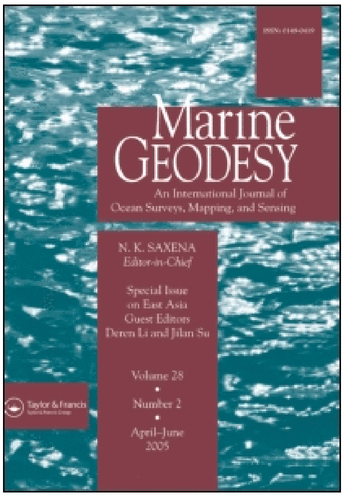

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Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS

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A new 30-arc second resolution global topography/bathymetry grid (SRTM30_PLUS) has been developed from a wide variety of data sources. Land and ice topography comes from the SRTM30 and ICESat topography, respectively. Ocean bathymetry is based on a new satellite-gravity model where the gravity-to-topography ratio is calibrated using 298 million edited soundings. The main contribution of this study is the compilation and editing of the raw soundings, which come from NOAA, individual scientists, SIO, NGA, JAMSTEC, IFREMER, GEBCO, and NAVOCEANO. The gridded bathymetry is available for ftp download in the same format as the 33 tiles of SRTM30 topography. There are 33 matching tiles of source identification number to convey the provenance of every grid cell. The raw sounding data, converted to a simple common format, are also available for ftp download.

Keywords Global bathymetry, satellite altimetry

Introduction

The depth to the ocean floor and the roughness of the bottom vary throughout the oceans because of numerous geologic processes (Brown et al. 1998). This seafloor topography (Figure 1) influences the ocean circulation and mixing that moderate the Earth's climate (Kunze and Llewellyn Smith 2004; Munk and Wunsch 1998) and the biological diversity and food resources of the sea (Koslow 1997). The ocean floor records the geologic history and activity of the ocean basins (Muller et al. 1997), revealing areas that may store resources such as oil and gas (Fairhead et al. 2001), and generate earthquakes and tsunamis (Mofjeld

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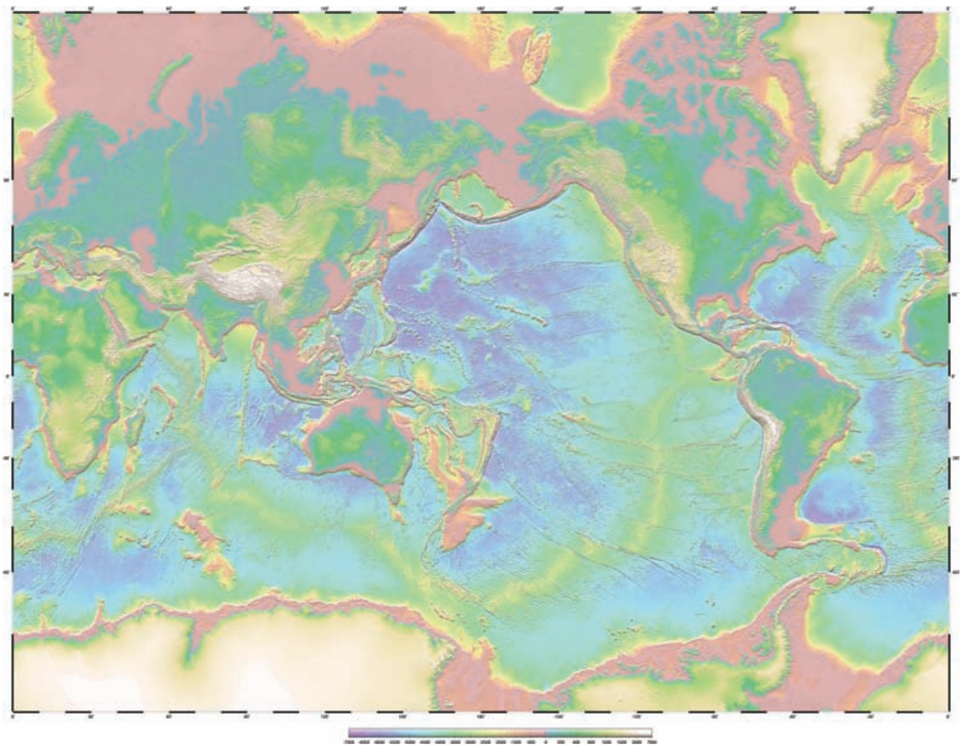

Figure 1. Global bathymetry and topography at 30 arcsecond resolution, Mercator projection between latitudes of +80/−78. The global grid consists of 33 tiles following the SRTM30 format. Data grids and images are available at http://topex.ucsd.edu/WWW_html/srtm30_plus.html.

et al. 2004). Despite the importance of Earth's ocean floor to our quality of life, we have made much better maps of the surfaces of other planets, moons, and asteroids.

After five decades of surveying by ships carrying echo sounders, most of the ocean floor (∼90% at 1 minute resolution) remains unexplored, and there are large gaps between survey lines (Figure 2). There are two primary reasons why the global mapping of the seafloor is so incomplete. First, seafloor mapping is difficult, expensive, and slow. For example, a systematic mapping of the deep oceans by ships would take more than 120 ship-years of survey time. Moreover, because the swath width of a multibeam echo sounder is proportional to depth, it takes much longer (750 ship-years) to survey the shallow (<500 m) continental margins (Carron et al. 2001). The second reason is that the existing raw sounding data sets are extremely heterogeneous. Most of the data in remote ocean basins were collected during an era of curiosity-driven exploration (1950–1967), depths were measured by single-beam analog echo sounders, and satellite navigation was largely unavailable (NGDC 2006; Smith 1993). Recent deep ocean surveys using advanced technology (i.e., GPS navigation and multibeam acoustic swath mapping systems) are funded through a peer-review system emphasizing hypothesis testing; the result is that ships tend to revisit a limited number of localities. Thus the majority of the data in the remote ocean basins are old and of poor quality (Smith 1993, 1998). These remarks apply to publicly available data; additional data exist that are proprietarily held for commercial or political reasons or are classified as

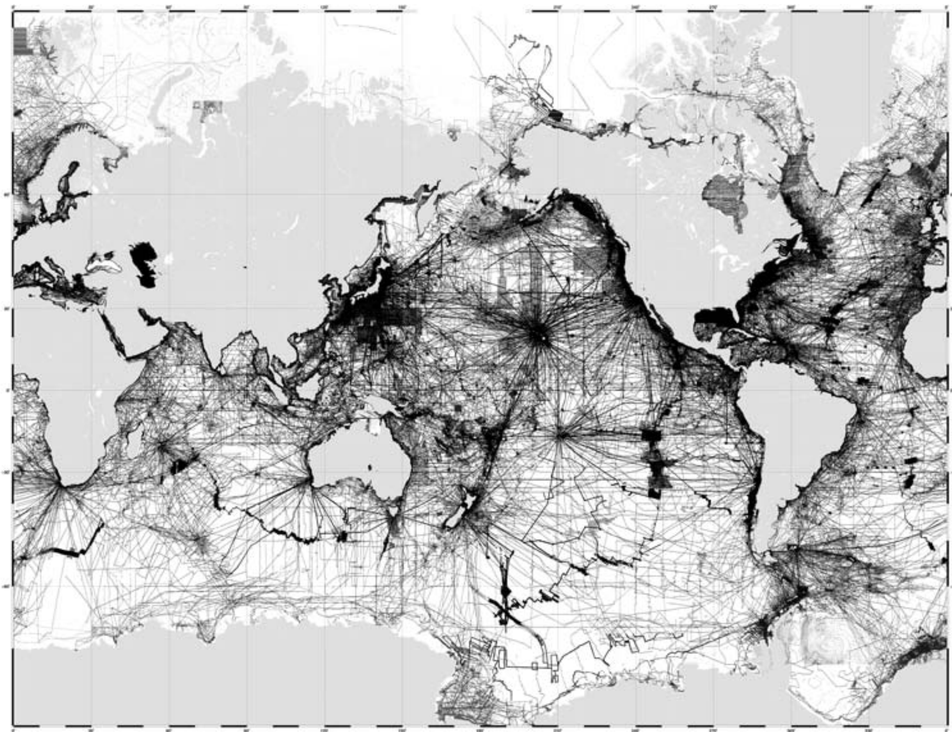

Figure 2. Ship track plots of all the soundings used in the SRTM30_PLUS global bathymetry grid. Tracks of high latitude data are not shown because areas north of 80° latitude are based in IBCAO bathymetry (Jakobssen et al. 2008).

secret for military purposes. The largest such data set, the Ocean Survey Program of the U.S. Navy, covers primarily the northern oceans (Medea 1995).

While shipboard surveys offer the only means for high-resolution seafloor mapping, moderate accuracy ($\sim$100 m) and resolution (12–17 km full wavelength) can be achieved using satellite radar altimetry at a fraction of the time and cost. Radar altimeters aboard the ERS-1 and Geosat spacecraft have surveyed the marine gravity field over nearly all of the world's oceans to a high accuracy and moderate spatial resolution (Cazenave et al. 1996; Sandwell and Smith 1997; Tapley and Kim 2001). In the wavelength band 10–160 km, variations in gravity anomaly are highly correlated with seafloor topography and, in principle, can be used to recover topography (Baudry and Calmant 1991; Dixon et al. 1983; Jung and Vogt 1992; Ramillien and Cazenave 1997; Smith and Sandwell 1994). The sparse ship soundings constrain the long wavelength ($>$160 km) variations in seafloor depth and calibrate local variations in the topography to gravity ratio associated with varying tectonics and sedimentation (Smith and Sandwell 1994).

This study focuses on the production of a global bathymetry grid at 30 arc seconds of resolution. The main contributions summarized in this report are: assembly of an array of mostly publicly available depth soundings (Figure 2) from a wide variety of sources; statistical and visual assessment of all soundings through a comparison with a previously published 2-minute global bathymetry grid; hand editing of all suspect data (single beam trackline, multibeam swaths, sparse sounding, and contributed grids); and finally using these soundings to modify global satellite bathymetry based on the latest altimeter-derived gravity models. This 30 arc second grid is basically equivalent to a 1-minute resolution grid that was produced using the same new soundings and gravity field (Smith and Sandwell 2008). However, since the 1-minute satellite bathymetry only extends to a latitude of 80.5 degrees, the Arctic bathymetry ($>$80 latitude) is based on the IBCAO 1-minute compilation (Jakobsson et al. 2008). Land elevations are based on a combination of SRTM30 topography (Farr et al. 2007; Rosen et al. 2000) (latitude $<$55 deg), GTOPO30 topography (USGS 1997) in the Arctic, and ICESat derived topography (DiMarzio et al. 2007) in Antarctica. Previous versions of our global grid, (i.e., V8.2 Smith and Sandwell 1997; Sandwell and Smith 2001), contained a flag indicating whether a 2-minute cell was constrained by a depth sounding or whether it was interpolated from satellite gravity. For this new compilation, we have constructed a companion grid that contains a source identification number (SID) that is used to identify the data source for a particular 30-second grid cell. This SID grid is essential for identification and editing of the raw soundings on a cruise-by-cruise basis.

Ocean Data Sources

More than 290 million soundings are used to create SRTM30_PLUS bathymetry (Figure 2). Most of the data is publicly available and can be downloaded. Our contribution is to convert all the data files to a common format (Appendix A), edit the raw soundings, and make the soundings and grids available. Our compilation of soundings is actually a compilation of other compilations. The composite data assembly consists of 5,512 individual files; most of these files came from an individual month-long expedition of a research vessel, so thousands of scientists have been involved in collection of the data. Each data file is assigned a unique source identification number (SID) so every data point in the grid can be traced back to the original cruise file and eventually back to the original data source. We are working on linking additional metadata to each SID number.

The major compilations are listed in the order of decreasing percentage of seafloor covered (Table 1). Many of the compilations offer data at a resolution far better than needed for constructing a 30-arc second grid so these high-resolution data sets were blockmedian processed at 500 m for our compilation using the GMT software (Wessel and Smith 1995, 1998). The analysis presented in this table is based on 1-minute Mercator cells. These 1-minute cells, (technically these are 1-meridionial part cells), better represent the 2–3 km diameter footprint of the single-beam echo sounder data, which are the dominant contribution to global grids. We find that approximately 10% of the seafloor has been mapped by echo sounders at a 1-minute resolution.

(1) The most important compilation (NGDC_GEODAS) is the Marine Geophysical Trackline Data (NGDC 2006), which comprises publicly available, single beam echo soundings that have been archived at the National Geophysical Data Center in Boulder, Colorado, USA.
(2) The second most important compilation (MGG_COMMUNITY) is an assembly of data grids and raw data files contributed by many scientists of the marine geology and geophysics community. The largest of these contributions comes from the Ridge Multibeam Synthesis Project (Marine Geoscience Data System 2008), which is itself a compilation of numerous surveys of the global midocean ridge. Other major contributions come from GEOMAR, NSF Polar Programs, SOEST, and the WHOI/GLOBEC program.

Table 1
Sources of raw soundings

Source	#Cells	%TOT	%Ocean	Web Address
SRTM30_ICESAT	103531622	27.74	0.00	ftp://e0srp01u.ecs.nasa.gov
				http://www.nsidc.org/data/docs/daac/nsidc0304_0305_glas_dems.gd.html
NGDC_GEODAS	12261191	3.28	4.55	http://www.ngdc.noaa.gov/mgg/geodas/geodas.html
MGG_COMMUNITY	5027580	1.35	1.86	http://ocean-ridge.ldeo.columbia.edu/general/html/home.html
SIO_MULTI	4150106	1.11	1.54	http://nsdl.sdsc.edu/
NGA_DNC (private)	2073081	0.56	0.77	NA
JAMSTEC_MULTI	1681985	0.45	0.62	http://www.jamstec.go.jp/cruisedata/e/
NOAA_GRIDS	612283	0.16	0.23	http://www.ngdc.noaa.gov/mgg/fliers/04mgg01.html
				http://www.pifsc.noaa.gov/cred/hmapping/
IFREMER (private)	554750	0.15	0.21	http://www.ifremer.fr/anglais/program/progi.htm
CCOM_MULTI	541819	0.15	0.20	http://ccom.unh.edu/index.php?p=50|55|63&page=unclos/data.php
GEBCO_IHO	370146	0.10	0.14	http://www.bodc.ac.uk/data/online_delivery/gebco/
NAVOCEANO	130272	0.03	0.05	NA
TOTAL	130933395	35.08	10.16	

(3) The third largest contribution (SIO_MULTI) comes from swath bathymetry grids derived from Scripps multibeam cruises, including a significant amount of unpublished data that was collected during transits (Miller 2008). The relatively large area of seafloor covered by this compilation is mostly due to the finite width of the swath and not the areal extent of the cruises. In the future we hope to include all the multibeam data being assembled at the Marine Geoscience Data System (2008).
(4) The fourth largest contribution (NGA_DNC) comes from the National Geospatial-Intelligence Agency (RADM Christian Andreasen, personal communication 2007). These new data consist of shallow water (<300 m) soundings derived from NGA nautical charts for use in their compilation of shallow water grids. These data provide unique depth constraints for many near-shore areas including around Asia, Africa, and South America (Figure 2). Because of the proprietary nature of some of these soundings, their source and location have not been encoded in the SID files, but they have been used to construct the grids.
(5) The fifth largest contribution (JAMSTEC_MULTI) comes from multibeam grids contributed by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC 2008). These data primarily cover areas of the Japanese shelf and Western Pacific.
(6) The sixth largest contribution (NOAA_GRIDS) comes from two major seafloor mapping programs at NOAA, the NOAA Coastal Grids of the United States, and the NOAA Coral Reef Conservation Program.
(7) The seventh largest contribution (IFREMER) comes from the center beam of the 100 or so cruises of data collected by IFREMER scientists through the year 2000. The raw soundings are proprietary, but they were used in constructing the 30-second grids and the SID numbers are included so the processed soundings can be extracted from the grid.
(8) The eighth largest contribution (CCOM_MULTI) comes from the Center for Coastal and Ocean Mapping/Joint Hydrographic Center "Law of the Sea" multibeam grids (Gardner et al., 2006, 2008), including Alaska and the Arctic, the Marianas, Kingman Reef and Palmyra Atoll, the Western Atlantic Ocean, and the Gulf of Mexico.
(9) The ninth largest contribution (GEBCO_IHO) comes from a new effort by GEBCO to assemble a database of new global soundings. This includes many shallow water soundings contributed to GEBCO by various volunteering hydrographic offices around the world. International Hydrographic Organization Circular Letter 36/2006 and 2007/14 requested hydrographic offices to harvest soundings from their Electronic Navigational Charts (ENC) and send these to the International Hydrographic Bureau for inclusion into future GEBCO releases. Tony Pharaoh of IHB and Pauline Weatherall of BODC have kindly supplied these data. In many cases, these data duplicate the shallow water soundings provided by NGA_DNC.
(10) Finally, NAVOCEANO is working to make its holdings available for public distribution and have already contributed some important data sets from around the Hawaiian Islands. They are also working to improve the accuracy of the global shoreline that provided the zero depth contours in the global grids.

Editing Methods

Time series tools such as auto regressive (AR) filters and robust curve fitting do an excellent job of finding outlier points in sequential data such as bathymetric profiles collected by ships with single beam sounders. Unfortunately, there are many diverse ways that data can be corrupted (Smith 1993), and automated editing is less successful at discriminating and correcting some of these. To efficiently edit ∼298 million soundings contained in 5,512 files a software application, *cmEdit*, was written at SIO. Unlike existing, and more sophisticated, geophysical visualization programs, this simple tool is focused on one task: finding outliers in ship track data. Approximately 20 years ago, Paul Wessel and Walter HF Smith, developers of the Generic Mapping Tools (GMT) (Wessel and Smith 1998), wrote a similar application called GMTEdit that was the inspiration for this effort. *cmEdit* is written in Objective-C using the Apple Xcode 3.0 development system, and runs on OSX 10.5.

The premise of our data editing is that bathymetry predicted from altimetry is a low-pass filtered representation of the actual bathymetry. Visual comparison of ship data and the smooth predicted bathymetry frequently, but not always, illuminates a wide range of data outliers. Our goal was to enable an analyst to efficiently scan millions of soundings for blatant but difficult to parameterize data errors and flag the errors. The intention is to rescue as much data as possible from the thousands of "known bad" ship tracks that have an occasional bad patch but also have a substantial amount of useful data.

The files consist primarily of single beam sonar, although processed (gridded) multi-beam data, and a small number of other data types are present. All the data are first block median averaged at 500 m by 500 m cells and converted to a 10-column text format (Appendix A) so that the analyst and software developers can easily debug the various scripts and programs needed to convert the diverse data into a common format. Most of the obvious blunders in the raw data files are corrected during this format conversion. After this preprocessing and conversion there were ∼298 million bathymetry records in 5,521 files. We store the data as ASCII text for ultimate portability as well as to retain the ability to manipulate the files using standard UNIX commands such as *awk*, *grep*, and *sed*. If the data were going into an application to be used daily and interactively, a binary representation of the data stored in a relational database would be more efficient. Currently the approximately 298 million data points stored as ASCII text consumes about 40 gigabytes of disk space; this is relatively small compared to some geophysical data sets and perfectly manageable on a modern desktop computer.

The ASCII text file format contains 10 fields (Appendix A). The "time" field is simply a unique monotonically increasing index given to every sounding (row) in that file; it is either the data acquisition time or a sequence number when the time is unavailable. The latitude, longitude, and depth fields must be populated in units of degrees (+/−180) and meters (sea level 0, depths negative). For our purposes it is adequate to assume that measurements are made from mean sea level, and we make no attempt to deal with various vertical datum on local charts. The horizontal and depth uncertainties (meters) will be used in the future to provide error bars and currently just store the editing flag as 9999 (e.g., Marks and Smith 2009). The source ID number (SID) is stored in every data record, and there is a unique SID number for each of the 5,521 files. The last field stores the predicted depth or whatever depth one wishes to use in the visual editor. Because the gravity data used to generate the predicted bathymetry does not contain wavelengths shorter than about ∼20 km, it provides a smoothly varying nominal depth to compare against the actual soundings. After producing a first iteration depth grid at 1-minute resolution, this grid was smoothed to 2 minutes and used as the predicted depth for the next round of editing.

The data editing is a nonlinear process with no obvious ending point. The fundamental problem is that the data distribution is sparse and the raw soundings contain a wide array of error types and a wide range of error values. As discussed below, the global bathymetry predicted from altimetry is "polished" (Smith and Sandwell 1997) to exactly match the depth soundings after they are block median averaged into 30-arc second cells. The difficulty with this approach is that even a single bad depth sounding can create an artificial dimple in the grid. When the data were prepared for the 2-minute global grid V8.2 (Smith and Sandwell 1997) the blockmedian averaging of the data into 2-minute cells was able to hide millions of outliers because it was common to have 4–8 soundings in a cell. However, when the cell size is reduced to 30-arc second (1/16 of the area of a 2-minute cell), the trackline data usually have only one sounding per cell so outliers cannot be hidden. The difficulty of the editing job is further highlighted by the final editing statistics. Out of the 5,521 data files available, we found at least one bad data point in 3851 (70%) of these files. However, out of the 298 million soundings available, only 4.2 million or 1.4% of the soundings were flagged as bad. Therefore, every file must be examined and the editing must be nearly 100% accurate to avoid blemished due to outliers; the process involves a lot of work by undergraduate students (coauthors on the paper).

The editing process has a cycle that was repeated about five times to achieve the current V5.0 of the SRTM30_PLUS grid. The cycle starts with predicted depth grid generated from a combination of ship soundings and a new version of the satellite-derived gravity (Sandwell and Smith 2008) as described in Smith and Sandwell (1994). This predicted depth is inserted into the last data field of each cm-file and gross blunders (e.g., zero depth, digitizing errors from analog records, or scale factor errors such as conversions from fathom to meter (Smith 1993)) are flagged using the *cmEdit* tool (discussed below). The global grid is then refined, or *polished*, using these ship soundings. A standard remove/restore procedure is used for the refinement. The predicted depth is *removed* from the nonflagged soundings, and the residuals are gridded using a spline in tension algorithm (Smith and Wessel 1990). The predicted depth is *restored* so the final depth grid exactly matches the soundings and makes a smooth transition to the predicted depth. A matching grid of SID numbers is also constructed. This first iteration polished depth grid had thousands of artifacts due to bad soundings that were not obvious during the initial visual editing of gross blunders. To identify the source of the artifacts, the depth and matching ship track (SID) grids are displayed side-by-side using an interactive display tool such as *ermapper*. The analyst zooms in on the offending data and records the SID number of the offending ship track. This screening process results in a list of bad cruises. To begin the second iteration, a new global grid is constructed by combining the predicted depths with the measured depths, but only the good cruises are used. The new grid is used to update the predicted field of the suspect cruises. The analyst visually examines these suspect cruises and flags more outliers. The entire process is repeated until one is satisfied with the look of the final grid. This editing cycle was first performed on a 1-minute resolution grid to flag most of the outliers and then again on the 0.5 minute grid to flag more outliers that become apparent because of the smaller number of points for the block median average. Since the data have a wide range of magnitude of the errors, there is no obvious stopping point. We stopped the editing when the last undergraduate student graduated.

To illustrate the use of the *cmEdit* tool, we have identified four cruises having four of the most common types of errors. These include: (1) a few bad soundings along an otherwise good track (Figure 3a), (2) a swath of multibeam data having errors especially in the far range (Figure 3b), (3) an error in the DC offset of the deeper soundings perhaps related to incorrect sound velocity model (Figure 3c), and finally (4) an error in the scale factor used to convert two-way travel time to depth (Figure 4). The *cmEdit* tool takes a single cruise file and displays the data in three windows. The **navigation** window (not shown in Figures 3 and 4) displays the trackline of the ship. The **statistics** window displays a plot of measured depth on the vertical axis versus predicted depth on the horizontal axis (Figures 3 and 4, left windows). The data points should lie on a straight line having a

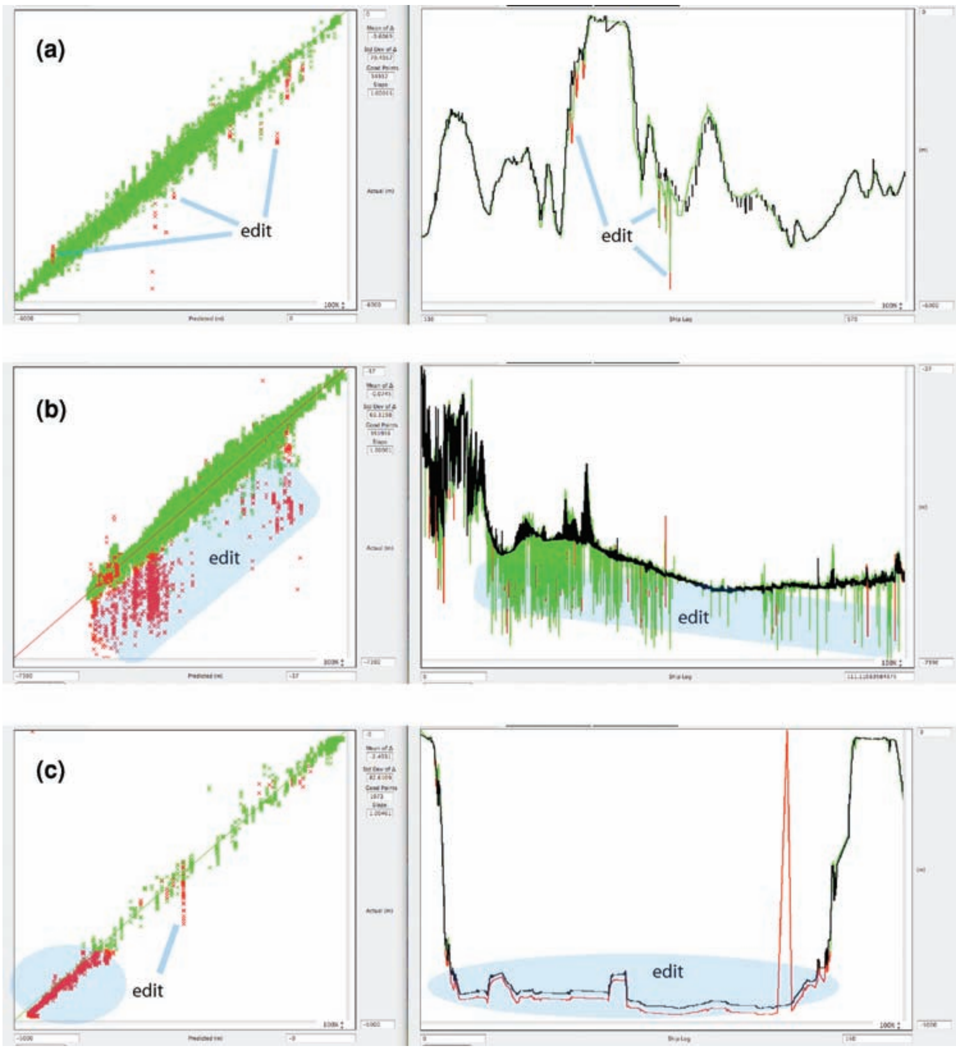

Figure 3. Three examples of editing files of sounding data using a program *cmEdit*. The three windows on the left show the **statistics** window where measured depth is compared with predicted depth and the misfit statistics are displayed. The three windows on the right show the **data** window where measured depth (green) and predicted depth (black) are plotted together. The analyst highlights bad soundings (red) and the flagged data are not used in the next version of the global bathymetry grid. **(a)** Example from a single-beam cruise having a few outliers. **(b)** Example from a multibeam cruise having numerous outliers. **(c)** Example from a single-beam cruise where the deep-ocean data have a bias perhaps due to an incorrect sound velocity correction.

slope of 1 and a standard deviation of less than about 100 m. The mean value of the depth differences should be less than about 10 m. The **data** window displays profiles of measured depth (green) and predicted depth (black) (Figures 3 and 4, right window). Outliers are apparent in the **statistics** window as deviations from the line of unit slope and in the **data** window as deviations between measured and predicted depth. The analyst uses the mouse to highlight a rectangular area of outlier data and then applies a command sequence (or

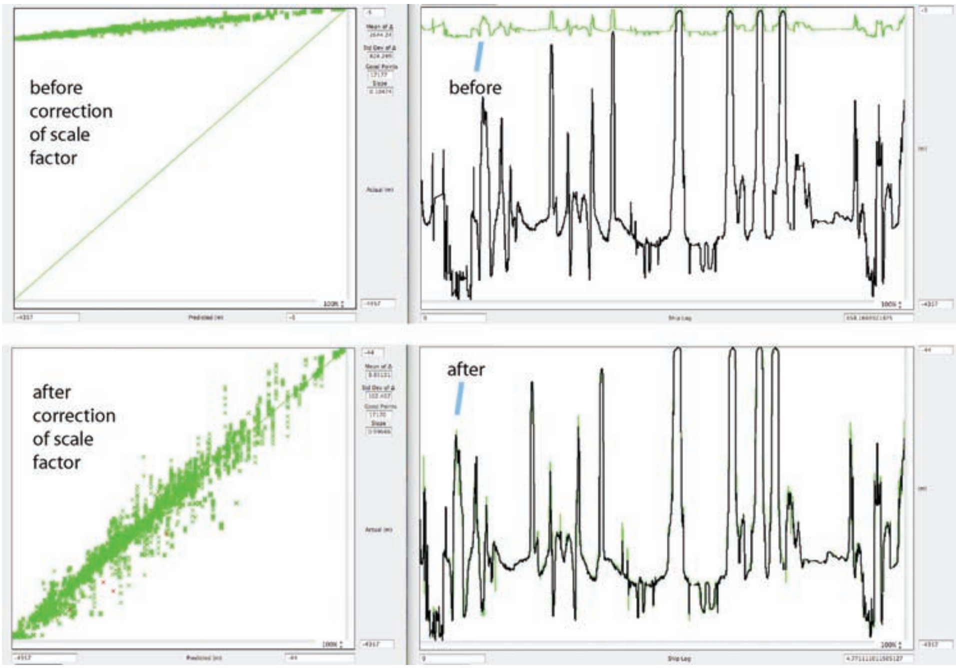

Figure 4. An example of assessing sounding data using the program *cmEdit*. This single-beam cruise has an error in scale factor (upper) that is easily corrected (lower). The corrected data were used in the final gridded bathymetry but not used in previous versions such as V8.2 (Smith and Sandwell 1997).

menu pull down) to flag these data. The flagged data appear as red in all three windows. When the editing is finished, a new output is written where flagged data have a 9999 in the uncertainty field. The improvements in these four example cruises highlight the benefits of this approach (Table 2). As the editing cycle proceeds, the outliers become more difficult to identify. Cruises having map-view errors that ultimately cannot be detected and flagged in *cmEdit* are placed on a permanent bad list and not used. The current bad list has 280 files. For comparison there were 1,300 files in the bad list when V8.2 was constructed (Sandwell and Smith 2000). At that time we did not have the tool and methods to rescue good soundings from nearly 1,000 cruises. The editing example shown in Figure 4 is an

Table 2
Statistical improvements from editing outliers

filename B-before	67010074.cm		SEAW05RR.CM		19050007.cm		cd018.cm	
A-after	B	A	B	A	B	A	B	A
mean (m)	−1.54	−0.61	−1.53	−0.07	−77.8	−2.5	2644.	9.67
slope	1.00	1.00	1.00	1.00	1.03	1.00	0.105	0.99
std (m)	86.2	79.4	106.1	69.3	116.5	82.6	823.3	102.7
number	35010	34932	400000	391956	5054	1973	17177	17177

interesting case because it is completely correctable by replacing the incorrect scale factor with the correct scale factor estimated from the misfit to the predicted. In almost every case one could design an automatic computer algorithm to correct the problem; however, the problems are so diverse that many programs would be needed. A human editor seems to produce the most accurate results.

Gridding Method and Source Identification

The SRTM30_PLUS topography/bathymetry and matching SID grids were constructed mostly using the tools available in GMT and UNIX. The processing details are to gather 298 million edited soundings from 5512 unique sources and sort them with *awk* into the 33 SRTM30 tiles. To avoid edge effects, each tile is extended 1 degree in each direction to create a boundary that is trimmed off after interpolation. The result is 33 large files, each with millions of essentially randomly located soundings. The depths are processed with *blockmedian* at a 30-arc second grid spacing and the value of the predicted bathymetry at each sounding is *removed* from the sounding. The depth difference is then interpolated with the GMT routine *surface* using a tension factor of 0.75, and the value of the predicted bathymetry is *restored* to the interpolated difference. The result is a "polished" grid that passes smoothly through each median sounding and has the value of the predicted bathymetry far from any sounding. As a final step, the land topography values derived from SRTM30, GTOPO30, or interpolated ICESat elevations were inserted in the grids. A new feature of the SRTM30_PLUS bathymetry is a matching grid of source identification number (SID). As described above, this SID grid is essential for identifying the cruise file containing outlier data as well as for establishing the source and processing history of the each sounding. The SID grid was assembled using a custom tool based on the *blockmedian* code (Wessel and Smith 1998) called *medianId*. The *medianId* tool calculates the median value of all soundings in each cell, and returns the SID of the sounding in each cell with the median value.

Results

The topography/bathymetry presented here (Figure 1) improves the V8.2 (Smith and Sandwell 1997) global bathymetry in four ways. (Note there is a V11.1 of the Smith and Sandwell (1997) analysis that is basically equivalent to this new SRTM30_PLUS grid). First, the number of soundings is significantly greater, and the soundings have received additional editing. Second, the gravity model used for the predicted depth has half the grid spacing, with half the noise, and extends to latitudes as high as 81 degrees. Third, the use of SRTM30 (Farr et al. 2007) and ICESat (DiMarzio et al. 2007) improves the land data. Finally, the use of (IBCAO 2008) adds the Arctic bathymetry. As discussed next, the overall improvement is considerable.

One general improvement of both V11.1 and SRTM30_PLUS V5.0 is the greatly reduced number of ship track artifacts. For example, the V8.2 global bathymetry had a significant artifact in the area southwest of the Hawaiian Islands (Figure 5a) that has now been eliminated by more complete editing (Figure 5b). A second general improvement is on the shallow continental margins where sediments are thick. In these areas of generally flat seafloor, the gravity is essentially uncorrelated with topography so the predicted depths are unreliable. When the predicted grid is polished using a small number of soundings, the result may be a falsely "dimpled" surface. An example of this artifact can be seen in the V8.2 global bathymetry of the Northeast Arabian Sea (23N-67E) (Figure 6a). Our

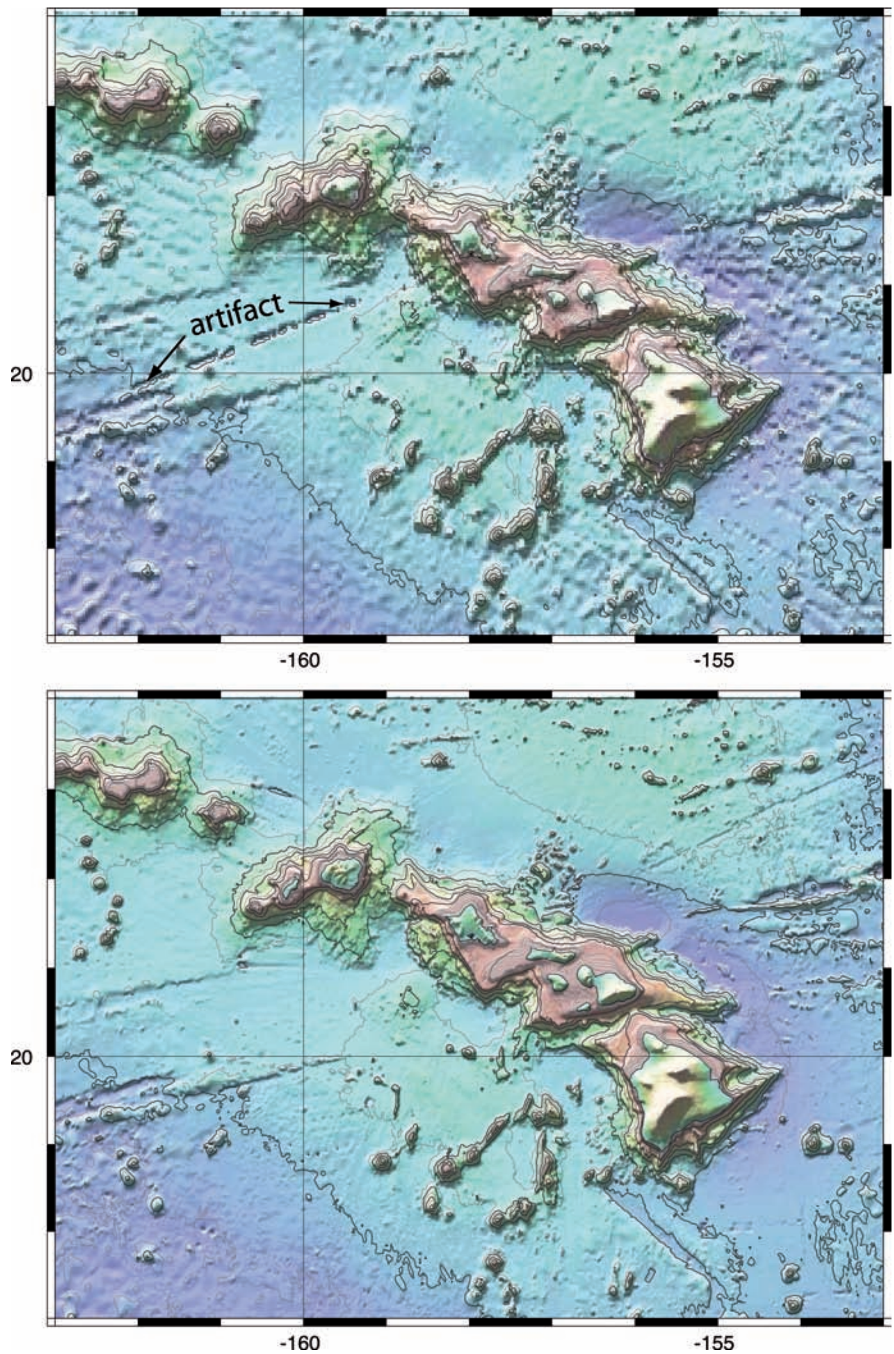

Figure 5. Bathymetry of the Hawaiian Islands region at (top) 2 minute resolution (V 8.2, Smith and Sandwell 1997) and the new SRTM30_PLUS grid at 30 second resolution (bottom). The V8.2 grid has an artifact that has been removed in the SRTM30_PLUS grid.

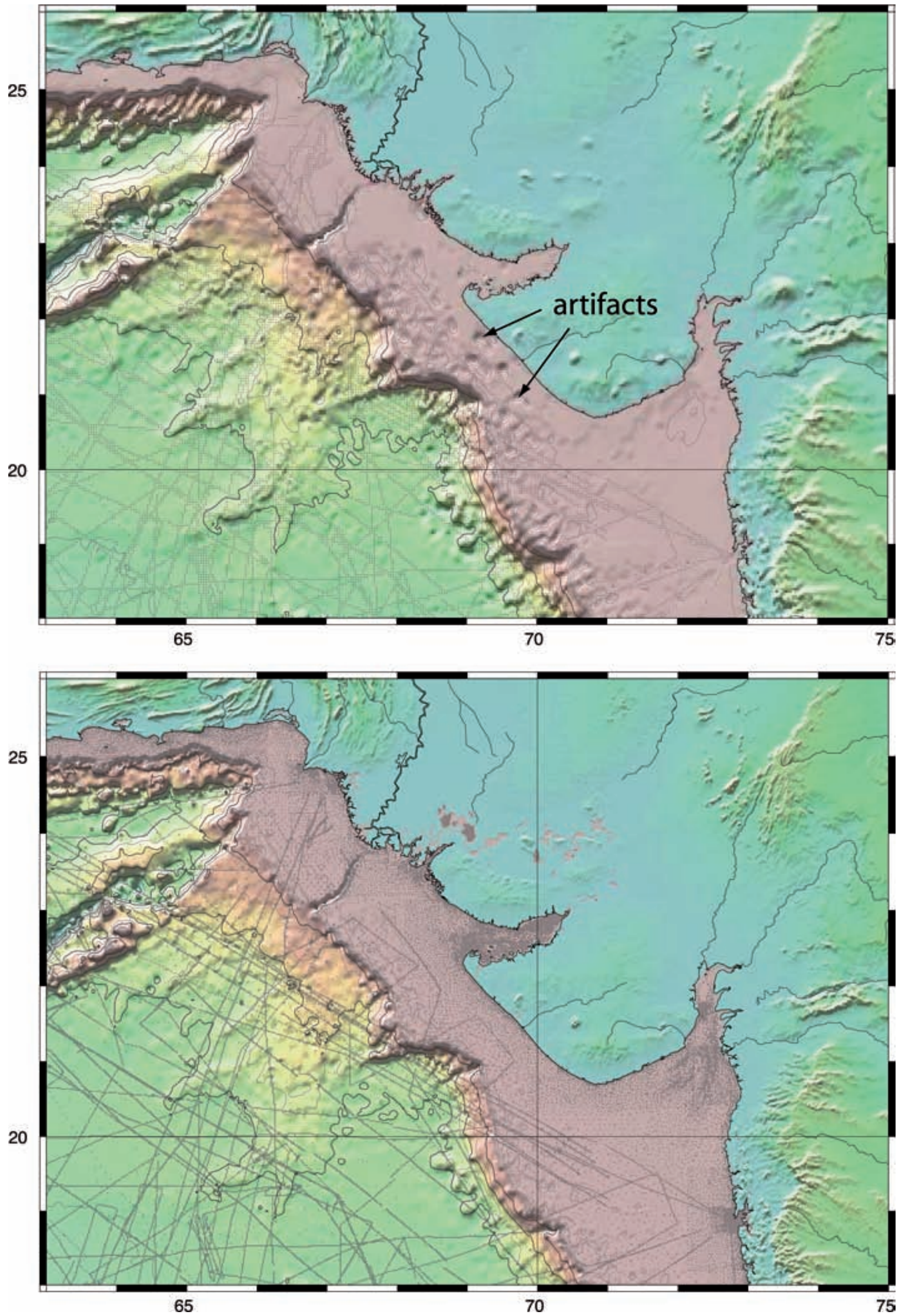

Figure 6. Bathymetry and topography of the Arabian Sea near Karachi, Pakistan, and western India. Grey dots show locations of soundings at 2 minute resolution (top) (V 8.2, Smith and Sandwell 1997) and the new SRTM30_PLUS grid at 30 second resolution (bottom). Soundings density on the shallow continental margin is high in the new SRTM30_PLUS grid and low in V8.2.

new bathymetry has a large number of soundings on the continental margin that constrain the predicted bathymetry well enough to remove most of the artifacts (Figure 6b). These data are soundings from electronic navigational charts provided through the International Hydrographic Organization and have accuracy and spacing similar to the shallow water NGA data used to compile bathymetric grids on most continental margins except Antarctica.

One question that is always asked after this type of analysis is what fraction of seafloor has been mapped by echo sounders and how has this fraction increased since the last global map was constructed? Of course the results are highly dependent on the size of the grid cell used for the assembly of the data. At 30 arc second resolution there are about 600 million ocean grid cells. Since our analysis starts with 290 million edited soundings one may incorrectly estimate that 45% of the seafloor has been mapped. However, many of these soundings are from multibeam data ($\sim$500 m grid) that are averaged together at 30 arc seconds, so after performing a blockmedian average we find that only 39 million depth cells, or 6.5%, are constrained by soundings (latitude $> 80^\circ$ not included in the analysis). When a similar analysis is performed at 1 minute resolution we find that $\sim$10% of the cells are constrained; at 2 minute resolution we find 24% of the cells are constrained. Since most of the data in our analysis comes from wide beam echo sounders having a footprint of $\sim$2 km (Marks and Smith 2009), we believe that the 10% estimate is most appropriate for our global analysis. As a final note, the V8.2 grid at 2 minute resolution had only 16% of the cells constrained by depth soundings so our new analysis includes about 50% more depth soundings.

Conclusions

The new global topography (SRTM30_PLUS and V11.1) is a substantial improvement on the widely used (Smith and Sandwell 1997) global bathymetry. SRTM30_PLUS was created with a 50% increase in the number of soundings. Maintaining the provenance of each sounding made it possible to identify and remove artifacts ranging from a single bad ping to entire ship tracks using a newly developed trackline editing tool. The large number of new soundings on the world's continental margins increases accuracy in heavily sedimented areas. The 33 topography/bathymetry and matching SID data files are available by anonymous ftp (ftp://topex.ucsd.edu/pub/srtm30_plus) and can be used in GMT and MATLAB (Appendix B) as well as any software that can read the SRTM30 data format.

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Appendix A: NAVO-NGA-NOAA-SIO Data Exchange Format

The common file (filename.cm) consists of ASCII text with variable precision depending on the precision of the original data. There are 7 columns as follows:

time	time since an epoch (sec), or record sequence number
longitude	decimal degrees (+/− 180.)
latitude	decimal degrees (+/− 90.)
depth	depth; below sea level is negative (corrected meters)
sigma_h	estimated uncertainty in navigation (m) (0 = no estimate)
sigma_d	depth uncertainty (m) (9999 = edited data; -1 = no estimate)
source_id	unique ID number for each source (0-65535). (NAVO uses 0 to 16383 NGA uses 16384 to 32767 NOAA uses 32768 to 49151 SIO uses 49152 to 65535)
pred_depth	predicted depth estimate (m) (used internally at SIO for editing)

An example from a multibeam grid from SIO cruise AVON07MV where the depth uncertainty is estimated to be 10 meter, but the navigation uncertainty is unknown:

Time OR #	LONGITUDE	LATITUDE	DEPTH	σ_H	σ_D	SID	PREDICTED DEPTH
1	−159.00500	31.08760	−5998	0	10	53914	−5780
2	−159.00200	31.06510	−5984	0	10	53914	−5796
3	−158.97100	31.06280	−5955	0	10	53914	−5805

Appendix B: Accessing Binary SRTM30_PLUS Data Files

GMT users read binary SRTM30_PLUS files with *xyz2grd* (Wessel and Chandler 2007; Wessel and Smith 1995; Wessel and Smith 1998).

```
set file = e020n40.Bathymetry.srtm
set region = '-R/20/60/-10/40'
xyz2grd $file $region -G$file.grd -ZTLh -F -L -I30c
```

The following fragment of MATLAB (MathWorks, 2007) reads a SRTM30_PLUS binary file and, just as an example, sets the land to zero.

```
topography = readImg(e020n40.Bathymetry.srtm, 4800)

bathymetry = topography;
bathymetry (find(topography>0)) = 0;

function topography = readImg(fileName, numCols)
% Read 16 bit SRTM30+ file, and keep it int16 to save memory.

fid = fopen(fileName,'r');
[topography, cnt] = fread(fid, inf, 'int16=>int16');
fclose(fid);

% make image a rectangle. SRTM30+ has 4800 columns north of 60S,
% but 7200 columns south of 60S. So user has say how many...

numRows = cnt / numCols;
topography = reshape(topography, numCols, numRows)';

% On a ``big endian'' CPU, (e.g., Intel Mac), swap bytes.

topography = swapbytes(topography);
end
```