NOAA Technical Memorandum NESDIS NGDC-41

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Contents

List of Figures

List of Tables

Digital Elevation Models of Yakutat, Alaska: Procedures, Data Sources and Analysis

1. Introduction

In May of 2009, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a set of integrated bathymetric–topographic digital elevation models (DEMs) covering the Yakutat, Alaska region (Fig. 1) for the Geophysical Institute at the University of Alaska at Fairbanks (UAF). These DEMs are nested at 8 arc-second[1], 8/3 arc-second and 8/15 arc-second, with the highest resolution grid centered on the harbor at Yakutat. The coastal DEMs will be used as input for the university-developed modeling system to simulate tsunami generation, propagation, and inundation (http://www.aeic.alaska.edu/tsunami/). The DEMs were generated from diverse digital datasets in the region (sources shown in Figure 4) and were designed to represent modern morphology. They will be used for tsunami inundation modeling by the Alaska Earthquake Information Center in support of the National Tsunami Hazard Mitigation Program (http://nthmp.tsunami.gov/). This report provides a description of the data sources and methodology used to develop the Yakutat DEMs.

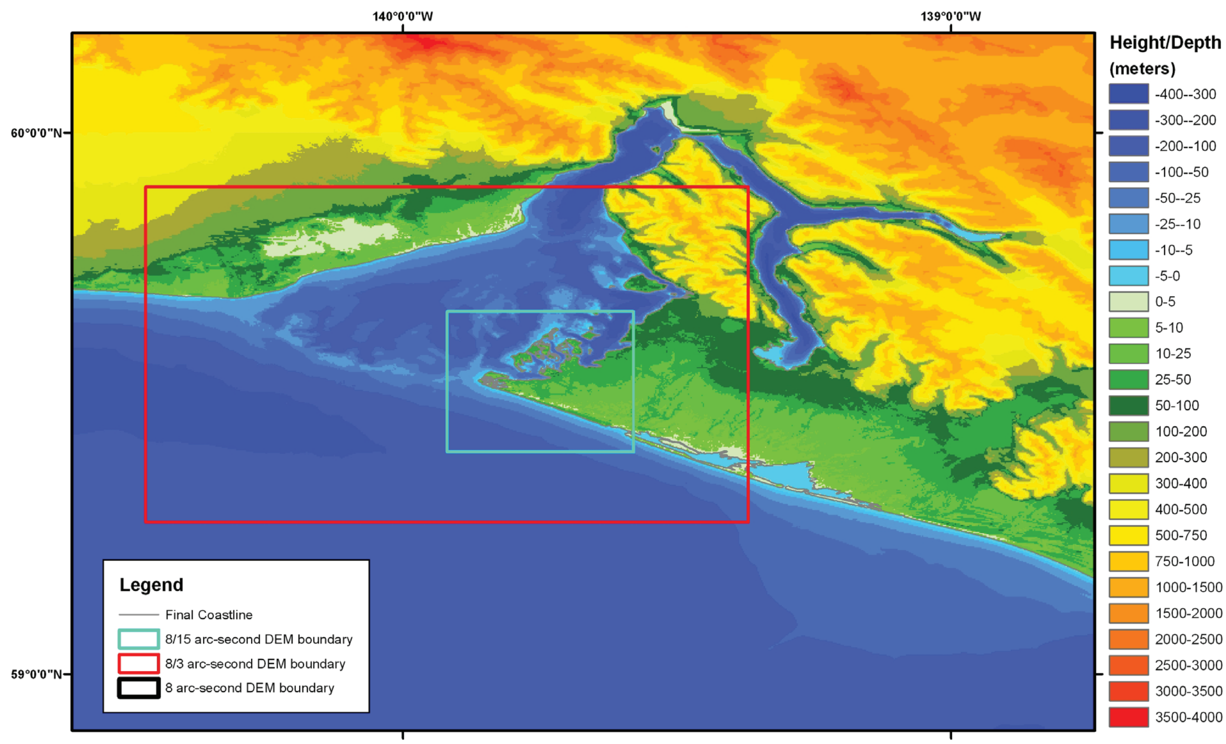

Figure 1. *Boundaries of the Yakutat, Alaska nested DEMs. Color image of the 8 arc-second DEM is in the background.*

1. In polar latitudes, longitude lines are spaced significantly closer together than latitude lines, approaching zero at the poles. While the DEMs are built upon grids of square cells in geographic coordinates, they are not square cells when converted to meters. At the latitude of Yakutat, Alaska (59º 32’ 59.38”N, 139º 47’ 39.69”W) 1 arc-second of latitude is equal to 32.04 meters; 1 arc-second of longitude is 15.89 meters.

2. Study Area

Yakutat is an isolated community in lowlands along the Gulf of Alaska, 212 miles northwest of Juneau and 225 miles southeast of Cordova. It is at the mouth of Yakutat Bay, which is surrounded by glaciers to the east, west, and north. Doggie Island, Khantaak Island and several smaller islands form natural breakwaters between Yakutat Harbor and Yakutat Bay to the west (Fig. 2). Millions of years of glaciation gradually carved away a coastal plateau creating a region with many tributary fiords and passageways, islands, and rocky shores. Approximately 800 people live in the town of Yakutat. Hubbard Glacier is the largest tidewater glacier in North America and is located just 30 miles by air or water from Yakutat (Fig. 3). In 1986 and again in the spring of 2002, the glacier advanced across the mouth of Russell Fiord, temporarily creating the world's largest glacial lake.

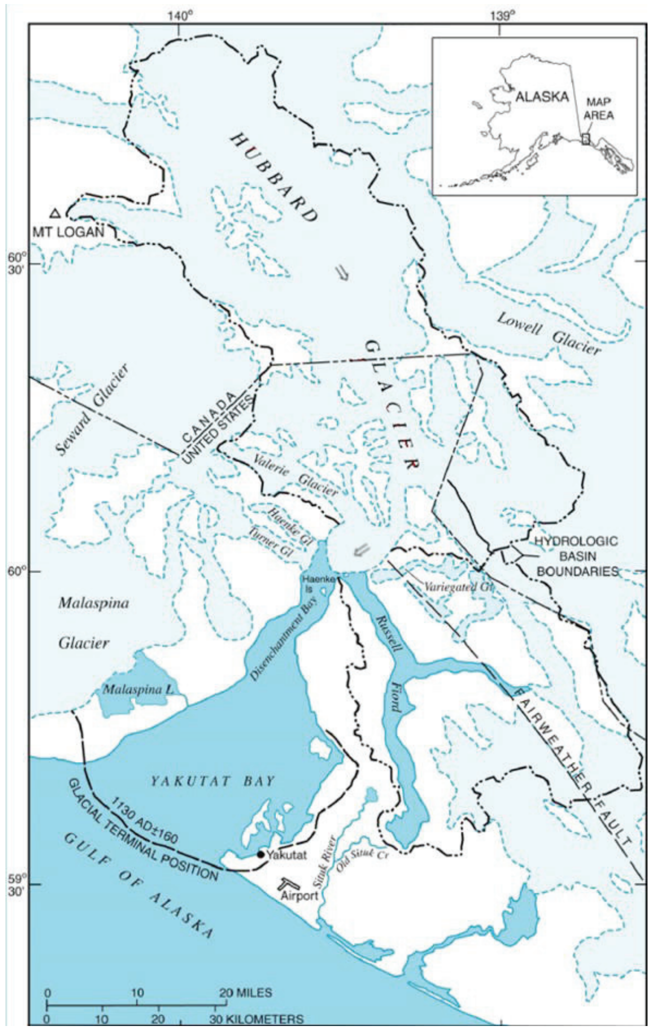

Figure 2. *Map of the region surrounding Yakutat, Alaska. Major geographical features identified. Source: Wikipedia (http://upload.wikimedia.org/wikipedia/commons/3/3d/Hubbard_Glacier_Alaska_Map.jpg)*

Yakutat is in an earthquake prone region with the Fairweather Fault to the northeast of town, making the area highly vulnerable to tsunamis. In early September 1899, the Yakutat Bay region was shaken by a series of major earthquakes. The main earthquake (magnitude 8.0) occurred on September 10th and caused major vertical displacements of up to 14.5 meters west of Disenchantment Bay and a tsunami of 10.6 meters in Yakutat Bay (http://earthquake.usgs.gov/earthquakes/states/events/1899_09_10.php).

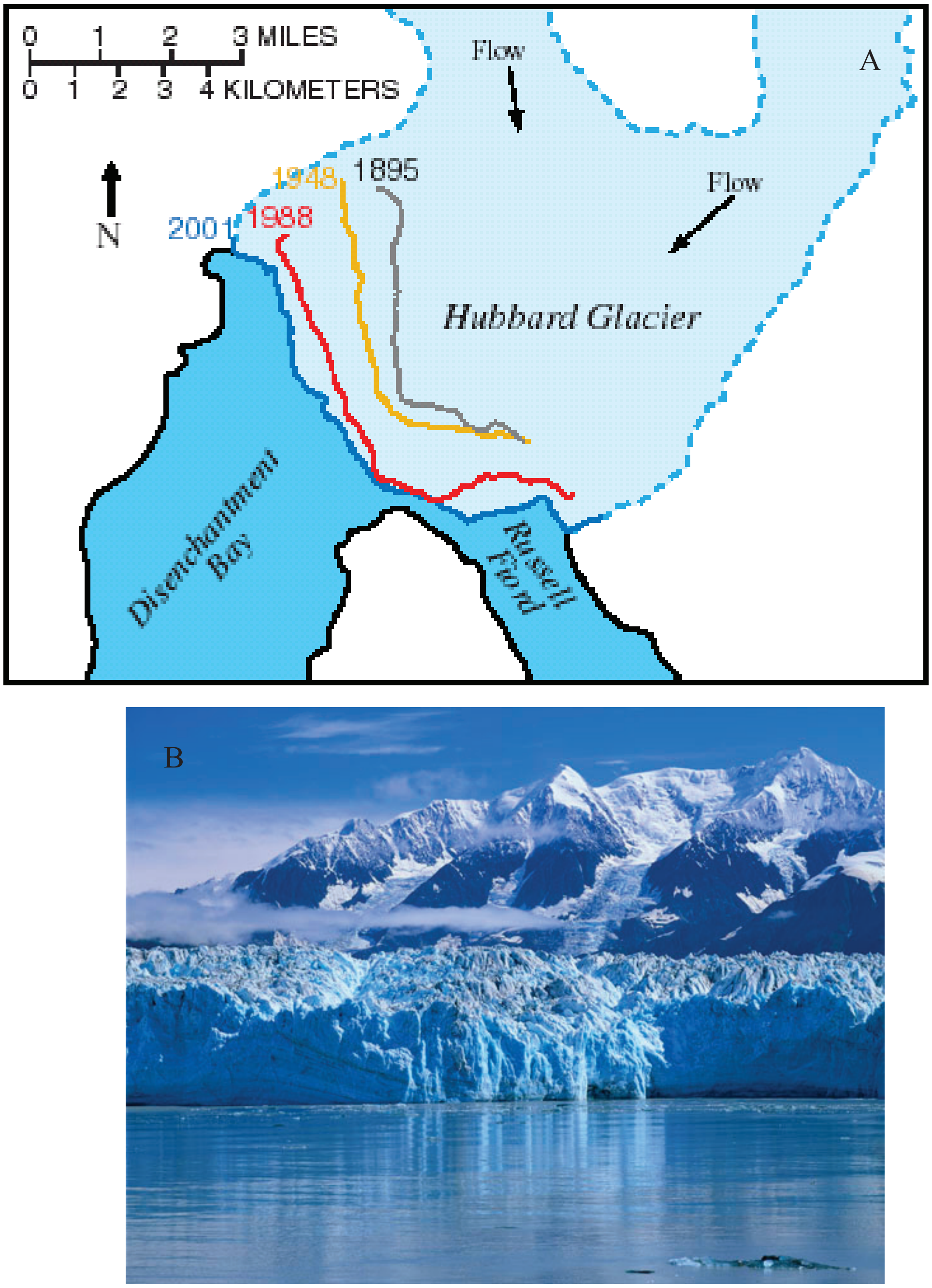

Figure 3. *Hubbard Glacier. A) Diagram of Hubbard Glacier showing the variations in the location of the glacial toe (http://pubs.usgs.gov/fs/fs-001-03/) B) Photograph of Hubbard Glacier (http://www.wainscoat.com/alaska/hubbard1.jpg)*

3. Methodology

The Yakutat DEMs were developed to meet the specifications in Table 1, which have slightly larger extents (~5 percent) than those required by UAF's tsunami modeling requirements. The best available digital data were obtained by NGDC and shifted to common horizontal and vertical datums: World Geodetic System 1984 (WGS 84) geographic[2] and Mean Higher High Water (MHHW), for modeling of maximum flooding, respectively. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1a: Specifications for the 8 arc-second Yakutat, Alaska DEM.

Grid Area	Yakutat, Alaska
Coverage Area	140.61º to 138.73º W; 58.89º to 60.19º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	Mean Higher High Water (MHHW)
Vertical Units	Meters
Cell Size	8 arc-second
Grid Format	netCDF

Table 1b: Specifications for the 8/3 arc-second Yakutat, Alaska DEM.

Grid Area	Yakutat, Alaska
Coverage Area	140.47º to 139.37º W; 59.27º to 59.91º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	Mean Higher High Water (MHHW)
Vertical Units	Meters
Cell Size	8/3 arc-second
Grid Format	netCDF

Table 1c: Specifications for the 8/15 arc-second Yakutat, Alaska DEM.

Grid Area	Yakutat, Alaska
Coverage Area	139.93º to 139.57º W; 59.41º to 59.67º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System 1984 (WGS 84)
Vertical Datum	Mean Higher High Water (MHHW)
Vertical Units	Meters
Cell Size	8/15 arc-second
Grid Format	netCDF

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

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 4) were obtained from several U.S. federal and academic agencies, including: NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS), and NGDC; the U.S. Fish and Wildlife Service (FWS); and the U.S. Geological Survey (USGS). Safe Software's (http://www.safe.com/) *FME* data translation tool package was used to shift datasets to NAD 83 horizontal datum and to convert into ESRI (http://www.esri.com/) *ArcGIS* shapefiles[3]. The shapefiles were then displayed with *ArcGIS* to assess data quality and manually edit datasets. The methodology used for vertical datum adjustments is described in Section 3.2.1.

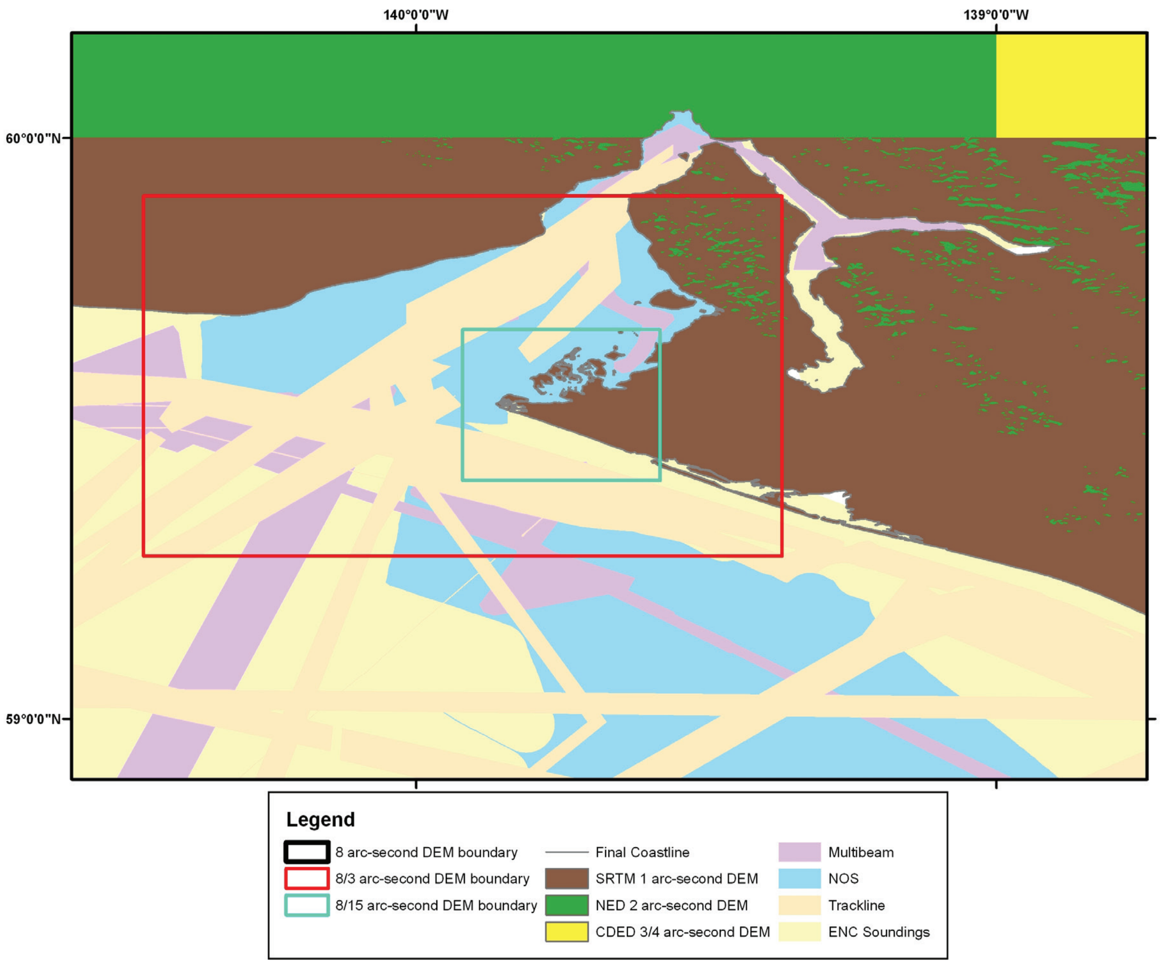

Figure 4. *Principal source dataset contributions to the Yakutat, Alaska DEMs.*

3. *FME* uses the North American Datum Conversion Utility (NADCON; http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.html) developed by NOAA's National Geodetic Survey (NGS) to convert data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformation.

3.1.1 Shoreline

Two digital coastline datasets of the Yakutat region were analyzed for inclusion in the Yakutat DEMs: NOAA ENCs (see Table 3) and U.S. Fish and Wildlife Service (FWS) statewide Alaska digital coastline (Table 2; Figs. 5 and 6). Comparisons between the two coastline datasets, NOS hydrographic surveys, and the NED and SRTM topographic DEMs showed that the FWS coastline best fit the topographic and bathymetric data overall and was merged with large-scale ENC coastlines to create a 'final coastline' for the Yakutat region.

Table 2. Shoreline datasets used in compiling the Yakutat, Alaska DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*
FWS	2006	Compiled coastline	Various	WGS 84 geographic	Undefined
NOAA nautical charts	1997-1998	Inferred MHHW coastline	Digitized from 1:10000,1:30000 and 1:80000 scale charts	WGS 84 geographic	Inferred MHHW

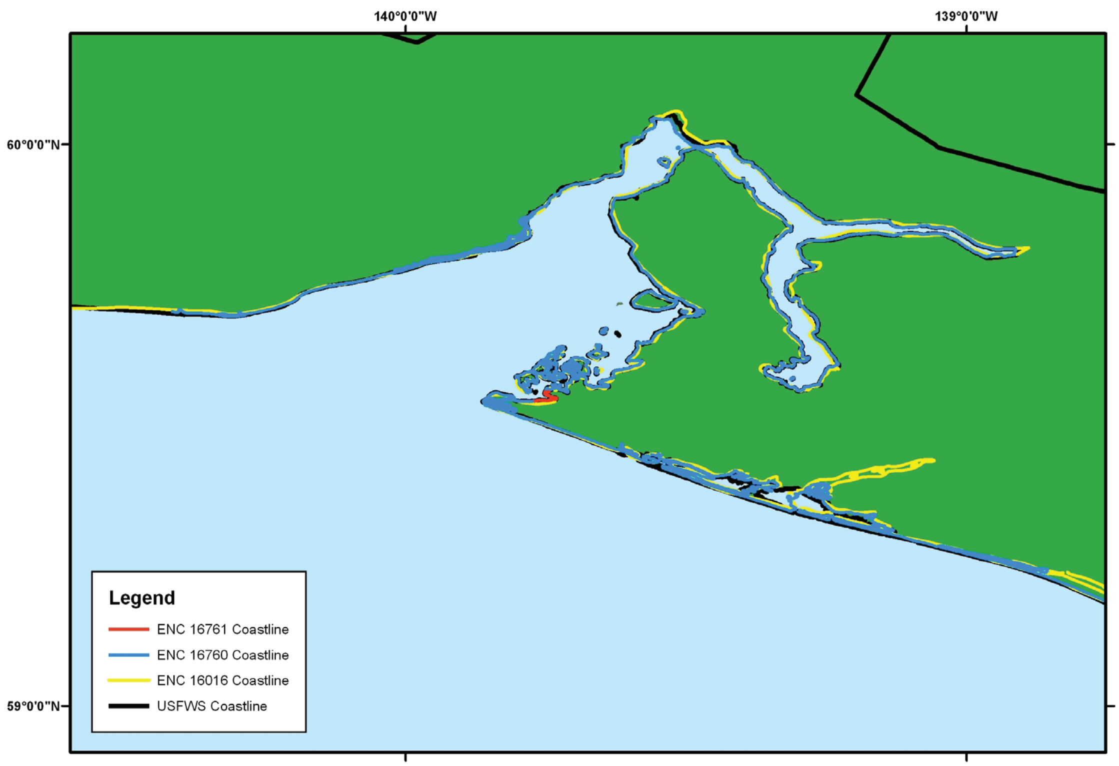

Figure 5. *Digital coastline datasets used to compile the 'final coastline' of the Yakutat region.*

Figure 6. *Digital coastline datasets of Phipps Peninsula to the southwest of Yakutat . The ENC coastlines were edited using georeferenced aerial imagery (see inset) from Google Earth (http://earth.google.com) to better represent the marshlands. The ENC coastlines were then used to adjust the final coastline. The final coastline (shaded in green) was used in developing the Yakutat DEMs.*

1) U.S. Fish and Wildlife Service

The U.S. Fish and Wildlife Service (FWS) has compiled a seamless digital coastline of the State of Alaska from a variety of sources, including: the National Hydrography Dataset, NOAA nautical charts, U.S. Fish and Wildlife Service, National Geographic Topo Software, U.S. Army Corps of Engineers, and Alaska Department of Natural Resources. This dataset was graciously provided to NGDC by Bret Christensen, U.S. Fish and Wildlife Service. Though efforts were made to obtain the highest resolution coastlines available, vertical datums were apparently not determined nor controlled in any way in compiling the FWS coastline; the horizontal datum of the compiled FWS coastline is WGS 84. The FWS coastline provides complete coverage of the Yakutat region.

2) NOAA nautical charts

Ten NOAA nautical charts were available for the Yakutat area (Table 3), and were downloaded from NOAA's Office of Coast Survey web site (http://www.nauticalcharts.noaa.gov/mcd/enc/index.htm). Nine of the charts were available as georeferenced Raster Nautical Charts (RNCs; digital images of the charts), which were used to assess the quality of bathymetric datasets. Four charts were available as Electronic Navigational Charts (ENCs) that represent chart features as individual digital objects. The ENCs are in S-57 format and include coastline data files referenced to Mean High Water (MHW). The ENC coastlines were assumed to be essentially the same at MHHW once adjusted to fit the bathymetric datasets. The average vertical offset from MHW to MHHW based on the Yakutat tide station is approximately 0.26 meters.

ENCs #16016 and #16760 provided detailed coastlines for the area surrounding Yakutat Bay. Each of the ENC coastline datasets contained many piers and other man-made structures that had to be removed when building the final coastline. In addition, RNC #16761 at 1:10,000 scale was used to manually digitize the coastline immediately surrounding Yakutat Harbor. Satellite imagery from Google Earth (http://earth.google.com) and photographs of Yakutat, Alaska were referenced while manually adjusting the coastline in the immediate vicinity of the harbor (e.g., Figs. 7 and 8).

Table 3. NOAA nautical charts in the Yakutat region.

Chart	*Title*	*Edition*	*Edition Date*	*Format*	*Scale*
531	Gulf of Alaska Strait of Juan de Fuca to Kodiak Island	17th	2009	ENC	1:2,100,000
16013	Cape St. Elias to Shumagin Islands	30th	2006	RNC	1:969,761
16016	Dixon Entrance to Cape St. Elias	21st	2007	ENC and RNC	1:969,756
16741	Icy Bay	11th	2005	RNC	1:40,000
16760	Cross Sound to Yakutat Bay	10th	2000	ENC and RNC	1:300,000
16761	Yakutat Bay	16th	2000	RNC	1:10,000 and 1:80,000
16762	Lituya Bay	9th	2002	RNC	1:10,000 and 1:20,000
17300	Stephens Passage to Cross Sound, including Lynn Canal	7th	2005	RNC	1:100,000 and 1:209,978
17301	Cape Spencer to Icy Point	8th	1998	ENC and RNC	1:40,000
17318	Glacier Bay	31st	2009	RNC	1:10,000 and 1:80,000

To obtain the best digital MHHW coastline of the Yakutat region, NGDC merged the FWS coastline and large-scale ENCs into a 'final coastline' (see Fig. 4). The final coastline was adjusted to the ENCs due to the enhanced representation of shoreline features in Yakutat harbor. The final coastline was also edited to be consistent with the NOS hydrographic survey data. Piers and docks were also manually removed from the final coastline.

The final coastline was sub-sampled to 10-meter spacing using NGDC's *GEODAS* software and converted to point data for use as a coastal buffer for the bathymetric pre-surfacing algorithm (see Section 3.3.2) to ensure that interpolated bathymetric values reached "zero" at the coast. The final coastline was used to clip the SRTM and NED topographic DEMs, which contained elevation values, typically zero, over the open ocean (Section 3.1.3).

Figure 7. *An oblique photograph of Yakutat Harbor. Source: http://www.yakutatcharters.com/images/yak2.jpg*

Figure 8. *An aerial photograph of Yakutat Harbor.*
Source: http://kcaw.org/modules/local_news/media/pictures/yakutat%20townsite.jpg

3.1.2 *Bathymetry*

Bathymetric datasets used in the compilation of the Yakutat DEMs included NOS hydrographic surveys, two recent USACE harbor surveys, NOAA ENC chart soundings, NGDC multibeam swath sonar surveys, and NGDC trackline surveys (Table 4).

Table 4. Bathymetric datasets used in compiling the Yakutat, Alaska DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
NOS	1896-2002	Hydrographic survey soundings	Ranges from 10 meters to 1.5 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	NAD 83, Early Alaskan Datum, Undetermined Datum	MLLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NOAA ENCs	2006-2009	NOAA digitized nautical chart soundings	~500 to 1200 meters	WGS 84 geographic	MLLW (meters)	http://www.nauticalcharts.noaa.gov/mcd/enc/index.htm
NGDC	1999-2004	Multibeam swath sonar	Raw MB files gridded to 8 arc-second	WGS 84 geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NGDC	1967-1989	Trackline	Raw MB files gridded to 8 arc-second	WGS 84 geographic	Assumed MSL	http://www.ngdc.noaa.gov/mgg/geodas/trackline.html
NGDC	2009	Digitized soundings	~10 to 100 meters	WGS 84 geographic	Inferred MHHW	

1) NOS hydrographic survey data

A total of 16 NOS hydrographic surveys conducted between 1896 and 2002 were used in Yakutat DEM development (Table 5; Fig. 9). The hydrographic survey data were originally vertically referenced to Mean Lower Low Water (MLLW) and horizontally referenced to NAD 83 geographic, Early Alaska, or "undetermined" datums.

Data point spacing for the surveys ranged from about 10 to 60 meters in shallow water up to 1.5 kilometers in deep water. All surveys were extracted from NGDC's online database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html) in their original datums (Table 5). The data were then converted to NAD 83 geographic using *FME* software, an integrated collection of spatial extract, transform, and load tools for data transformation (http://www.safe.com/). NOS surveys in Early Alaska or "undetermined" datums were manually shifted in *ArcGIS* to fit the final coastline. The surveys were subsequently clipped to a polygon 0.05 degrees (~5%) larger than the 8 arc-second gridding area to support data interpolation across DEM boundaries.

After converting all NOS survey data to MHHW (see Section 3.2.1), the data were displayed in ESRI *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and compared to the NED and SRTM topographic data and the final coastline.

Older NOS surveys were clipped to remove soundings that overlap more recent, higher-resolution NOS bathymetric surveys. All the soundings in surveys H02159, H06718, H06719, H06720, and H06721 were removed through this process.

Table 5. NOS hydrographic surveys used in compiling the Yakutat DEMs.

Name	*Year*	*Scale of Survey*	*Original Horizontal Datum*	*Original Vertical Datum*
H02159	1892	40000	Undetermined	MLLW
H06579	1940	200000	Early Alaska	MLLW
H06581	1940	100000	Early Alaska	MLLW
H06717	1941	5000	Early Alaska	MLLW
H06718	1941	10000	Early Alaska	MLLW
H06719	1941	20000	Early Alaska	MLLW
H06720	1941	20000	Early Alaska	MLLW
H06721	1941	20000	Early Alaska	MLLW
H09686	1977/1978	10000	Early Alaska	MLLW
H09687	1977	20000	Early Alaska	MLLW
H09688	1977	20000	Early Alaska	MLLW
H09694	1978	20000	Early Alaska	MLLW
H09695	1977	20000	Early Alaska	MLLW
H09778	1978	20000	Early Alaska	MLLW
H09779	1978	20000	Early Alaska	MLLW
H10902	1999	10000	NAD 83	MLLW

Note: Some earlier surveys were referenced to horizontal datums with no known conversions to NAD 83 geographic. These surveys were manually adjusted in ArcGIS to fit the final coastline.

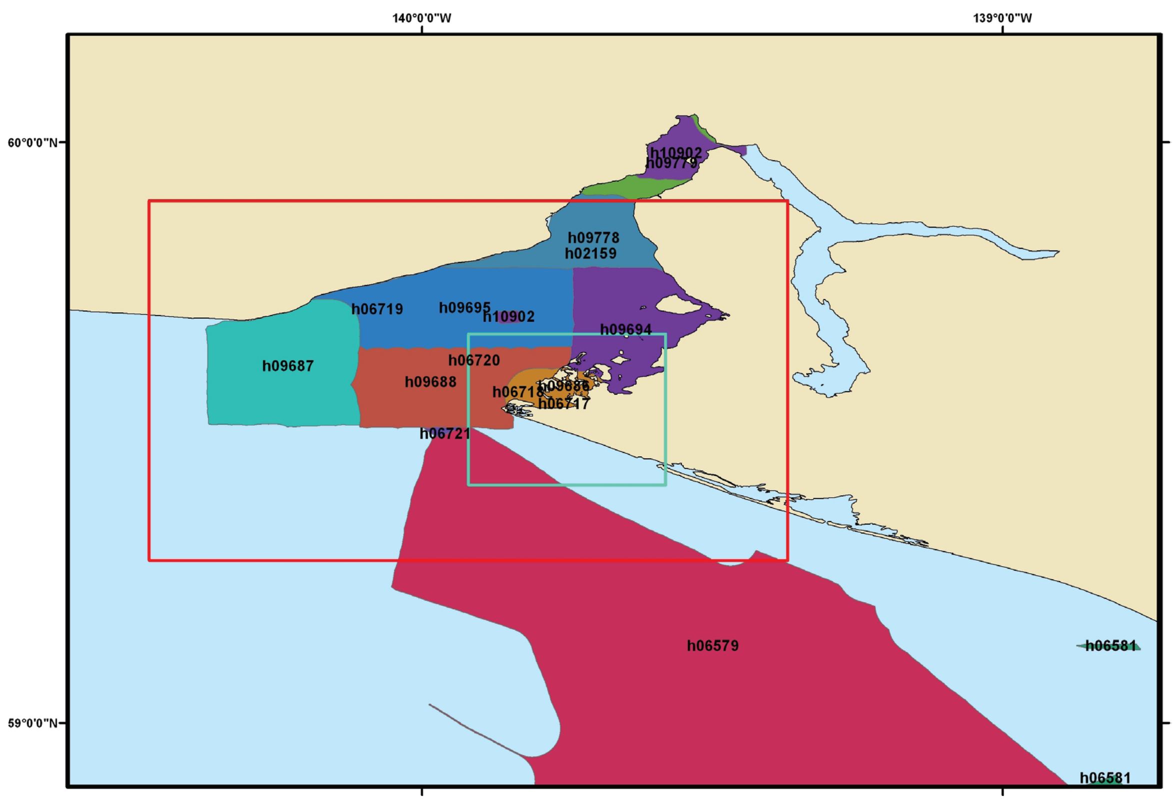

Figure 9. Digital NOS hydrographic survey coverage in the Yakutat region. Black denotes boundary of the 8 arc-second DEM. Red denotes boundary of the 8/3 arc-second DEM; blue denotes boundary of the 8/15 arc-second DEMs; coastline in black. Water areas without digital NOS soundings depicted as light blue.

2) OCS Electronic Navigational Chart soundings

Nautical charts #531, #16016, and #16760 were available from NOAA's Office of Coast Survey in ENC chart format and, as no bathymetric survey data were available for these areas, sounding data were extracted from these charts using *FME*. The point spacing and vertical resolution of the ENCs vary by the scale of the charts (see Table 3).

3) Multibeam swath sonar files

Four multibeam swath sonar surveys (Table 6, Fig. 4) were available from the NGDC multibeam sonar bathymetry database (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html) for use in building the Yakutat DEMs. The NGDC database is comprised of the original swath sonar files of surveys conducted mostly by U.S. educational fleets. Most of the NGDC multibeam swath sonar surveys were transits rather than dedicated seafloor surveys. All surveys have a horizontal datum of WGS 84 geographic and undefined vertical datum, assumed to be equivalent to mean sea level (MSL).

The downloaded data were gridded at 8 arc-seconds using the 'mbgrid' tool in *MB-System* to apply a tight spline tension. *MB-System* is an NSF-funded free software application specifically designed to manipulate multibeam swath sonar data (http://www.ldeo.columbia.edu/res/pi/MB-System/). The gridded data were converted to shapefiles and transformed to MHHW using *FME*.

Table 6. Multibeam swath sonar surveys used in compiling the Yakutat, Alaska DEMs.

Survey ID	*Ship*	*Year*	*Original Vertical Datum*	*Original Horizontal Datum*	*Institution*
EW0408	Ewing	2004	Assumed MSL	WGS 84 geographic	Columbia University
H10902	Rainier	1999	Assumed MSL	WGS 84 geographic	National Oceanic and Atmospheric Administration
H10985	Rainier	2000	Assumed MSL	WGS 84 geographic	National Oceanic and Atmospheric Administration
KM0514	Kilo Moana	2005	Assumed MSL	WGS 84 geographic	University of New Hampshire

4) Trackline data files

Twenty-six trackline surveys (Table 7) were available from the NGDC trackline survey database (http://www.ngdc.noaa.gov/mgg/geodas/trackline.html) for use in building the Yakutat DEMs. The Marine Trackline Geophysics database contains bathymetry, magnetics, gravity and seismic navigation data collected during marine cruises from 1953 to the present. All surveys have a horizontal datum of WGS 84 geographic and undefined vertical datum assumed to be equivalent to mean sea level (MSL). The downloaded data in xyz format were converted to shapefiles and transformed to MHHW using *FME* software.

Table 7. Trackline surveys used in compiling the Yakutat, Alaska DEMs.

Survey ID	*Institution*	*Year*
POL6769	NOAA	1967
YAQ68SEP	Oregon State University	1968
POL6991	NOAA	1969
17473	Defense Mapping Agency	1970
POL7001	National Ocean Service	1970
YAQ702	Oregon State University	1970
YAQ703	Oregon State University	1970
RC1407	Lamont-Doherty Geological Observatory	1971
POL7103	NOAA	1971
CONMALAS	National Ocean Service	1972
T274EG	USGS Branch of Pacific Marine Geology	1974
G17SEG	US Department of Interior	1975
S175EG	USGS Branch of Pacific Marine Geology	1975
L476WG	USGS Branch of Pacific Marine Geology	1976
S176EG	USGS Branch of Pacific Marine Geology	1976
L677EG	USGS Branch of Pacific Marine Geology	1977
S277EG	USGS Branch of Pacific Marine Geology	1977
S877EG	USGS Branch of Pacific Marine Geology	1977
L378EG	USGS Branch of Pacific Marine Geology	1978
S578EG	USGS Branch of Pacific Marine Geology	1978
S678EG	USGS Branch of Pacific Marine Geology	1978
LSSALE55	Minerals Management Service	1979
S1079EG	USGS Branch of Pacific Marine Geology	1979
F186GA	USGS Branch of Pacific Marine Geology	1986
FARN0689	Natural Environment Research Council	1989
FARN0789	Natural Environment Research Council	1989

5) NGDC Digitized Features

In regions of poor data coverage, NGDC digitized points using nearby ENC/RNC soundings to approximate depths. In the upper reaches of Russell Fiord, only 11 soundings were available from ENC #16760. To better represent the bathymetry in the region, NGDC used linear interpolation to digitize soundings in Seal Bay and Shelter Cove at approximately 500 meter intervals. For each of five digitized points between adjacent ENC soundings, one-sixth of the difference between the observed depths was cumulatively summed to approximate the values at each digitized point. Generally, the values ranged from -25 to -330 meters (Fig. 10).

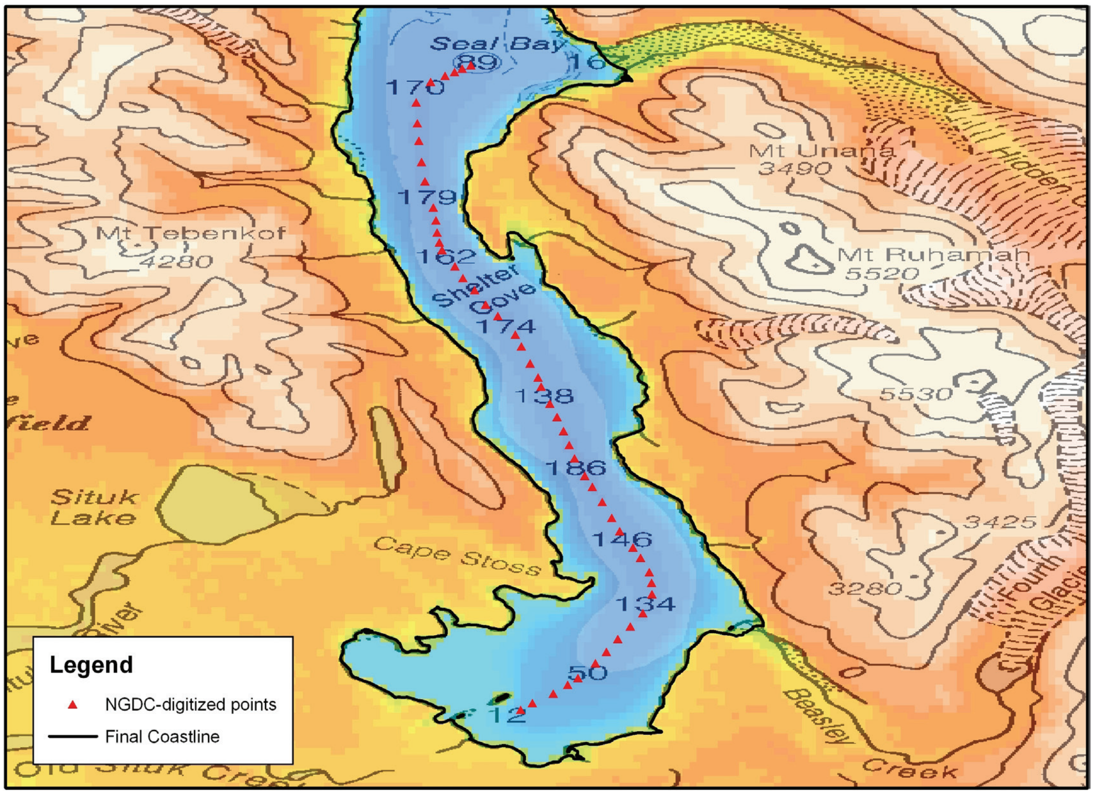

Figure 10. *NGDC-digitized points in Shelter Cove and Seal Bay. A color image of the 8 arc-second Yakutat DEM and RNC #16760 are in the background. Depths on the RNC are in fathoms.*

3.1.3 Topography

Topographic datasets of the Yakutat region were obtained from the U.S. Geological Survey and the Canadian Digital Elevation Dataset (CDED) (Table 8; Fig. 11).

Table 8. Topographic datasets used in compiling the Yakutat, Alaska DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*	*URL*
USGS NED	2006	Topographic DEM	2 arc-second grid	NAD 27 geographic	NGVD 29 (meters)	http://ned.usgs.gov/
NASA SRTM	2000	Topographic DEM	1 arc-second grid	WGS 84 geographic	WGS 84/ EGM 96 Geoid (meters)	http://srtm.usgs.gov/
CDED	2007	Topographic DEM	0.75 arc-second grid	NAD 83 geographic	MSL	http://www.geobase.ca/geobase/en/data/cded/index.html

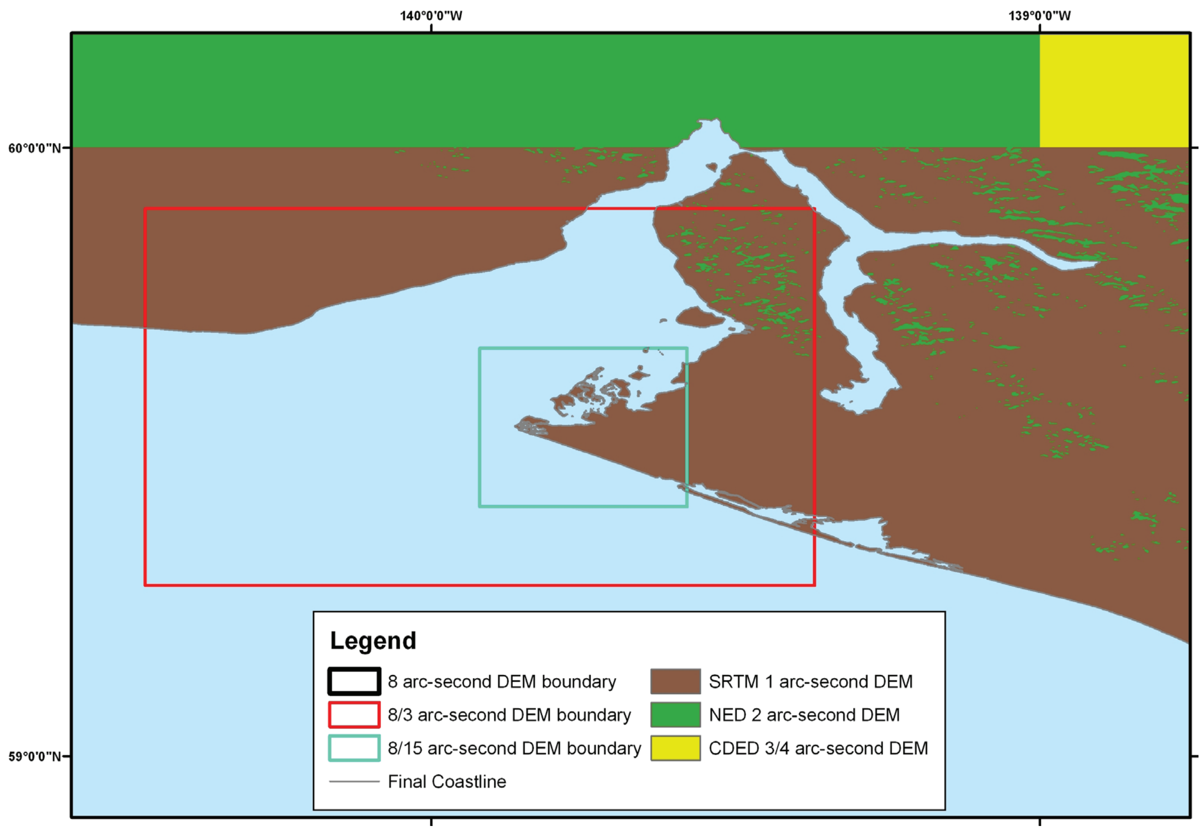

Figure 11. *Principal topographic dataset contributions to the Yakutat DEMs.*

1) **USGS NED topography**

The U.S. Geological Survey's (USGS) National Elevation Dataset (NED; http://ned.usgs.gov/) provides complete 2 arc-second coverage of Alaska[4]. Data are in NAD 27 geographic coordinates and NGVD 29 vertical datum (meters), and are available for download as raster DEMs. The extracted bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution. See the USGS Seamless web site for specific source information (http://seamless.usgs.gov/). The dataset was derived from USGS quadrangle maps and aerial photos based on surveys conducted in the 1970s and 1980s. The NED DEM contains values over the open ocean, which were deleted by clipping to the final coastline.

2) **NASA space shuttle radar topography**

The NASA Shuttle Radar Topography Mission (SRTM) obtained elevation data on a near-global scale (60° S to 60° N) to generate the most complete high-resolution digital topographic database of Earth[5]. The SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. Data from this mission have been processed into 1 degree × 1 degree tiles that have been edited to define the coastline, and are available from the USGS Seamless web site (http://seamless.usgs.gov/) as raster DEMs. The data are not processed to bare earth, but meet the absolute horizontal and vertical accuracies of 20 and 16 meters, respectively.

For the Yakutat region, the data have 1 arc-second spacing and are referenced to the WGS 84/EGM 96 Geoid. The SRTM data provide coverage of most of the Yakutat region, but exhibit numerous small areas with "no data" values (e.g., Fig. 12) necessitating the use of the lower-resolution NED topographic data in these areas. The SRTM DEM also contains values over the open ocean which were deleted by clipping to the final coastline.

4. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Alaska. The dataset provides seamless coverage of the United States, Hawai'i, Alaska, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD 83, except for Alaska, which is NAD 27. The vertical datum is NAVD 88, except for Alaska, which is NGVD 29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED web site]

5. The SRTM data sets result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA – previously known as the National Imagery and Mapping Agency, or NIMA), as well as the participation of the German and Italian space agencies, to generate a near-global digital elevation model (DEM) of the Earth using radar interferometry. The SRTM instrument consisted of the Spaceborne Imaging Radar-C (SIR-C) hardware set modified with a Space Station-derived mast and additional antennae to form an interferometer with a 60 meter long baseline. A description of the SRTM mission can be found in Farr and Kobrick (2000). Synthetic aperture radars are side-looking instruments and acquire data along continuous swaths. The SRTM swaths extended from about 30 degrees off-nadir to about 58 degrees off-nadir from an altitude of 233 km, and thus were about 225 km wide. During the data flight the instrument was operated at all times the orbiter was over land and about 1000 individual swaths were acquired over the ten days of mapping operations. Length of the acquired swaths range from a few hundred to several thousand km. Each individual data acquisition is referred to as a "data take." SRTM was the primary (and pretty much only) payload on the STS-99 mission of the Space Shuttle Endeavour, which launched February 11, 2000 and flew for 11 days. Following several hours for instrument deployment, activation and checkout, systematic interferometric data were collected for 222.4 consecutive hours. The instrument operated almost flawlessly and imaged 99.96% of the targeted landmass at least one time, 94.59% at least twice and about 50% at least three or more times. The goal was to image each terrain segment at least twice from different angles (on ascending, or north-going, and descending orbit passes) to fill in areas shadowed from the radar beam by terrain. This 'targeted landmass' consisted of all land between 56 degrees south and 60 degrees north latitude, which comprises almost exactly 80% of Earth's total landmass. [Extracted from SRTM online documentation]

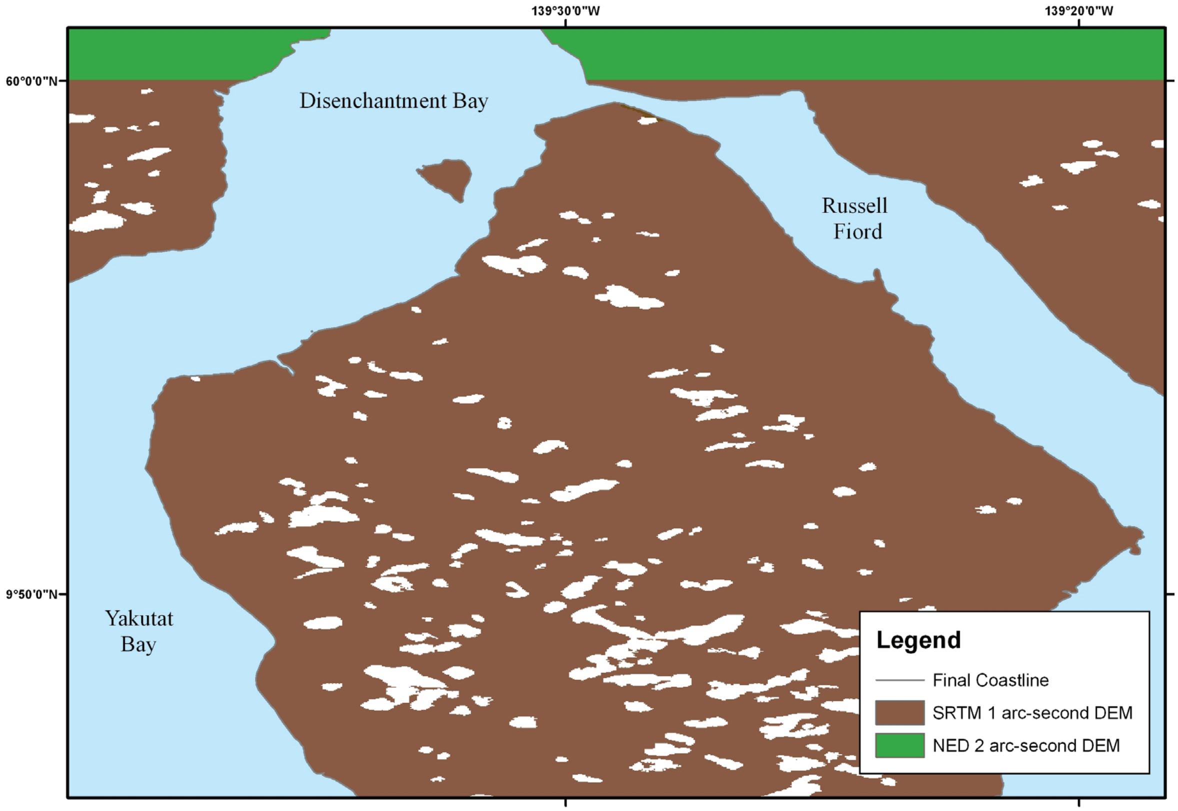

Figure 12. *Example of gaps (white area) in the SRTM data coverage around Disenchantment Bay and Russell Fiord. Gaps were filled with topographic data from the NED DEM. Final coastline in gray. Blue represents zero values over the open ocean. NED data coverage shown only north of 60° N.*

3) Canadian Digital Elevation Dataset

The Canadian Digital Elevation Data (CDED) (Fig. 11) consist of an ordered array of ground elevations at regularly spaced intervals at scales of 1:50,000 and 1:250,000. For the region surrounding Yakutat, the grid spacing is 0.75 arc-seconds at the 1:50,000 scale. Data are in NAD 83 geographic coordinates, referenced to MSL (meters), and are available for download as raster DEMs. The extracted elevations have a vertical accuracy of +/- 5 to 10 meters depending on the source data resolution. See the CDED web site for specific source information (http://www.geobase.ca/geobase/en/data/cded/index.html).

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Yakutat DEMs were originally referenced to a number of vertical datums including: Mean Lower Low Water (MLLW), Mean Sea Level (MSL), WGS 84/EGM 96 Geoid, and North American Vertical Datum of 1929 (NGVD 29). All datasets were transformed to MHHW for modeling of maximum flooding. Vertical datum transformations to MHHW were accomplished using *FME* and *ArcGIS*, based upon data from the NOAA tide station in the region.

1) Bathymetric data

The NOS hydrographic surveys, multibeam swath sonar surveys, trackline surveys, and the nautical chart soundings were transformed from either MSL or MLLW to MHHW, using *FME* software, by subtracting a constant offset (1.45 and 3.06 meters, respectively) measured at the NOAA Yakutat tide station (Table 9).

2) Topographic data

The NED and SRTM DEMs were originally referenced to NGVD 29 and WGS 84/EGM 96 Geoid vertical datums, respectively. There are no survey markers in the vicinity of Yakutat that relate these two geodetic datums to the local tidal datums. Thus, it was assumed that both datums are essentially equivalent to MSL in this area (Table 9). The CDED DEMs were originally referenced to MSL. Conversion to MHHW, using *FME* software, was accomplished by subtracting a constant offset value of 1.45 meters.

Table 9. Relationship between Mean Higher High Water and other vertical datums at the Yakutat tide station.

Name	*Id*	*Longitude*	*Latitude*	*MHHW*	*MHW*	*MSL*	*MLW*	*MLLW*
Yakutat, Yakutat Bay	9453220	-139.735	59.548333	3.72	3.46	2.27	1.08	0.66

3.2.2 Horizontal datum transformations

Datasets used to compile the Yakutat DEMs were originally referenced to Early Alaska, “undetermined”, and NAD 27, NAD 83, and WGS 84 geographic horizontal datums. The relationships and transformational equations between the geographic horizontal datums are well established. All of the NAD27 data were converted to a horizontal datum of NAD 83/WGS 84 geographic using *FME* software. The NOS surveys referenced to Early Alaska and “undetermined” horizontal datums were manually shifted in *ArcGIS* to fit the final coastline.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shapefiles were checked in ESRI *ArcMap* and *Quick Terrain Modeler* for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Data values over the open ocean in the NED and SRTM topographic DEMs. Each dataset required automated clipping to the final coastline.
- Lack of good bathymetric data in the Russell and Nunatak Fiords.
- Lack of good bathymetric data near the coastline, particularly in and near retreating glaciers.
- Misaligned NOS surveys with Early Alaska or "undetermined" horizontal datums.
- Significant changes in elevations at 60º N between the NED and SRTM due to glacial melting.
- Piers and docks in the coastline datasets that had to be removed.

3.3.2 Smoothing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the Yakutat DEMs. In both deep water and near shore, the NOS survey data have point spacing up to 1.5 kilometers apart. In order to reduce the effect of artifacts in the form of lines of "pimples" in the DEMs due to this low resolution dataset, and to provide effective interpolation into the coastal zone, bathymetric 'pre-surfaces' or grids were generated using *GMT*, an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/).

The Yakutat 8/15 arc-second, 'pre-surface' grid was compiled from NOS hydrographic point data, ENC soundings, trackline surveys, and NGDC multibeam swath sonar bathymetry data by converting the files to xyz format. These xyz files were combined into a single file, along with points extracted every 10 meters from the final coastline. To provide a slightly negative buffer along the entire coastline, the extracted points were assigned values of -1 meter to make sure that the offshore elevations remained negative; this was necessary due to the sparseness of the bathymetric data near the coast. These point data were then smoothed using the *GMT* tool 'blockmedian' onto a 8/15 arc-second grid. The *GMT* tool 'surface' was then applied to interpolate values for cells without data values. The netcdf grid created by 'surface' was converted into an ESRI Arc ASCII grid file using the *MB-System* tool 'mbm_grd2arc'. Conversion of this Arc ASCII grid file into an Arc raster permitted clipping of the grid with the final coastline (to eliminate data interpolation into land areas). Pre-surface grids for the 8/3 and 8 arc-second grids were built following the same methodology.

The 'pre-surfaces' were compared with the original soundings to ensure grid accuracy, converted to a shapefile, and then exported as an xyz file for use in the final gridding process (Table 10). The statistical analysis of the differences between the 8/15 arc-second bathymetric surface at Yakutat and NOS survey H09686 show that the majority of the NOS soundings are in good agreement (Fig. 13) with the bathymetric surface. The few exceptions where the differences reached up to 18.89 meters are attributed to rugged bathymetry where two or more closely positioned points were averaged to obtain the elevation of one grid cell.

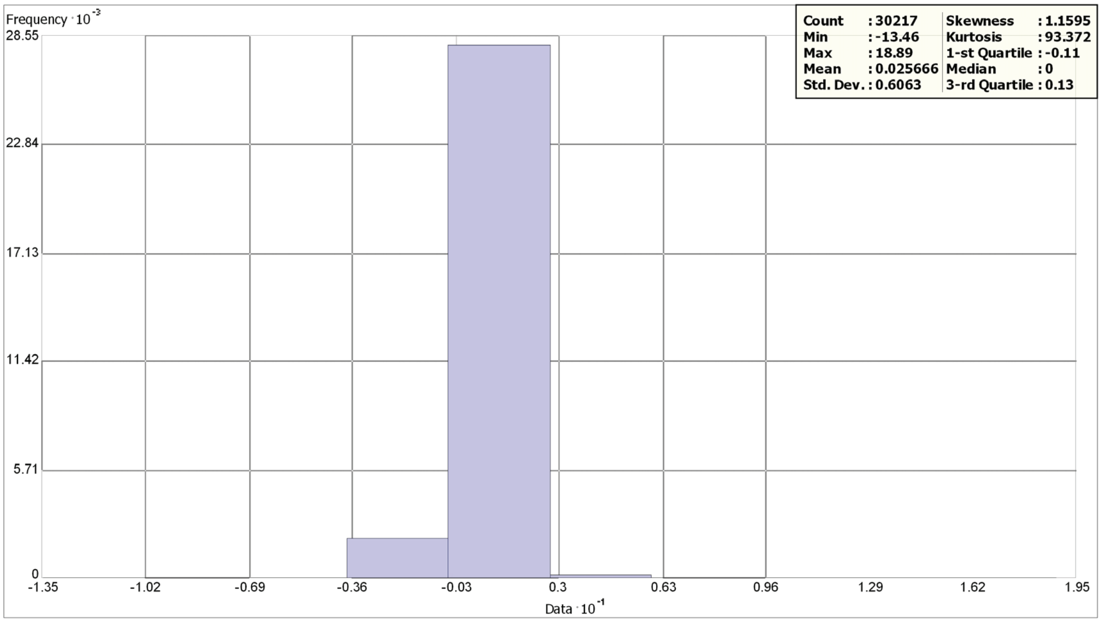

Figure 13. *Histogram of the differences between NOS hydrographic survey H09686 and the 8/15 arc-second pre-surfaced bathymetric grid of Yakutat, Alaska. Large differences result from averaging of multiple, closely-spaced NOS soundings in regions of steep bathymetry.*

3.3.3 Building the DEMs with MB System

MB-System was used to create the 8, 8/3, and 8/15 arc-second DEMs of Yakutat, Alaska. The *MB-System* tool 'mbgrid' applied a tight spline tension to the xyz data, and interpolated values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 10. Greatest weight was given to the SRTM topographic DEM, ENC soundings and NGDC digitized features. Least weight was given to the pre-surfaced bathymetric grids and trackline soundings. As noted in the hierarchy, higher resolution DEMs generated by NGDC (8/15 and 8/3 arc-second) served as sources for the coarser 8/3 and 8 arc-second grids.

Table 10. Data hierarchy used to assign gridding weight in MB-System.

Dataset	*Relative Gridding Weight*
SRTM topographic DEM	100
ENC soundings	100
NGDC-digitized features	100
USGS NED topographic DEM	10
NOS hydrographic surveys	10
Final coastline at 0 meters elevation	10
Higher resolution DEMs	10
NGDC hydrographic sonar multibeam	10
Pre-surfaced bathymetric grid	1
Trackline soundings	0.1

3.4 Quality Assessment of the DEMs

3.4.1. Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Yakutat DEMs are dependent upon the DEM cell size and datasets used to determine corresponding DEM cell values. Topographic features have an estimated horizontal accuracy of approximately 50 to 75 meters, based on the documented accuracy of the NED, SRTM, and CDED DEMs. Bathymetric features in areas covered by early 20th-century NOS hydrographic soundings—along the margins of the DEM—are resolved only to within a few tens of meters in shallow water, and to a few hundred meters in deep-water areas; their positional accuracy is limited by the sparseness of soundings, and potentially large positional accuracy of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the DEMs are also highly dependent upon the source datasets contributing to grid cell values. Topographic datasets have vertical accuracies of between 10 and 15 meters (NED: ~10 meters; SRTM: < 16 meters; and, CDED: ~10 meters). Bathymetric values are derived from a wide range of input data, consisting of single and multibeam sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys. Modern NOS standards are 0.3 m in 0 to 20 m of water, 1.0 m in 20 to 100 m of water, and 1% of the water depth in 100 m of water. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations in deep water to about 5% of water depth.

3.4.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the 8/15 arc-second Yakutat DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 14). The DEM was transformed to NAD 83/UTM Zone 7 coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of all the DEMs (Figs. 15 through 17) was accomplished using *POV Ray,* a shareware tool for generating three-dimensional graphics (http://www.povray.org/). Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEMs.

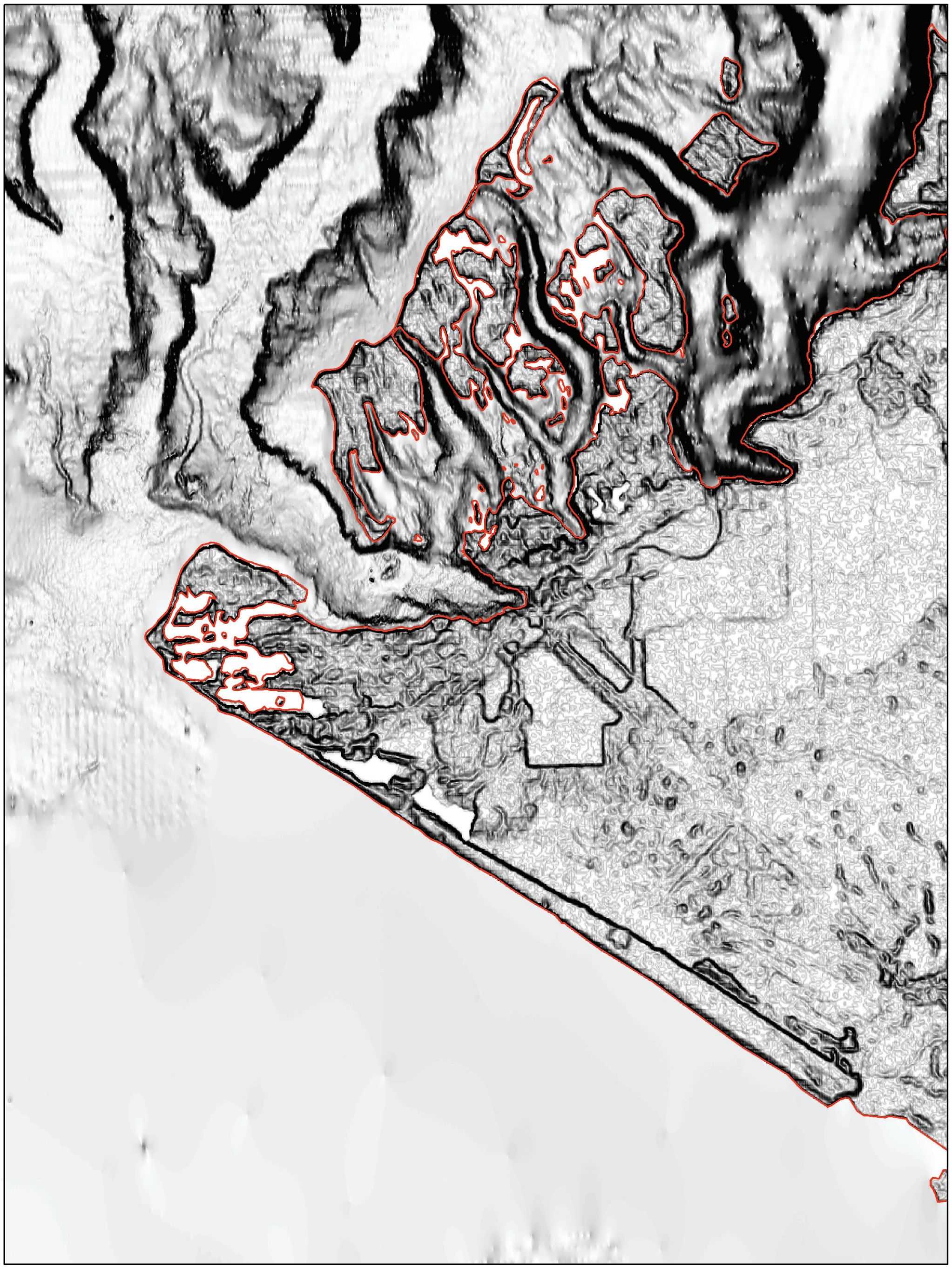

Figure 14. *Slope map of the 8/15 arc-second Yakutat DEM. Flat-lying slopes are white; dark shading denotes steep slopes; final coastline in red.*

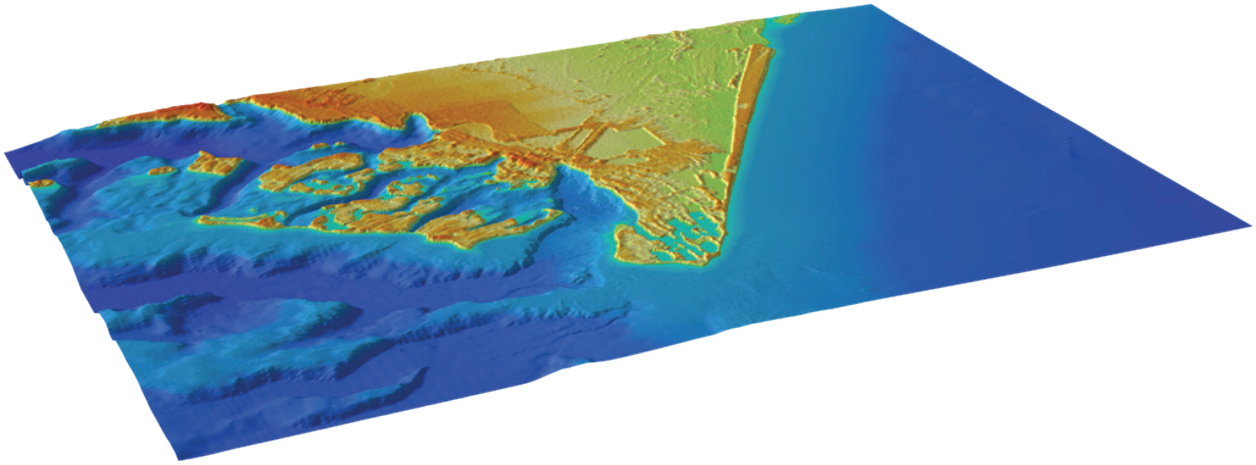

Figure 15. Perspective view from the northwest of the 8/15 arc-second Yakutat DEM.
Vertical exaggeration–times 2.

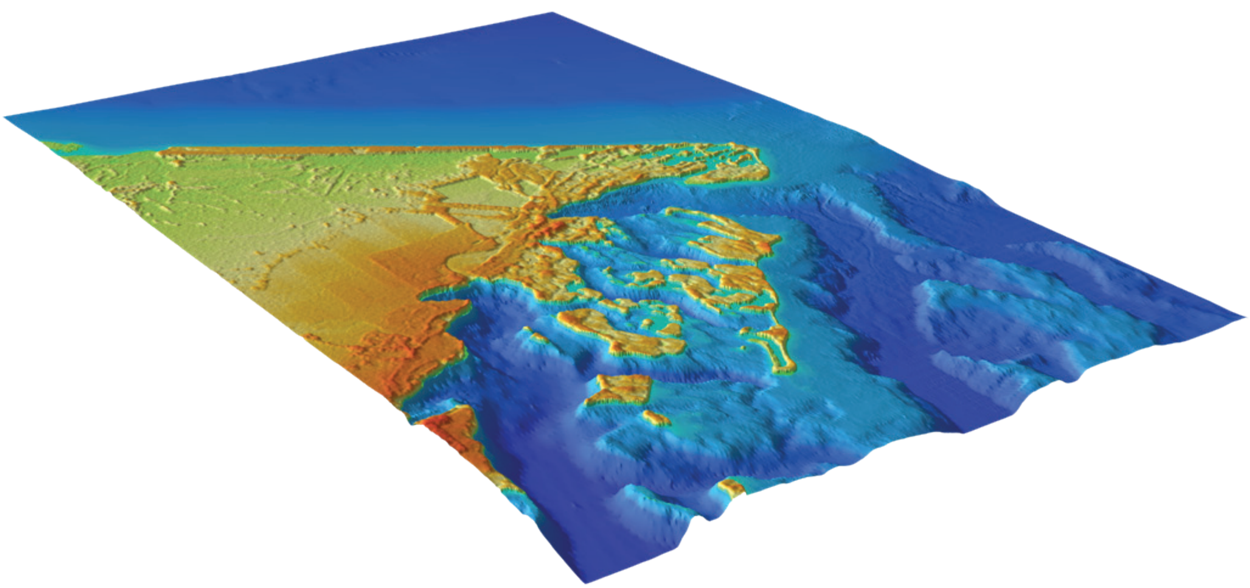

Figure 16. Perspective view from the northeast of the 8/3 arc-second Yakutat DEM.
Vertical exaggeration–times 2.

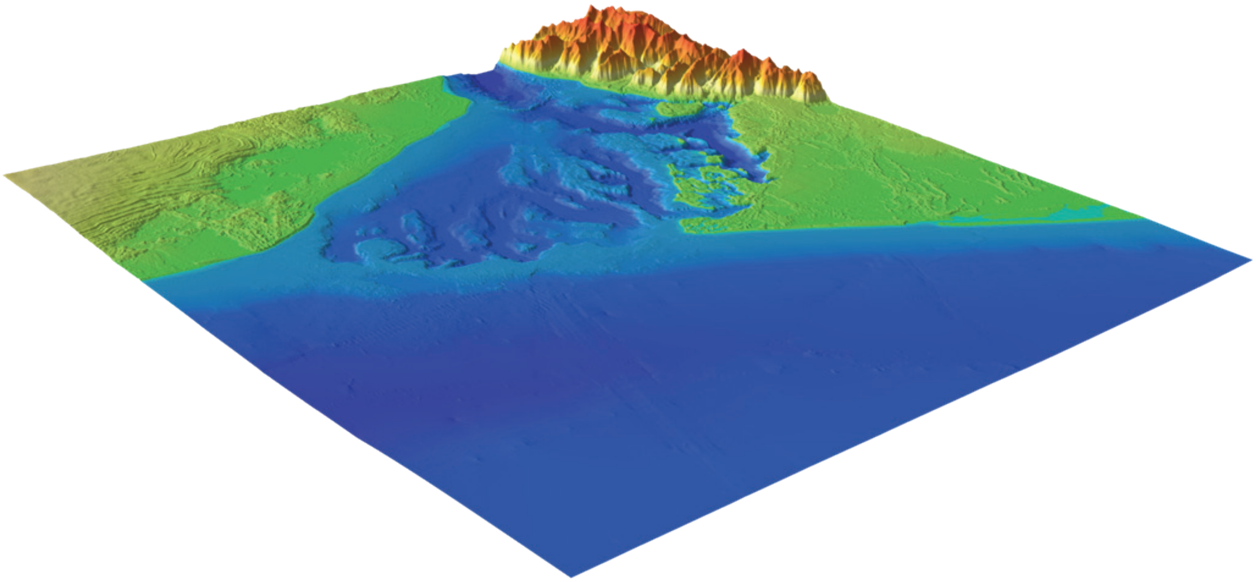

Figure 17. *Perspective view from the southwest of the 8 arc-second Yakutat DEM. Vertical exaggeration–times 2.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the 8/15 arc-second Yakutat DEM was compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas. A histogram of the differences between selected SRTM data points and the 8/15 arc-second Yakutat DEM is shown in Figure 18.

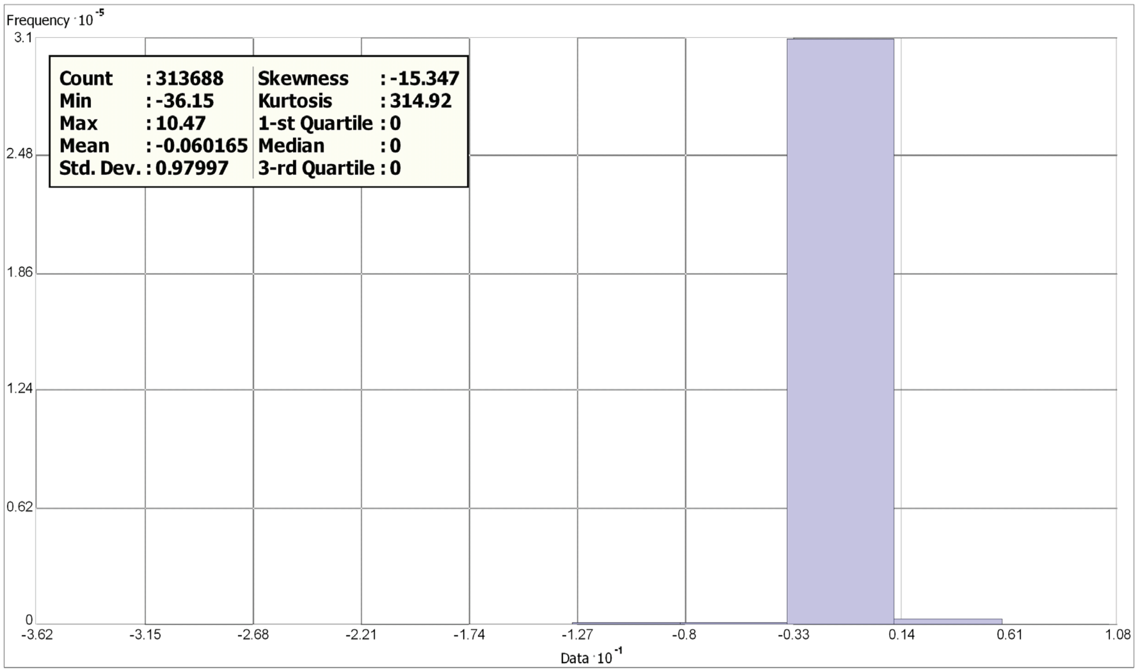

Figure 18. *Histogram of the differences between the SRTM topographic data and the 8/15 arc-second Yakutat DEM.*

3.4.5 Comparison with USGS topographic contours

USGS topographic quadrangles, Yakutat C-5 SW and Yakutat C-5 SE, were downloaded in the vicinity of Yakutat, Alaska and, Mount Saint Elias A-5 was downloaded for the upper portion of Disenchantment Bay near Hubbard Glacier (http://agdc.usgs.gov/index.html). The Yakutat C-5 SW and C-5 SE quadrangles give positions and elevations in NAD 27/UTM Zone 7 and NGVD 29 vertical datum (in meters) and have a scale of 1:25,000 with a 10-meter contour interval. The Mount Saint Elias A-5 quadrangle gives position and elevation in NAD 27/UTM Zone 7 and NGVD 29 vertical datum (in feet) and has a scale of 1:63,360 with a 100-foot contour interval.

A contour map with a 10-meter interval was created using the 8/15 arc-second DEM at Yakutat Harbor. The contour map was then compared against the USGS topographic quadrangles (Fig. 19). Although the figures show that differences exist between the 8/15 arc-second DEMs and the USGS topographic map contours, the morphology of the regions surrounding Yakutat Harbor is preserved. The largest differences exist in forested regions (e.g., Fig. 20) where the SRTM DEM provided elevations that were not referenced to “bare earth”, leading to differences of several to many meters in some locations.

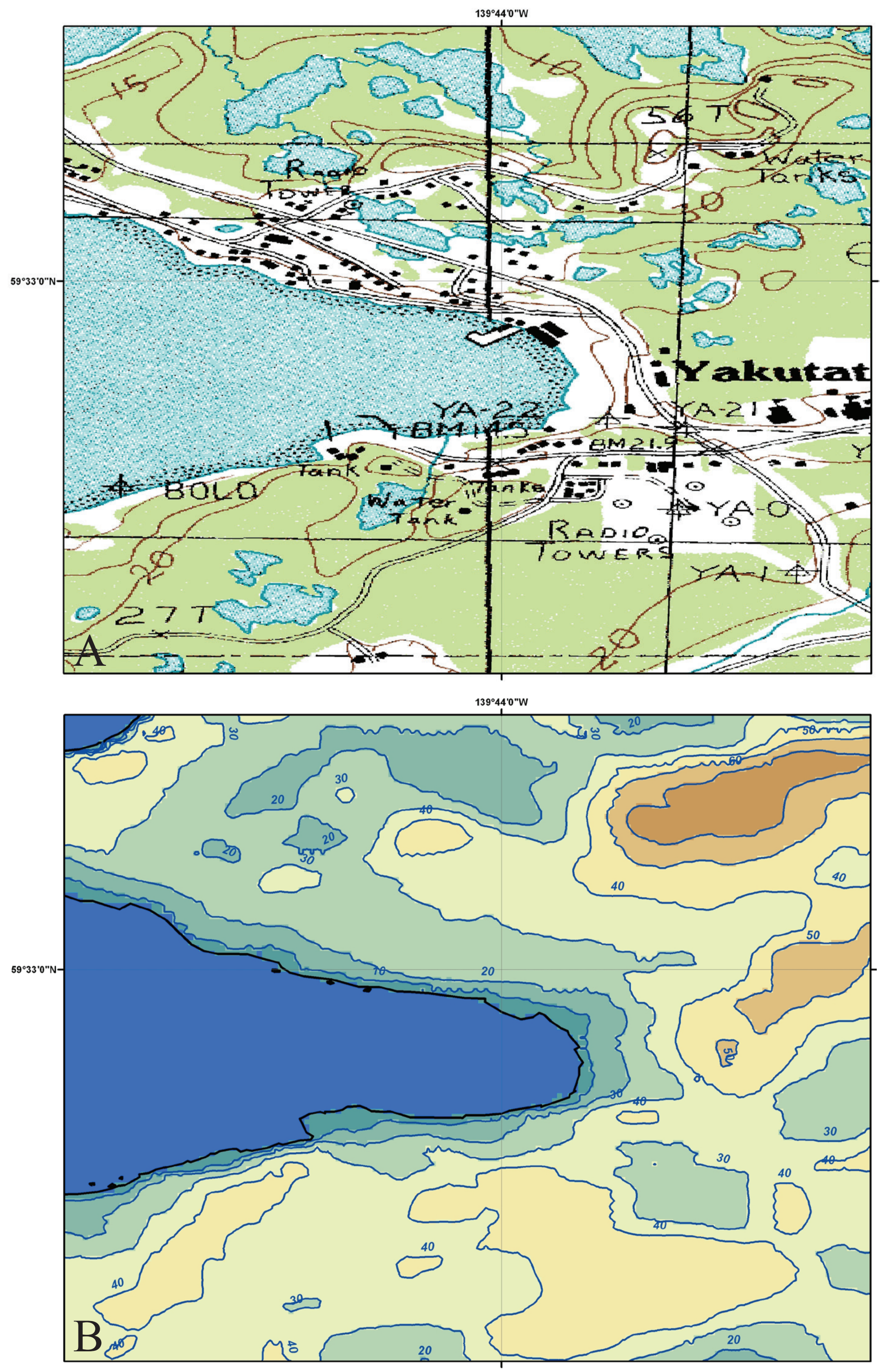

Figure 19. *Comparison between USGS topographic contours and topographic contours from the 8/15 arc-second Yakutat DEM. A) Brown lines and numbers represent 10-meter contours from the USGS topographic map. B) Blue lines and numbers represent 10-meter contours from the 8/15 arc-second Yakutat DEM.*

__Figure 20.__ Georeferenced satellite imagery of Yakutat Harbor. Image extracted from Google Earth (http://earth.google.com).

4. Summary and Conclusions

Three nested, integrated topographic–bathymetric digital elevation models of the Yakutat, Alaska area, with cell sizes of 8 arc-second, 8/3 arc-second, and 8/15 arc-second, were developed for the University of Alaska at Fairbanks (UAF) Geophysical Institute. The best available digital data were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI *ArcGIS*, *FME*, *GMT*, *Quick Terrain Modeler*, and *MB-System* software.

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

- Digitize older NOS surveys that are not in digital format.
- Conduct bathymetric surveys in coastal areas and in the southwestern quarter of the 8 arc-second DEM area where digital sounding data are sparse or non-existent.
- Obtain more recent data in the area of Russell and Nunatak Fiords.
- Establish, via survey, the relationships between tidal and geodetic datums in the Yakutat region.
- Determine the relationship between Early Alaska and NAD 83/WGS 84 geographic horizontal datums.
- Acquire improved topographic data for the region north of 60º N to better represent modern glacial profiles.
- Conduct topographic LiDAR surveys of the community of Yakutat.

5. Acknowledgments

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Nautical Chart #17318 (RNC), 31st Edition, 2009. Glacier Bay. 1:10,000 and 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 9.2, developed and licensed by ESRI, Redlands, California, http://www.esri.com/

FME 2008 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/

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

GMT v. 4.3.0 – Generic Mapping Tools, free software developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

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

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