NOAA Technical Memorandum NESDIS NGDC-24

ETOPO1 1 ARC-MINUTE GLOBAL RELIEF MODEL: PROCEDURES, DATA SOURCES AND ANALYSIS

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ETOPO1 1 ARC-MINUTE GLOBAL RELIEF MODEL: PROCEDURES, DATA SOURCES AND ANALYSIS

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http://www.ngdc.noaa.gov/mgg/global/global.html

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1. INTRODUCTION

In August 2008, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA) developed the ETOPO1 1 Arc-Minute Global Relief Model as an improvement to the ETOPO2v2 Global Relief Model. ETOPO1 is available in "Ice Surface" (top of Antarctic and Greenland ice sheets; Fig. 1) and "Bedrock" (base of the ice sheets; Fig. 2) versions. Both versions of ETOPO1 were generated from diverse global and regional digital data sets (coverage shown in Figs. 3 and 4), which were shifted to common horizontal and vertical datums, and then evaluated and edited as needed. This report provides a summary of the data sources and methodology used in developing ETOPO1.
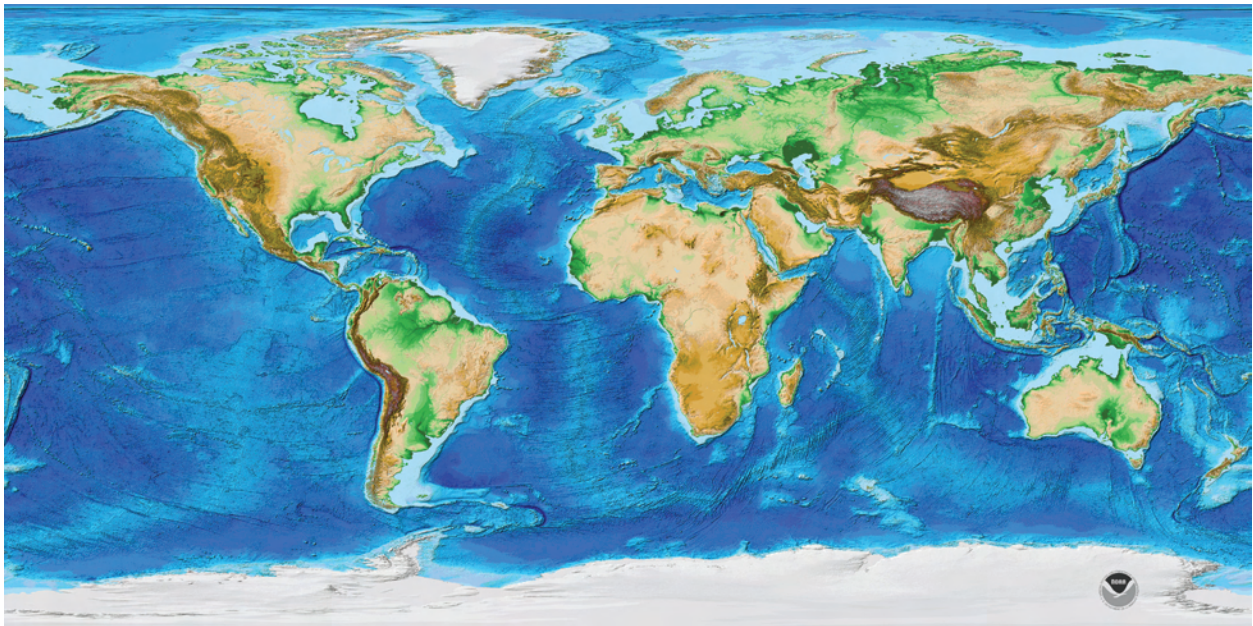
Figure 1. Color, shaded-relief image of the ETOPO1 Ice Surface Global Relief Model.
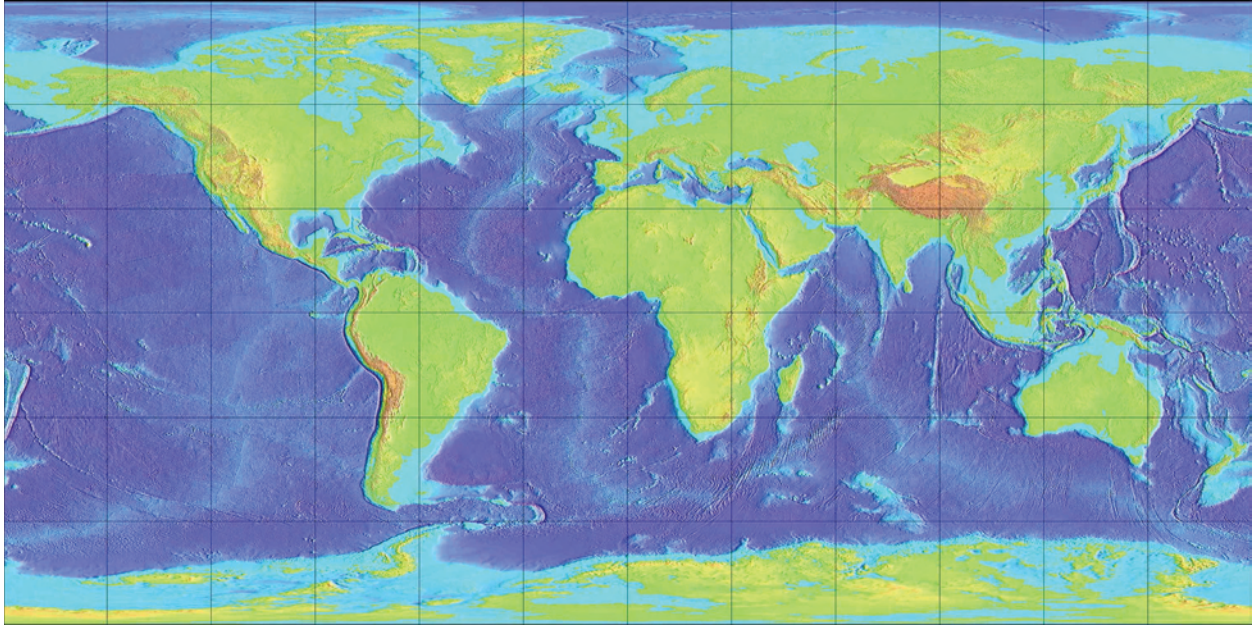
Figure 2. *Color, shaded-relief image of the ETOPO1 Bedrock Global Relief Model. Illumination from the east.*

2. Study Area

ETOPO1 provides complete global topographic and bathymetric coverage between -90° to +90° in latitude and -180° to +180° in longitude.

3. Methodology

ETOPO1 was developed to improve the resolution and accuracy of the ETOPO2v2 2 arc-minute Global Relief Model, and was designed to support tsunami forecasting, modeling and warning, as well as ocean circulation modeling and Earth visualization. The best available regional and global digital data sets were obtained by NGDC and shifted to common horizontal and vertical datums: World Geodetic System 1984 (WGS 84) and sea level. Data processing, evaluation, assembly and assessment of ETOPO1 are described in the following subsections.

Table 1: Specifications for ETOPO1.

Versions	Ice Surface, Bedrock
Coverage Area	Global: -180° to 180°; -90° to 90°
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	Sea Level
Vertical Units	Meters
Cell Size	1 arc-minute
Grid Format	Multiple: netCDF, g98, binary float, tiff, xyz

3.1 Data Sources and Processing

Shoreline, bathymetric, topographic, integrated bathymetric–topographic, and bedrock digital data sets (data footprints shown in Figs. 3 and 4) were obtained from several U.S. government agencies, international agencies and academic institutions. Safe Software's (http://www.safe.com/) *'Feature Manipulation Engine'* (*FME*) data translation tool package was used to shift data sets to WGS 84 horizontal datum and sea level vertical datum, and to convert them into ESRI (http://www.esri.com/) *ArcGIS* shape files and rasters. The shape files and rasters were then displayed with *ArcGIS* to assess data quality and manually edit data sets. *Wessel and Smith's* [1991, 1995] *'Generic Mapping Tools'* (*GMT*) version 4.3 (http://gmt.soest.hawaii.edu) and *Caress and Chayes'* [1995] *'MB-System'* version 5.1.0 (http://www.ldeo.columbia.edu/res/pi/MB-System/) were used to grid the data and build the global relief model.
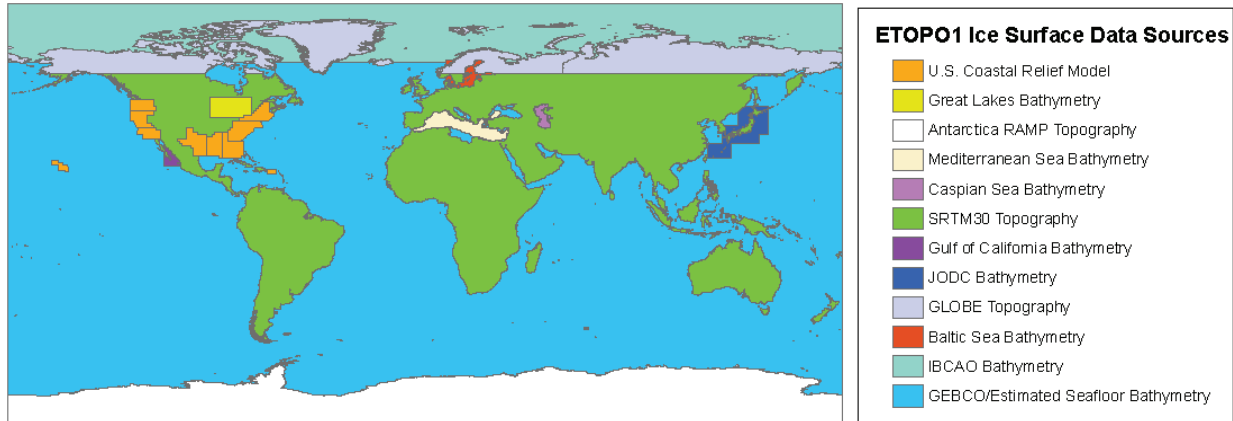

Figure 3. *Source and coverage of data sets used to compile the ETOPO1 Ice Surface Global Relief Model.*
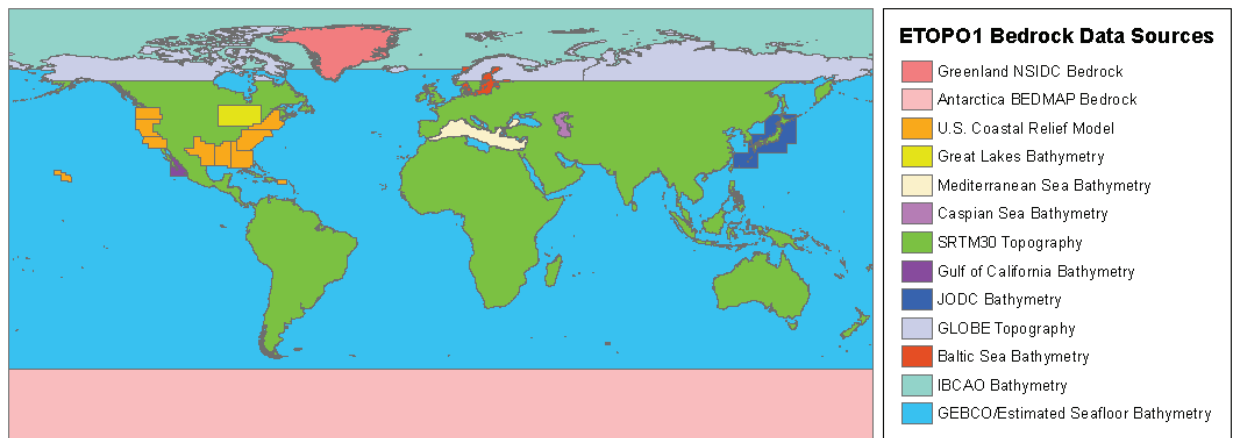
Figure 4. *Source and coverage of data sets used to compile the ETOPO1 Bedrock Global Relief Model.*

3

3.1.1 Shoreline

Coastline data sets were obtained from NGDC and the Antarctica Digital Database (Table 2). Both coastline data sets were used in evaluating individual source data sets and ETOPO1. They were also used to clip some data sets to the coastline to eliminate anomalous values.

Table 2: Shoreline data sets used in evaluating ETOPO1 source data sets.

Source	Name	Year	Data Type	Spatial Resolution	Original Horizontal Datum/Coordinate System	Original Vertical Datum	URL
NGDC	GSHHS	2003	Hierarchically arranged closed polygons	Approximately 100 m	WGS 84 geographic	MSL	http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html
ADD	Antarctica Coastline	1993 to 2006	Derived from maps	Ranges from 5 m to 5 km	WGS 84 geographic	MSL	http://www.add.scar.org:8080/add/

1) GSHHS

NGDC disseminates the GSHHS (Global Self-consistent, Hierarchical, High-resolution Shoreline) in *ArcGIS* format. GSHHS is a high-resolution shoreline data set created from the two well-known, public domain data sets [*Wessel and Smith*, 1996]. World Data Bank II (WDB; also known as CIA Data Banks) contains global coastlines, lakes, political boundaries, and rivers at an approximate working scale of 1:3,000,000, which means that the features are considered to be accurately located on maps using that scale or smaller. The other data set is the World Vector Shoreline (WVS), which only contains shorelines along the ocean and land interface. The WVS data has superior quality and resolution with a working scale of 1:100,000 and thus the GSHHS was created using the WVS data when possible and supplementing it with WDB data. The data have undergone extensive processing and are free of internal inconsistencies such as erratic points and crossing segments.

2) Antarctica Coastline

The Antarctic Digital Database provides a medium-resolution coastline for Antarctica, south of 60° S, created by the British Antarctic Survey. The database is managed by the Scientific Committee on Antarctic Research (SCAR).

3.1.2 Bathymetry

Bathymetric data sets used in compiling the ETOPO1 Global Relief Model were obtained from the Japan Oceanographic Data Center (JODC), NGDC, the Caspian Environment Programme (CEP), and the Mediterranean Science Commission (CIESM; Table 3).

Table 3: Bathymetric data sets used in compiling ETOPO1.

Source	Name	Year	Data Type	Spatial Resolution	Original Horizontal Datum/ Coordinate System	URL
JODC	JODC Bathymetry		Grid derived from hydrographic survey soundings	0.5 km	WGS 84 geographic	http://www.jodc.go.jp/ data_set/jodc/jegg_intro. html
NGDC	Gulf of California Bathymetry	2006	Grid derived from multibeam swath sonar bathymetric surveys	7 arc-second	WGS 84 geographic	
CEP	Caspian Sea Bathymetry	1999	Digitized depth contours	1 arc-minute	WGS 84 geographic	http://www. caspianenvironment.org/ dim/menu5.htm
CIESM	Mediterranean Sea Bathymetry	2005	Grid derived from multibeam swath sonar bathymetric surveys	0.5 km	WGS 84 geographic	http://www.ifremer.fr/ drogm_uk/Realisation/ carto/Mediterranee/index. html

1) JODC Bathymetry

The JODC data set provides bathymetric data for three areas surrounding Japan:

(1) latitude: N 34 to 46 (degrees), longitude : E 135 to 148 (degrees)
(2) latitude: N 30 to 38 (degrees), longitude : E 128 to 144 (degrees)
(3) latitude: N 24 to 30 (degrees), longitude : E 122 to 132 (degrees)

The underlying hydrographic survey soundings were collected by the Hydrographic and Oceanic Department of the Japan Coast Guard and various ocean research institutes. The data were then integrated and gridded at 500 meter intervals in the WGS 84 geographic coordinates. Since there is a variety of data quality and density, JODC smoothed the data to prevent improper steps. In areas void of data or with rapid bathymetry changes, such as coastal areas or seamounts, there are instances where the adopted values are moderately different from observed values.

2) Gulf of California Bathymetry

A 7 arc-second grid of multibeam swath sonar bathymetric surveys in the mouth of the Gulf of California, previously created by one of the authors, was used in building ETOPO1. This grid is not currently available to the public, although all of the multibeam swath sonar bathymetric data can be obtained from the online NGDC multibeam bathymetric database (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html).

3) Caspian Sea Bathymetry

The Caspian Environment Programme provides digitized contour lines of the Caspian Sea ranging from zero to 1000 meters in depth, in the WGS 84 geographic coordinate system. The digitized contour lines were created from 'The Navigation Map' published by the Navigation and Oceanography Department of the Defense Ministry of the USSR in 1987 at a scale of 1:1,000,000 in the Mercator projection. NGDC gridded the contours with the *ArcGIS* 'Topo to Raster' tool to infill depths between contours (Fig. 5). The contour intervals were originally referenced relative to local lake level—approximately 28 meters below mean sea level. The grid was shifted 28 m vertically, to be consistent with sea level, before use in gridding ETOPO1.
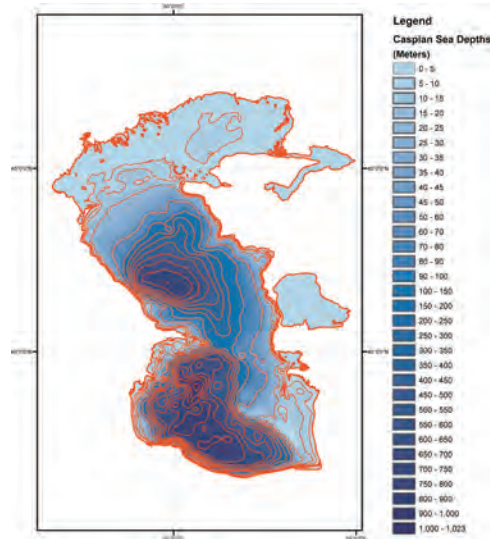
Figure 5. *Color image of Caspian Sea depth contours and bathymetric grid. NGDC used the ArcGIS 'Topo to Raster' tool to create a "hydrologically correct" surface from the contours.*

4) Mediterranean Sea Bathymetry

The Mediterranean Science Commission (CIESM) has produced a morpho-bathymetric map (Fig. 6) of the Mediterranean Sea derived from multibeam swath sonar surveys [*Medimap Group et al.*, 2005]. A 1-km grid of this data was graciously provided to NGDC by Benoit Loubrieu, Ifremer, which was used in building ETOPO1.
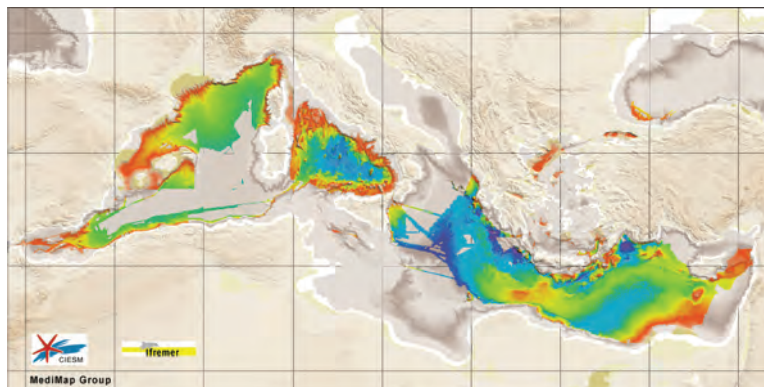
Figure 6. *Color image of Mediterranean Sea morpho-bathymetric map. [Image from CIESM web site.]*

3.1.3 Topography

Topographic data sets used in compiling the ETOPO1 Global Relief Model were obtained from NGDC, NASA, and the National Snow and Ice Data Center (NSIDC; Table 4).

Table 4: Topographic data sets used in compiling the ETOPO1 Global Relief Model.

Source	Name	Year	Data Type	Spatial Resolution	Original Horizontal Datum/ Coordinate System	URL
NASA	SRTM30	2000	30 arc-second grid derived from SRTM radar topography	30 arc-seconds	WGS 84 geographic	http://www2.jpl.nasa.gov/ srtm/
NGDC	GLOBE	1999	Grid derived from various data sets	30 arc-seconds	WGS 84 geographic	http://www.ngdc.noaa.gov/ mgg/topo/globe.html
NSIDC	Antarctica RAMP	2001	Grid derived from satellite radar altimetry, airborne radar surveys, topographic maps	400 m	WGS 84 polar stereographic	http://nsidc.org/data/ nsidc-0082.html

1) SRTM30 Global Topography

In February 2000, the Space Shuttle *Endeavour* flew the 'Space Shuttle Radar Topography Mission' (SRTM), which obtained nearly complete high-resolution digital topographic coverage of Earth between 56° S and 60° N. This data was processed into a 3 arc-second coverage database that is distributed to the public through the USGS 'Seamless Server'. It was subsequently converted into a global topographic data set at 30 arc-second cell size by incorporating GTOPO30 gridded data into areas without SRTM data. The geodetic reference for SRTM30 is the WGS 84 EGM96 geoid. NGDC utilized the SRTM30 data between 56° S and 60° N—excluding Greenland— while eliminating ocean-surface "zero" values and GTOPO30 data outside the original SRTM survey region, though other anomalous data points had to be removed manually (e.g., Fig. 7).
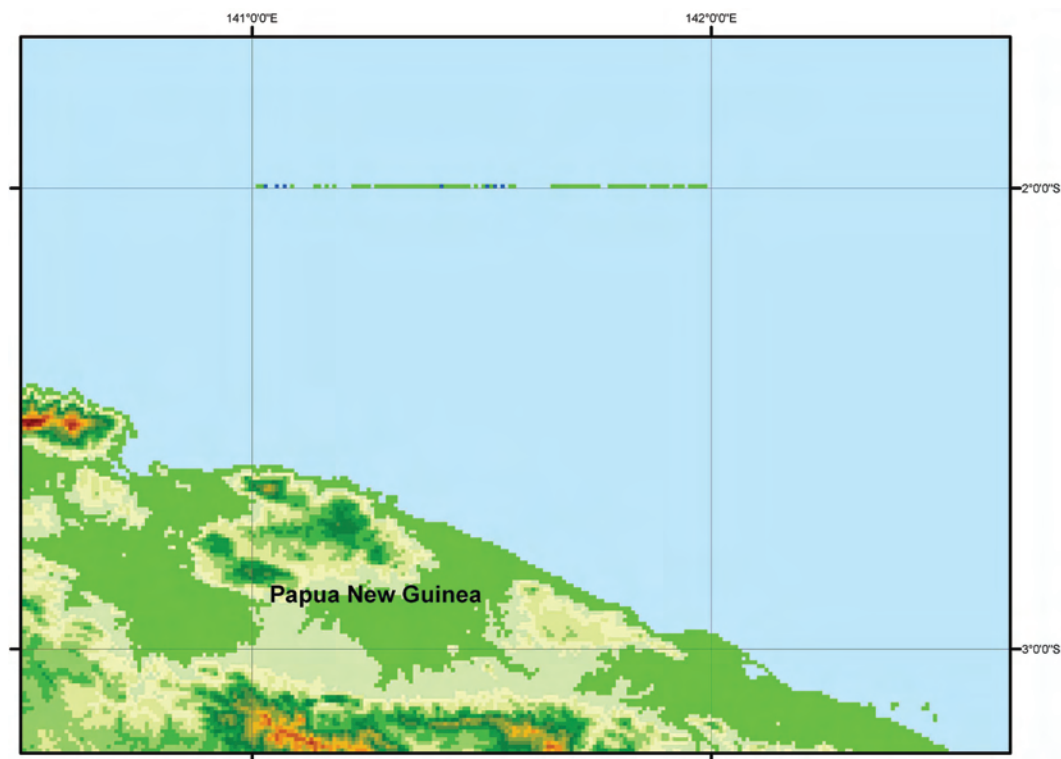
Figure 7. *A row of bad data, along 2°S, present in the SRTM30 data set. The bad data were manually removed before the gridding of ETOPO1.*

2) GLOBE Topography

The NGDC GLOBE Topography data sets provides complete 30 arc-second cell-registered coverage of global topography [*Hastings and Dunbar*, 1999]. The data are in WGS 84 geographic coordinates and have a sea level vertical datum. GLOBE was created from both global and regional data sources. The underlying global data sources used were Digital Terrain Elevation Data (DTED) and Digital Chart of the World (DCW). Various regional data sources included DEMs for Australia, Japan, Italy, New Zealand, Greenland, Antarctica, and for parts of South America and Asia. ETOPO1 incorporates GLOBE topographic data north of 60° N (Fig. 8)—excluding Greenland—and in a few small areas south of 56° S that have islands not represented in the Antarctic RAMP data set.
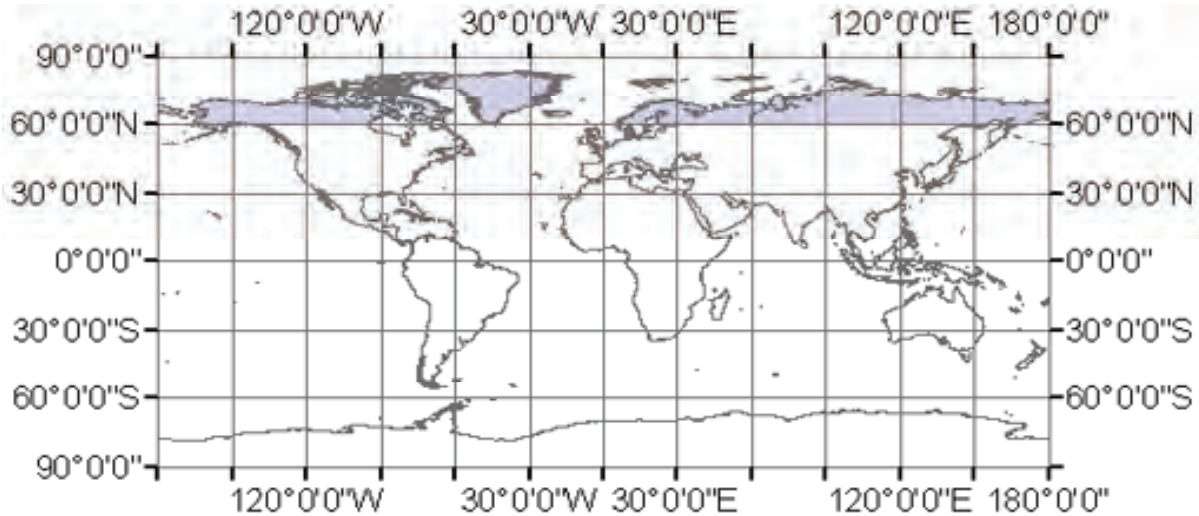
Figure 8. *Coverage of GLOBE topography (blue) that was used in building ETOPO1. GSHHS coastline in gray.*

3) Antarctica RAMP Topography

The Radarsat Antarctic Mapping Project (RAMP) DEM combines topographic data from a variety of sources to provide consistent coverage of all of Antarctica. Version 2 improves upon the original version by incorporating new topographic data, error corrections, extended coverage, and other modifications [*Liu et al.*, 2001]. The topographic data sources include satellite radar altimetry, airborne radar surveys, the recently-updated Antarctic Digital Database (version 2), and large-scale topographic maps from the U.S Geological Survey (USGS) and the Australian Antarctic Division. While most of the data has been collected during the 1980s and 1990s, some of the data originates as far back as the 1940s. The RAMP DEM was created to assist in processing RAMP radar data but it does not utilize any RAMP radar data. NGDC utilized the 400-m grid, version 2, in building the ETOPO1 Ice Surface Global Relief Model.

3.1.4 Integrated Bathymetry–Topography

Integrated bathymetric and topographic data sets used in compiling the ETOPO1 Global Relief Model were obtained from Scripps Institute of Oceanography (SIO), the Leibniz Institute for Baltic Sea Research (LIBSR), and NGDC (Table 5).

Table 5: Integrated bathymetric-topographic data sets used in compiling ETOPO1.

| Source	Name	Year	Data Type	Spatial Resolution	Original Horizontal Datum/ Coordinate System	URL
SIO	Measured and Estimated Seafloor Topography	2008	Grid derived from satellite altimetry and hydrographic survey soundings	2 arc-minute	WGS 84 geographic	http://topex.ucsd.edu/ marine_topo/
LIBSR	Baltic Sea Bathymetry	2001	Grid derived from hydrographic survey soundings	0.5 to 2 arc-minutes	WGS 84 geographic	http://www.io-warnemuende.de/research/ en_iowtopo.html
NGDC	IBCAO	2008	Grid derived from hydrographic survey soundings, digitized contours, grids and point information	2 km	WGS 84 polar stereographic	http://www.ibcao.org/
NGDC	U.S. Coastal Relief Model	1999 to 2005	Grid of NOS hydrographic soundings and land topography	3 arc-second	WGS 84 geographic	http://www.ngdc.noaa.gov/ mgg/coastal/coastal.html
NGDC	Great Lakes Bathymetry	1996 to 2005	Grid of hydrographic soundings, bathymetric contours, and land topography	3 arc-second	WGS 84 geographic	http://www.ngdc.noaa.gov/ mgg/greatlakes/greatlakes. html

1) **Measured and Estimated Seafloor Topography**

The Measured and Estimated Seafloor Topography grid provides a 1 arc-minute gridded representation of seafloor topography for all ice-free ocean areas within +/- 80 degrees latitude in Mercator projection [*Smith and Sandwell*, 1997]. Topographic data are derived from GTOPO30. Bathymetric values are derived from known soundings and sea-surface satellite altimetry measurements, which were first used to calculate free-air gravity anomaly and then converted to inferred ocean depths using nearby soundings both as constraints and to save gravity-bathymetry relationships. Inaccuracies in the estimated seafloor grid were evident in shallow water throughout the data set (e.g., Fig. 9). NGDC down-sampled an older version of the estimated seafloor grid to 2 arc-minutes for use in building ETOPO1 (D. Sandwell, pers. request).
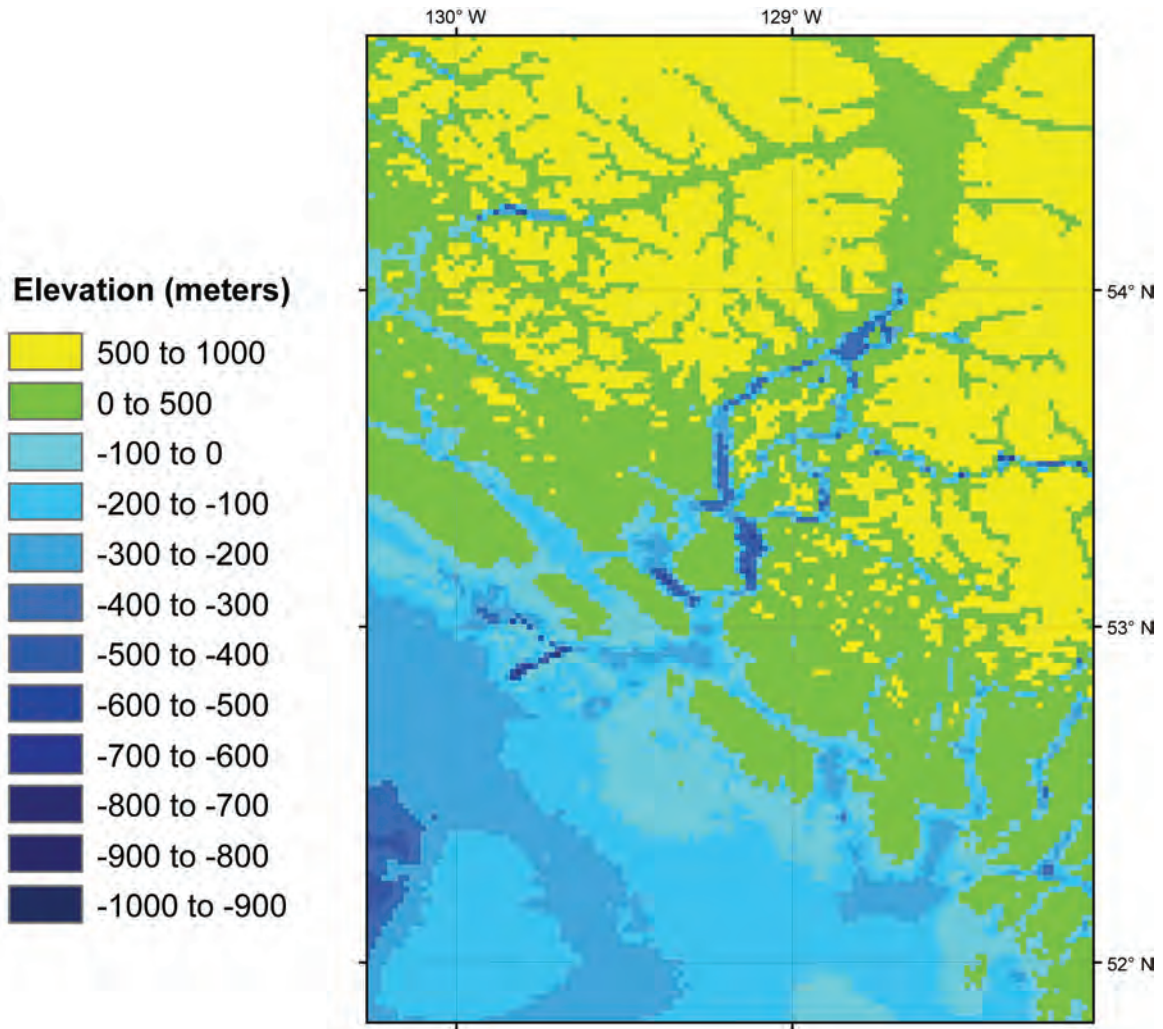
Figure 9. *Anomalous depth values in the Measured and Estimated Seafloor Topography grid in shallow coastal waters north of Vancouver Island. Depths in the grid exceed 1000 meters in many places in this region, although actual charted depths are typically on the order of a few tens of meters.*

3) Baltic Sea Bathymetry

The Leibniz Institute for Baltic Sea Research's high resolution spherical grid topography of the Baltic Sea, 2nd edition, contains two separate grids of the Baltic Sea [*Seifert et al*., 2001]. The Baltic Sea grid covers the entire Baltic Sea from 9° to 31° E and from 53°30′ to 66° N, with a resolution of 2 arc-minutes of longitude and 1 arc-minute of latitude. The Belt Sea grid contains the region of the Belt Sea from 9° to 15°10′ E and from 53°30′ to 56°30′ N, with a resolution of 1 arc-minute of longitude and 0.5 arc-minutes of latitude. In order to create a more accurate coastline, both grids used land masks derived from global high-resolution shorelines, GSHHS and RANGS (Regionally Accessible Nested Global Shoreline; http://www2008.io-warnemuende.de/homepages/rfeistel/rangs.htm). Most of the underlying data sets were sampled from sea charts of different scales. Some data sets included digitized soundings, and only Reissmann's "Bathymetry of four deep Baltic basins" data came from ship-borne measurements. Both grids contain topographic data from GTOPO30, though only bathymetric values were used in compiling ETOPO1.

4) IBCAO Bathymetry

The International Bathymetric Chart of the Arctic Ocean (IBCAO) grid version 2.0 was created from ship track data, contours, grids and point information [Fig. 10; *Jakobsson et al*., 2008]. The majority of the echo sounding data was collected from surface vessels extracted from the following four archives: NGDC, the U.S. Naval Research Laboratory (NRL), the Canadian Hydrographic Service (CHS), and the Royal Danish Administration of Navigation and Hydrography (RDANH). The NGDC database was the primary source and the other three sources were used where there was not any NGDC data available. Where the ship track database information was limited in the central Arctic Ocean, contour information was derived from Russia's Head Department of Navigation and Oceanography Bottom relief of the Arctic Ocean map. In addition, contours were extracted from the GEBCO Digital Atlas in the southern Norwegian-Greenland Seas, in Baffin Bay and in some areas of the Canadian Arctic. In the Gulf of Bothnia, the IBCAO grid used bathymetric data derived from the Seifert and Kayser digital grid of the Baltic Sea. NGDC extracted IBCAO bathymetric data north of 65 degrees latitude and surrounding Greenland to create ETOPO1. IBCAO topographic data of Greenland were also used in building ETOPO1. The original IBCAO grid was in polar stereographic projection and was converted to WGS 84 geographic coordinates using *ArcGIS*.
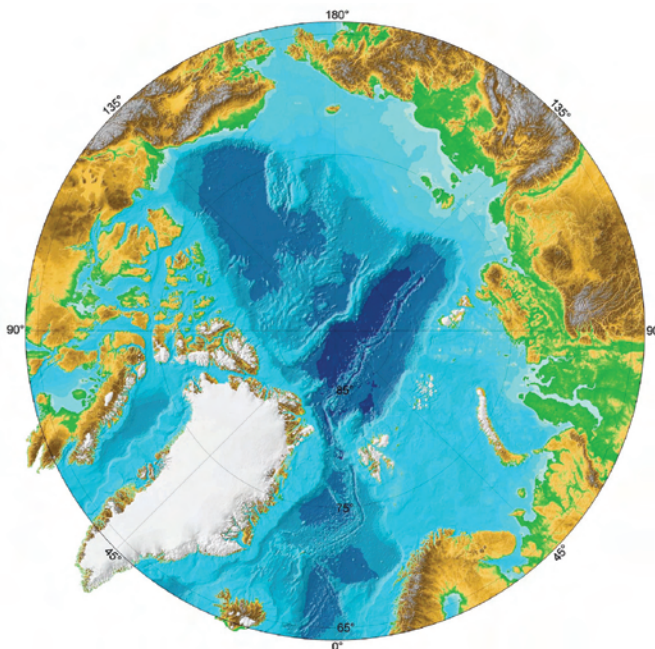

Figure 10. *Color image of the IBCAO v.2 grid of the Arctic.*

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5) U.S. Coastal Relief Model

NGDC's U.S. Coastal Relief Model (CRM) provides 3 arc-second (~90 m) resolution for the East and West Coasts, Gulf of Mexico, Hawaii and Puerto Rico (see Fig. 11). The database extends from the coastal state boundaries to as far as the National Ocean Service hydrographic data is available, which in many cases reaches out to, and in some places even beyond, the continental slope. The bathymetric data sources include hydrographic surveys from the U.S. National Ocean Service (NOS), Monterey Bay Aquarium Research Institute (MBARI), U.S. Army Corps of Engineers LIDAR (SHOALS), and various other academic institutions. In addition, bathymetric contours from the International Bathymetric Chart of the Caribbean Sea and Gulf of Mexico were used where applicable. Topographic data are from the USGS National Elevation Data set (NED). Only bathymetric values were used in building ETOPO1.
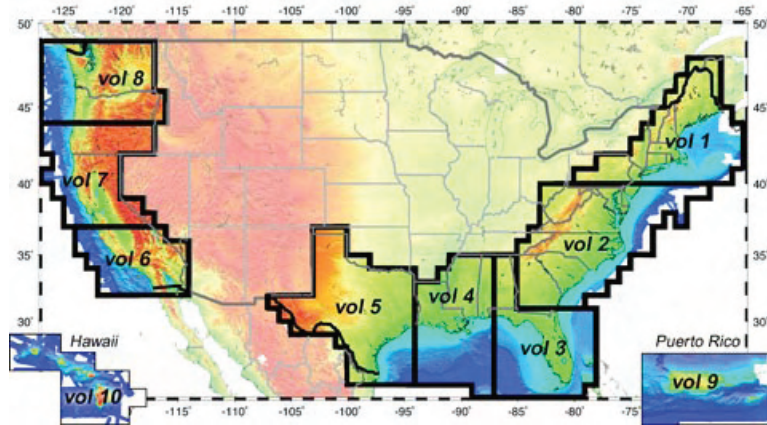
Figure 11. *Areas of the U.S. coast covered by NGDC's Coastal Relief Model.*

6) Great Lakes Bathymetry

NGDC, in cooperation with NOAA's Great Lakes Environmental Laboratory and the Canadian Hydrographic Service, has compiled detailed vector bathymetric contours and 3 arc-second (~90 m) bathymetric grids for most of the U.S. Great Lakes. This integrated bathymetric–topographic grid was extracted at 15 arc-seconds for use in building ETOPO1.

3.1.5 Bedrock

Bedrock data sets depicting the bedrock elevation underneath the Antarctic and Greenland ice sheets were obtained from the National Snow and Ice Data Center (NSIDC), European Ice Sheet Modeling Initiative (EISMINT) and the Scientific Committee on Antarctic Research (SCAR; Table 6).

Table 6: Bedrock elevation data sets used in compiling the ETOPO1 Bedrock Global Relief Model.

Source	Name	Year	Data Type	Spatial Resolution	Original Horizontal Datum/ Coordinate System	URL
NSIDC	Greenland Bedrock	2001	Grid derived from satellite altimetry, Airbourne Topographic Mapper (ATM), photogrammetric digital height, ice penetrating Radar, airbourne echo sounder	5 km	WGS 84 Polar Stereographic	http://nsidc.org/data/ nsidc-0092.html
EISMINT / SCAR	Antarctica BEDMAP	2000	Grid derived from terrestrial methods of measurement, primarily radar and seismic soundings	5 km	WGS 84 Polar Stereographic	http://www.antarctica. ac.uk//bas_research/data/ access/bedmap/

1) Greenland NSIDC Bedrock

The National Snow and Ice Data Center (NSIDC) has built 5-km grids of ice surface, ice thickness and bedrock elevation for Greenland in polar stereographic projection [*Bamber et al.*, 2001a, 2001b]. NGDC utilized the bedrock grid, resampled to 30 arc-second cell size, in building the ETOPO1 Bedrock grid. NSIDC first created an ice-surface DEM from a combination of ERS-1 and Geostat satellite radar altimetry data, Airbourne Topographic Mapper (ATM) data, and photogrammetric digital height data. The ice-thickness grid was derived from approximately 700,000 data points collected from a University of Kansas airborne ice penetrating radar (IPR), in addition to nearly 30,000 data points collected in the 1970s from a Technical University of Denmark (TUD) airborne echo sounder. The bedrock-elevation grid was created by subtracting the ice-thickness grid from the ice-surface grid. It is in WGS 84 polar stereographic projection, with standard parallel of latitude 71° N, projection parallel of 90° N, and 39° W central meridian.

2) Antarctica BEDMAP Bedrock

The European Ice Sheet Modeling Initiative (EISMINT) and the Scientific Committee on Antarctic Research's (SCAR) created the Antarctica BEDMAP grid, which contains the bedrock elevation data beneath the grounded ice sheet of Antarctica [*Lythe et al.*, 2000]. It includes the entire geosphere south of 60° S at a nominal grid spacing of 5 km in WGS 84 polar stereographic projection. It was created from terrestrial methods of measurement, primarily radar and seismic soundings. The Antarctica BEDMAP provides an improved delineation of the boundary between East and West Antarctica. It also more accurately describes the morphology of the contiguous East Antarctica landmass, which is under an average of 2,500 meters of ice.

3.2   Establishing Common Datums

3.2.1   *Vertical datum transformations*

Data sets used in the compilation and evaluation of ETOPO1 Global Relief Model were all originally referenced to sea level with the exception of the Caspian Sea data set. The contour intervals contained in this data set were originally referenced relative to local lake level. The grid was shifted 28 m vertically to be consistent with sea level before use in gridding ETOPO1.

3.2.2   *Horizontal datum transformations*

Data sets used to compile ETOPO1 Global Relief Model were originally referenced to WGS 84 geographic and WGS 84 polar stereographic. The relationships and transformational equations between these horizontal datums are well established. All data were converted to the WGS 84 geographic horizontal datum using *FME* software.

3.3   Digital Elevation Model Development

3.3.1   *Verifying consistency between data sets*

After horizontal and vertical transformations were applied, the resulting *ArcGIS* shape files and rasters were checked in ArcMap for consistency between data sets. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shape files were then converted to xyz files in preparation for gridding. Problems included:

- Inconsistencies between IBCAO and the Measured and Estimated Seafloor Topography data sets in coastal regions
- Row of data errors in SRTM30 data set. Manual editing of the data was necessary to minimize these artifacts.
- SRMT30 data set contains zero values over the open ocean. These values were removed using *FME*.

3.3.2   *Gridding of coastal bathymetry*

NGDC created bathymetric pre-surfaces in order to interpolate bathymetric data into coastal regions, which were poorly represented in some bathymetric data sets (e.g., Fig. 12). A global bathymetric pre-surface—excluding south of 60° S—was created using the Measured and Estimated Seafloor Topography data (between -500 m and 0 m). These data were gridded at 1 arc-minute cell size using *GMT*'s 'surface' tool. Points extracted from the GSHHS coastline were also included, at -1 m elevation, to force bathymetric interpolation into the coastal zone. The resulting surface, created in quadrangles, was clipped to the GSHHS coastline and the -120 m contour. Values between -50 and 0 m were then extracted from the clipped quadrangle grids and were used in building ETOPO1 (e.g,. Fig. 13). An Iceland bathymetric pre-surface was also created, utilizing the Measured and Estimated Seafloor Topography bathymetric values and the GSHHS coastline with points assigned at -5 m elevation, due to the deep fjords surrounding Iceland. This bathymetric pre-surface was also utilized in compiling ETOPO1 (see Table 7).
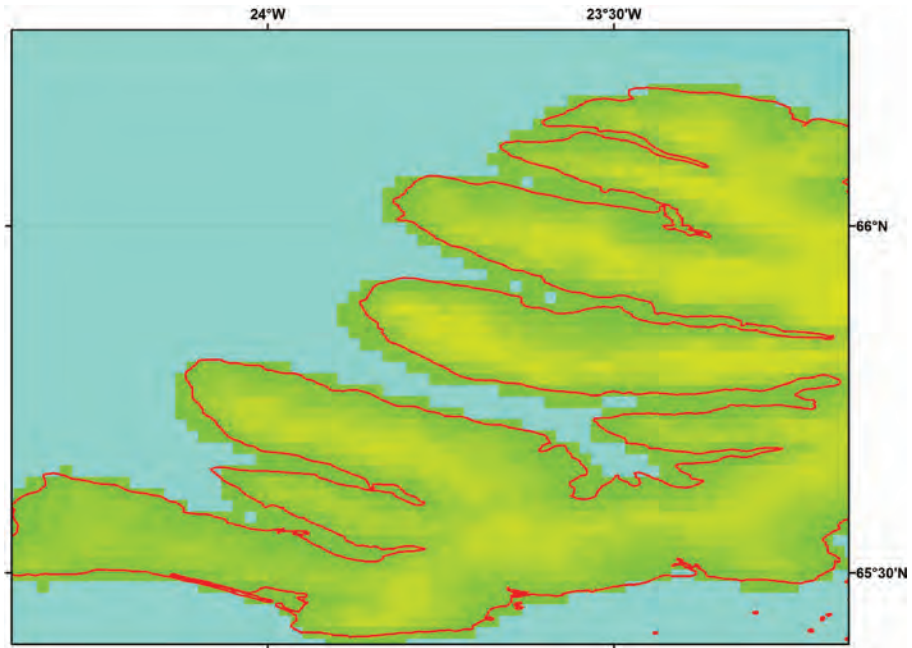
Figure 12. Color image of the IBCAO grid along Iceland's northwest coast. Note the presence of positive, topographic values in many of Iceland's fjords. GSHHS coastline in red.
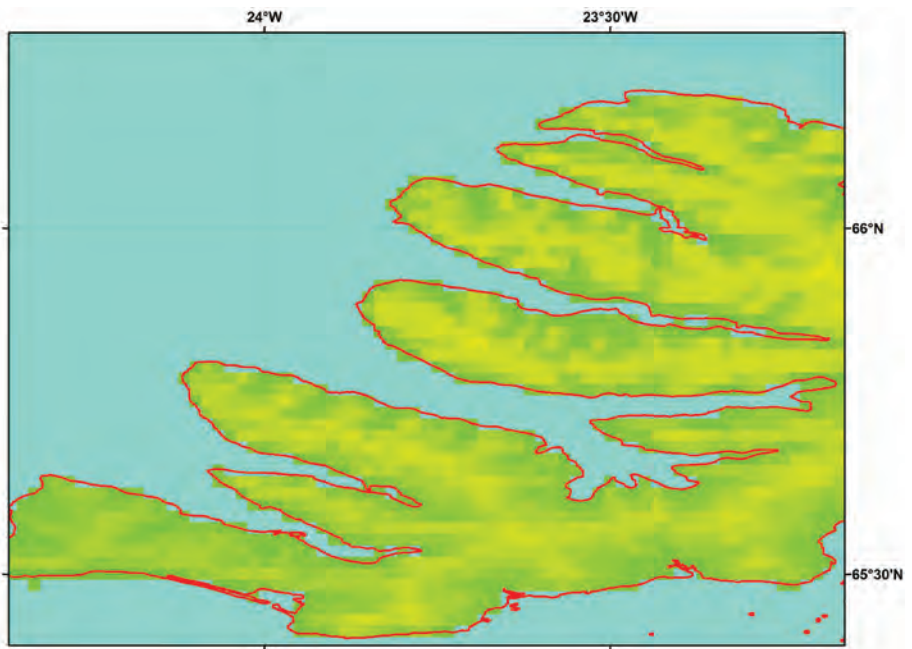
Figure 13. Color image of Iceland's northwest coast in ETOPO1. ETOPO1 incorporates a bathymetric pre-surface that forces interpolation of bathymetric values into coastal zones, enhancing their representation in the global relief model. GSHHS coastline in red.

3.3.3   Gridding the data with MB-System

MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/) was used to create the 1 arc-minute ETOPO1 DEM. *MB-System* is an NSF-funded free software application that manipulates a wide variety of data types, including generic xyz data. The *MB-System* tool 'mbgrid' was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 7. The greatest weight was given to the Antarctica RAMP ice surface topography, Antarctica BEDMAP bedrock topography and the Greenland NSIDC bedrock topography data sets. Least weight was given to the global data sets and the interpolated bathymetric surface. Data were gridded in 16 regional tiles that were seamlessly integrated to produce the final ice surface and bedrock grids.

Table 7: Data hierarchy used to assign gridding weight in MB-System.

Data set	Relative Gridding Weight
Antarctica RAMP Topography	100
Antarctica BEDMAP Bedrock	100
Greenland NSIDC Bedrock	100
Gulf of California Bathymetry	10
Mediterranean Sea Bathymetry	10
JODC Bathymetry	10
Baltic Sea Bathymetry	10
IBCAO Bathymetry	10
Caspian Sea Bathymetry	10
U.S. Coastal Relief Model	10
Great Lakes Bathymetry	10
Created Iceland Bathymetric Surface	10
SRTM30 Global Topography	1
GLOBE Topography	1
Measured and Estimated Seafloor Topography	1
Bathymetric pre-surface	1

3.3.4   Registration of grids

The ETOPO1 Ice Surface and Bedrock global relief models are available in both grid/node-registration and cell/pixel-registration. Figure 14 illustrates the differences between these two registrations. An individual grid cell in either registration has one elevation value that represents the average elevation over the extent of the cell. This value can alternatively be represented as a point at the center of the cell. The differences between the two registrations are in how the grid ranges are defined (red lines in Fig. 14). Ranges for grid- or node-registered grids refer to the centers of the cells that lie along the boundaries of the grid (panel A), and the footprints of the cells extend 1/2 cell width outside the range. Ranges for cell- or pixel-registered grids refer to the outside edges of the boundaries of the grid (panel B). This means for two grids with the same range, the grid-registered grid will have one more row and one more column than the cell-registered version. For global grids, a grid-registered grid has cells along the northern boundary that sit atop the North Pole, and similarly for the South Pole. Cell-registered grids have cells along the northern boundary that just touch the North Pole. Cell-registered grids are more typically used in images, while grid-registered are more commonly used for representing discrete, though averaged, point data.

ETOPO1 was built as a global, grid-registered, 1 arc-minute grid that spans from pole to pole and from -180° to 180° in longitude. It is 21601 cells by 10801 cells in dimension, with multiple duplicate cells sitting atop the North and South poles and on the -180°/180° longitude line. A cell-registered version (21600 by 10800 cells) was created from the grid-registered version by resampling, using *GMT*'s 'grdsample' tool. This resampling introduces some flattening of relief, due to averaging of four grid-registered cell values to produce one cell-registered value (see Fig. 14). Both types are global, though the grid-registered version should be considered the authoritative version. The cell-registered version may be more appropriate for creating maps and images.
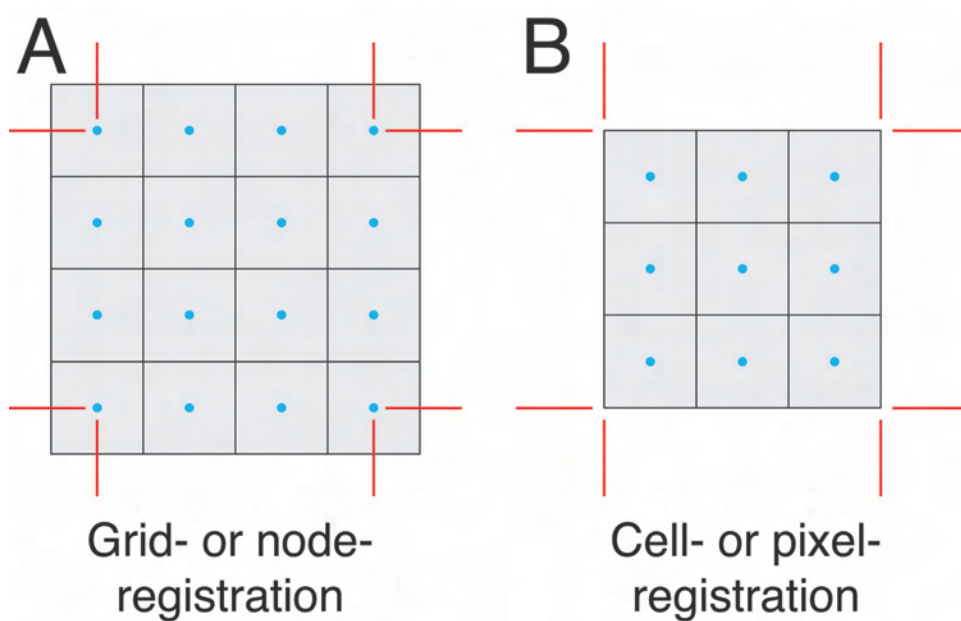
Figure 14. *Differences between grid-registration and cell-registration. Grid-registered grids have cells centered on gridlines (lines of latitude and longitude for ETOPO1), while cell-registered grids have cells lying between gridlines.*

3.4   Quality Assessment of the DEM

3.4.1. *Horizontal and Vertical accuracy*

The horizontal and vertical accuracy of topographic and bathymetric features in the ETOPO1 is dependent upon the data sets used to determine corresponding DEM cell values. Thus far, only a qualitative assessment of ETOPO1 has been performed. The GSHHS and the Antarctica Digital Database coastlines were used to assess the integration of topography and bathymetry. Further qualitative evaluation will involve the use of slope maps and 3-D perspectives in ETOPO1. A quantitative evaluation by comparing ETOPO1 with select source data sets and international nautical charts will be performed in the future.

4. SUMMARY AND CONCLUSIONS

ETOPO1 is a global, integrated bathymetric–topographic, digital elevation model with cell size of 1 arc-minute. It is available in two versions: Ice Surface, which depicts the surface of the Antarctic and Greenland ice sheets; and Bedrock, which depicts the bedrock underneath the ice sheets. The best available digital data from diverse global and regional digital data sets were obtained, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data and DEM were quality checked, processed and gridded using *ArcGIS*, *FME*, *MB-System,* and *GMT* software.

Recommendations to improve the ETOPO1 Global Relief Model include:
- Incorporate international hydrographic soundings in coastal waters
- Quantitatively assess by comparing to source data sets and international nautical charts

5. ACKNOWLEDGMENTS

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7. DATA PROCESSING SOFTWARE

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

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

GMT v. 4.3 – 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/