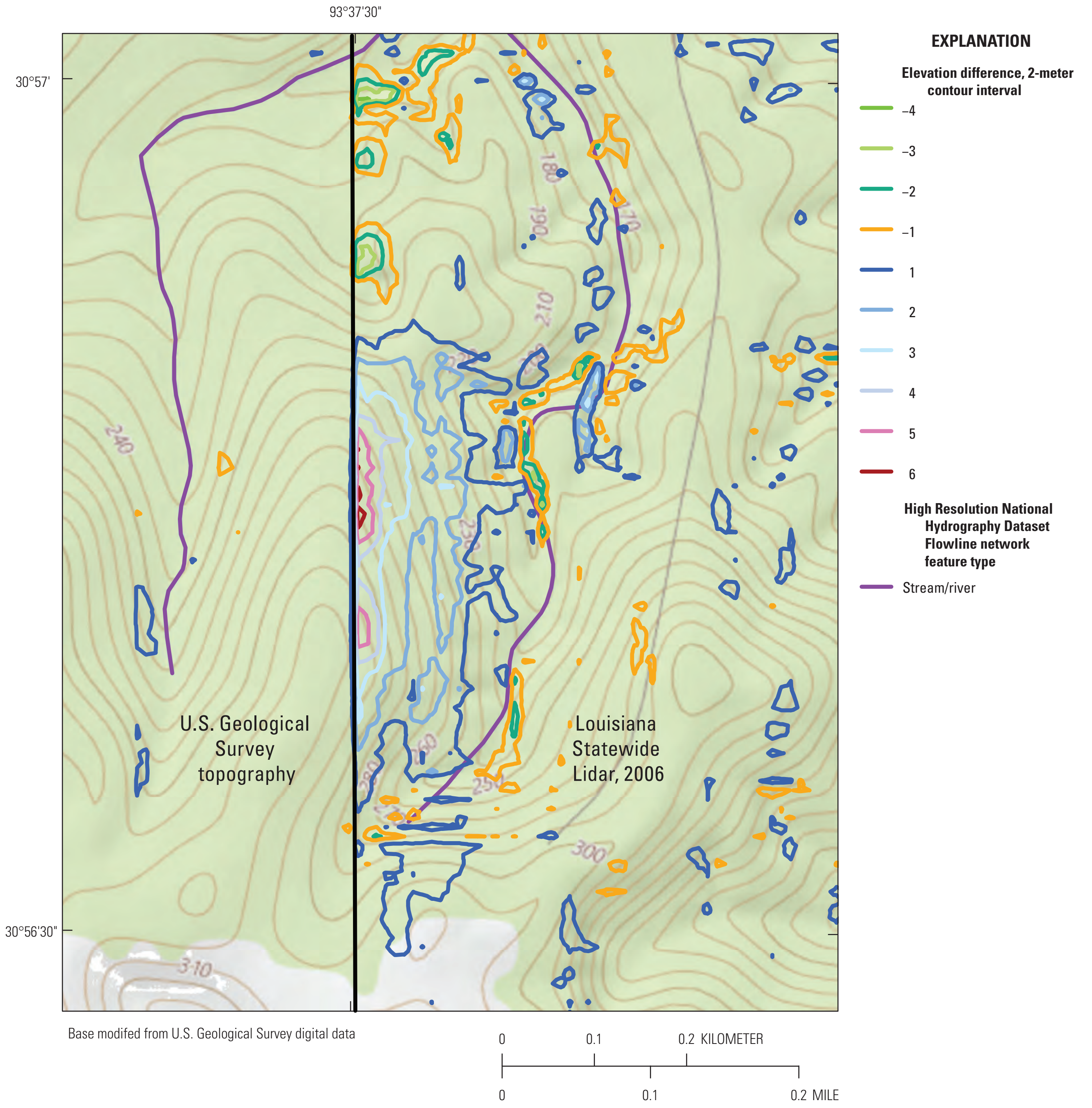

Figure 19. Edge matching the U.S. Geological Survey Louisiana Statewide Lidar, 2006, and National Elevation Dataset, 1942–2006 projects.

wetlands that border the river systems, or coastal estuarine environments.

Evaluating contoured differences and edge matching indicates elevation differences across source project edge cell boundaries are commonly in the range of tenths to hundredths of a meter. There also are some areas of larger variation between edge cell elevations found between integrated TBDEM topographic source projects and between these and bathymetric or topobathymetric source projects. The National Map 3DEP DEM specifications do not currently include a tolerance or limit for differences. Organizations developing and providing bathymetric and topobathymetric datasets do not address requirements for edge-matching. Therefore, there are no specifications from other sources to gauge the quality of results for integration between these and 3DEP 1/3 arc-second DEMs.

For areas of the Northern Gulf of Mexico TBDEM where the 3DEP maintains 1/3 arc-second DEMs, an estimated 45 percent of the TBDEM data agree 99 to 100 percent with 3DEP 1/3 arc-second DEMs. An estimated 95 to 98 percent of the TBDEM data agree with 3DEP 1/3 arc-second DEMs within plus or minus (±) 2 meters. Difference contour patterns often identify river and stream flowpaths that were recognized as hydroflattened surface-water flow networks in 3DEP 1/3 arc-second DEMs and (or) High Resolution National Hydrography Dataset (HR NHD) Flowline network stream/river or other flowline network data types. Other contoured difference patterns develop as patch-like fabric or flattened polygons at the edge of integrated TBDEM source projects or 3DEP 1/3 arc-second DEMs and TBDEM source projects.

Some of the anomalous difference contour patterns in integrated topographic datasets are interpreted as outlier elevations in the TBDEM source project. These disparities could be because the topographic datasets integrated in the TBDEM source project were developed using different lidar data collection, interpolation, or processing techniques, because an original project includes misclassified lidar data points, or possibly because all the source projects may not be derived from lidar survey datasets.

Although coverage of acoustic bathymetric surveys is small compared to coverage that is provided by topographic and topobathymetric DEMs, results for evaluating these datasets indicate how well bathymetric surveys may integrate with 3DEP 1/3 arc-second DEMs. The historical, 1888 lead-line bathymetric projects for Vermilion Bay, Louisiana, generally integrate well with topobathymetry or other projects integrated in the TBDEM, though the analysis of edge-matching with the Wicks Bay lead-line survey revealed edge cell differences that could be as large as 5 to 7 meters. Multibeam bathymetric datasets are well edge-matched with other integrated projects after buffering to include all river meanders, banks, and connected channels. Buffering these projects added some of the surrounding topographic elevation data to channel footprint shapefiles or as for the TBDEM Morgan City, La., project incorporated adjacent topobathymetry, which seemed to improve connectivity between initially disconnected, no-difference contours proximal to channel bank edges. The TBDEM Mobile Bay, Ala., project appears to include river channel bathymetry that correlates to HR NHDFlowline network features, and the TBDEM successfully interpolates elevations at seams between project edge cells where steep elevations smoothly transition from the Mobile Bay, Ala., project to adjacent model projects. There are some internal Mobile Bay, Ala., dataset differences that could be seen in the fabric of the map document for differencing; however, elevation profiles across these areas indicated differences of less than a tenth of a meter.

As could be expected, National Oceanic and Atmospheric Administration (NOAA) vertical datum transformation topobathymetric projects developed by merging USGS DEMs and bathymetric data seamlessly merge with almost all adjacent TBDEM projects. The one identified exception is in the northwestern part of the TBDEM where the integrated NOAA Northern Gulf Coast topobathymetric DEM includes elevations delineating river channels that terminate at the seam between the topobathymetric DEM and the Baldwin County, Ala., topographic lidar project.

Conclusion

Evaluating agreement of the TBDEM with 3DEP 1/3 arc-second lidar DEMs provided insight into the success and potential issues related to integrating bathymetric, topobathymetric, and topographic datasets from variable source data projects. Results for assessing elevation differences between the Northern Gulf of Mexico TBDEM and 3DEP 1/3 arc-second DEMs often indicate the two models' elevation delineations generally agree but that there are some areas in the TBDEM with elevation disparities at the seams of source projects and 3DEP 1/3 arc-second DEMs and seams between integrated TBDEM source projects. For much of the analysis, differences with 3DEP DEMs are identified in areas covered by surface-water features; however, differences also are found within some integrated topographic lidar DEM source projects. Moderate to poor edge-matching at some project and 3DEP 1/3 arc-second DEM boundaries located areas where disparities could be due to differences in data vintage or processing. Agreement of the TBDEM and 3DEP DEMS might be improved through updating incompatible datasets or by modifying interpolation techniques implemented in the model's software process.

The National Map 3DEP goals and specifications described in U.S. Geological Survey Circular 1399 and Techniques and Methods 11–B4 and 11–B9 include providing seamless elevation layer datasets with specified vertical accuracies, which are created in conjunction with acquisition of high-resolution elevation data produced almost entirely from lidar and interferometric synthetic aperture radar. Specifications developed for single and integrated bathymetric and topobathymetric datasets would need to describe single and integrated source project datasets created from acoustic, lidar, and possibly other data type surveys. Variable vertical accuracy reporting for bathymetric projects, as well as the difference in vertical accuracies reported for the NOAA topobathymetric projects, highlights the need to develop specifications for consistent vertical accuracy reporting for bathymetic and topobathymetric DEMs if the 3DEP implements a category for bathymetric and topobathymetric data collections. To coordinate 3DEP technical methods, specifications for vertical accuracies relative to vegetated or nonvegetated survey targets would probably need to be addressed, but because aquatic vegetation might be difficult to characterize, it could be difficult to develop similar vertical accuracy categories.

The Northern Gulf of Mexico TBDEM integrates topographic, bathymetric, and topobathymetric datasets from a range of data vintage, survey types, and sources that can offer a unique and useful reference to available elevation data to local and regional agencies and businesses. Incorporating the TBDEM or other projects that provide bathymetric or topobathymetric elevation data in a 3DEP collection would support the 3DEP mission to provide three-dimensional elevation data for natural and constructed features. Without vertical accuracy reporting and because of elevation differences within and between integrated source projects, this initial Northern Gulf of Mexico TBDEM will be available as a USGS Original Product Resolution DEM instead of through 3DEP. However, the TBDEM developed by the CoNED is being updated with new topographic and hydrographic elevation datasets so that the revised model can provide more consistent dataset parameters, updated elevation surfaces, and required vertical accuracy parameters that could align with possible 3DEP bathymetric and topobathymetric data collection requirements in the future.

Bathymetric and topobathymetric elevations provide important digital hydrographic data for communities living in potential floodplain environments, water resource management, environmental monitoring and protection programs, wildlife and range management programs, and businesses. Recognizing the significance of accurate bathymetric and topobathymetric datasets for inland to coastal zones, which are home to most of the U.S. population, the National Geospatial Program 3DEP supports developing a bathymetric and topobathymetric survey data collection program and is managing activities to evaluate needs and support hydrographic data collection. In the nationwide 3D Nation Requirements and Benefits Study sponsored by the 3DEP in collaboration with the National Oceanic and Atmospheric Administration, a questionnaire requesting information for how inland, nearshore, and offshore topographic and bathymetic elevation data are needed and used, agency and business requirements for elevation survey parameters, and benefits provided by 3DEP data was provided to Federal, State, local, Tribal, and national business entities. Another nationwide activity includes coordinating efforts to reach out to USGS Water Science Centers and other USGS Programs to discuss inland bathymetric survey procedures and data parameters so that the 3DEP can better understand existing survey project activities and requirements for datasets and products. In 2018 the 3DEP initiated the USGS Bathymetric and Topobathymetric Data Inventory to evaluate the geographic distribution of USGS inland bathymetric and topobathymetric surveys and datasets or DEMs, and to characterize survey parameters relevant to data collection, processing, and quality. The inventory is available on line as a section in the U.S. Geological Survey Community for Data Integration, Earth Science Themes Working Group Elevation Focus Group. The 3DEP activities are helping to evaluate the benefits and feasibility for developing bathymetric and topobathymetric dataset collections in the 3DEP and can pave the way for developing acquisition procedures and priorities in addition to requirements and specifications for implementing a 3DEP bathymetric and topobathymetric data collection program.

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Appendix

Table 1.1. Northern Gulf of Mexico topobathymetric digital elevation model source projects.

[m, meter; La., Louisiana; Miss., Mississippi; Ala., Alabama; Fla., Florida; DEM, digital elevation model; Co., County; Tex., Texas; USACE, U.S. Army Corps of Engineers]

Survey type and collection year	Source project	Location	Acquired data or product resolution
Bathymetric: Multibeam and side-scan sonar (2008)	National Oceanic and Atmospheric Administration Department of Commerce (2008; 1888a, b, c)	2 projects—Vermilion Bay	2 m
Bathymetry—Sonar, sounding (1888a)	National Oceanic and Atmospheric Administration Department of Commerce (2008; 1888a, b, c)	Vermilion Bay	1 m
Bathymetry—Sonar, sounding (1888b)	National Oceanic and Atmospheric Administration Department of Commerce (2008; 1888a, b, c)	Vermilion Bay	Unknown
Bathymetry—Sonar, sounding (1888c)	National Oceanic and Atmospheric Administration Department of Commerce (2008; 1888a, b, c)	Wicks Bay	Unknown
Global topobathymetry (multiple years)	National Oceanic and Atmospheric Administration National Centers for Environmental Information, 2004	Global Bathymetry, ETOPO5, 1985	100 m
Multibeam bathymetry (2012)	Coastal Planning and Engineering, Inc., 2012	Morgan City, Atchafalaya River, La.	3 m
Multibeam bathymetry (2010)	U.S. Army Corps of Engineers, 2010	Atchafalaya River	3 m
Multibeam bathymetry (2010)	U.S. Army Corps of Engineers, 2013b	Mississippi River	3 m
Topobathymetry (1917–2011)	U.S. Geological Survey, Coastal National Elevation Database, 2013	Mobile Bay	3 m
Topobathymetry (2005)	U.S. Army Corps of Engineers, 2006	Mississippi merged lidar data, 2005	3 m
Topobathymetry (2005–12)	U.S. Geological Survey, Coastal National Elevation Database, 2012 (unpublished)	Chandeleur Island, La., 2005–12	3 m
Topobathymetry lidar (2005)	U.S. Army Corps of Engineers, 2011	2005 Post Hurricane Katrina Levee Surveys	3 m
Topobathymetry lidar (2010)	U.S. Army Corps of Engineers, 2011	Louisiana Coast, Lake Pontchartrain and Mississippi Barrier Islands, 2010	3 m
Topobathymetry: Sonar bathymetry, lidar topography (1917–2007)	Taylor and others, 2008, Tsunami Inundation (National Oceanic and Atmospheric Administration)	Biloxi, La./Miss./Ala.	10 m
Topobathymetry: Sonar bathymetry, lidar topography (data age unknown)	National Oceanic and Atmospheric Administration National Geophysical Data Center, 2001	Coastal Relief, Central Gulf of Mexico	100 m

Table 1.1. Northern Gulf of Mexico topobathymetric digital elevation model source projects.—Continued

[m, meter; La., Louisiana; Miss., Mississippi; Ala., Alabama; Fla., Florida; DEM, digital elevation model; Co., County; Tex., Texas; USACE, U.S. Army Corps of Engineers]

Survey type and collection year	Source project	Location	Acquired data or product resolution
Topobathymetry: Sonar bathymetry/ lidar topography (1888–2010)	Love and others, 2010; National Oceanic and Atmospheric Administration, Southern Louisiana Hurricane Forecast Improvement Project	4 projects—SLA_HFIP_DEM projects	10 m
Topobathymetry: Sonar bathymetry/ lidar topography (1873–2010)	Love and others, 2012, National Oceanic and Atmospheric Administration, Vertical Datum Transformation Tool	Northern Gulf Coast, VDatum DEM: Miss./Fla./La./Ala.	30 m
Topobathymetry: Sonar bathymetry/ lidar topography (2011)	Love and others, 2011, National Oceanic and Atmospheric Administration, Vertical Datum Transformation Tool	New Orleans, La., VDatum DEM, 1888–2009: La./Miss.	10 m
Topographic lidar (multiple years)	Stoker and others, 2009	Katrina Regional Lidar Mosaic	3 m
Topographic lidar (2003)	U.S. Army Corps of Engineers, 2003	Pearl River Co., Miss.	3 m
Topographic lidar (2005)	U.S. Army Corps of Engineers, 2005	Hancock and Jackson Co., Miss., 2005	3 m
Topographic lidar (2006)	U.S. Geological Survey, 2017a, b	Escambia Co., Fla.	3 m
Topographic lidar (2006–7)	Hansen and Howd, 2008	5 projects—Coastal Louisiana barrier islands	30 m
Topographic lidar (2006–7)	U.S. Geological Survey, Barrier Island Comprehensive Monitoring program, 2006	Louisiana coastal zone, Breton Island	1 m
Topographic lidar (2007)	Smith and others, 2008	Northern Gulf of Mexico	2 m
Topographic lidar (2007)	U.S. Geological Survey, 2017a, b	Orange Co., Tex.; Camp Shelby, Miss.; Jefferson Co., Tex.	3 m
Topographic lidar (2008)	Nayegandhi and others, 2008	Jean Lafitte National Historical Park, 2006	3 m
Topographic lidar (2008)	Nayegandhi and others, 2009	Pearl River Delta, La.	3 m
Topographic lidar (2009)	U.S. Army Corps of Engineers, 2012	Post-Hurricane Gustav and Ike, 2009	3 m
Topographic lidar (2010)	Bonisteel-Cormier and others, 2012	North Shore, Lake Pontchartrain	3m
Topographic lidar (2010)	U.S. Army Corps of Engineers, 2010	2010 USACE La.; Miss.	3 m
Topographic lidar (2010)	Nayegandhi and others, 2012a, b	Alligator Point; Central Wetlands	3 m
Topographic lidar (2010)	U.S. Geological Survey, 2017a, b	Mobile Bay, Ala.; Baldwin Co.	3 m
Topographic lidar (2012)	U.S. Geological Survey, 2014	Lafourche, La., Levees, 2012	3 m
Topographic lidar (2013)	U.S. Geological Survey, 2017a, b	3 projects—Atchafalaya Basin, La.; Vermilion Bay, La.	1 m
Topographic lidar (2013)	U.S. Geological Survey, 2017a, b	10 projects—Barataria Basin, La.	2 m
Topography (1942–2006)	U.S. Geological Survey, 2017a, b	3 projects—Louisiana	10 m

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