The International Bathymetric Chart of the Southern Ocean (IBCSO) Version 1.0—A new bathymetric compilation covering circum-Antarctic waters

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[1] The International Bathymetric Chart of the Southern Ocean (IBCSO) Version 1.0 is a new digital bathymetric model (DBM) portraying the seafloor of the circum-Antarctic waters south of 60°S. IBCSO is a regional mapping project of the General Bathymetric Chart of the Oceans (GEBCO). The IBCSO Version 1.0 DBM has been compiled from all available bathymetric data collectively gathered by more than 30 institutions from 15 countries. These data include multibeam and single-beam echo soundings, digitized depths from nautical charts, regional bathymetric gridded compilations, and predicted bathymetry. Specific gridding techniques were applied to compile the DBM from the bathymetric data of different origin, spatial distribution, resolution, and quality. The IBCSO Version 1.0 DBM has a resolution of 500 × 500 m, based on a polar stereographic projection, and is publicly available together with a digital chart for printing from the project website (www.ibcso.org) and at http://dx.doi.org/10.1594/PANGAEA.805736. **Citation:** Arndt, J. E., et al. (2013), The International Bathymetric Chart of the Southern Ocean (IBCSO) Version 1.0—A new bathymetric compilation covering circum-Antarctic waters, *Geophys. Res. Lett.*, *40*, 3111–3117, doi:10.1002/grl.50413.

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1. Introduction

[2] Knowledge about the bottom topography of the World Oceans is imperative for a broad variety of scientific research. Despite modern icebreakers' mapping capabilities, available bathymetric portrayals of the Southern Ocean are poorly constrained. In addition, problems of using satellite altimetry to guide interpolation of depths in between soundings when sea ice is present and on continental shelves imply specific challenges for the compilation of bathymetric portrayals of the Earth's polar regions [*Smith and Sandwell*, 1997].

[3] The northern equivalent project to the International Bathymetric Chart of the Southern Ocean (IBCSO), the International Bathymetric Chart of the Arctic Ocean (IBCAO), was initiated in 1997 in St. Petersburg, Russia, with the major objective of gathering all available bathymetric data north of 64°N to create the most up-to-date bathymetric portrayal of the Arctic Ocean [*Jakobsson et al.*, 2000]. This project showed that by gathering regional knowledge, some of the challenges of high-latitude mapping could be overcome, and specifically, more data could be made available for the compilation. IBCAO recently released Version 3.0 of their digital bathymetric model (DBM) [*Jakobsson et al.*, 2012]. While local bathymetric compilations have been created for sections of the Antarctic continental shelves [e.g., *Davey*, 2004; *Graham et al.*, 2011; *Nitsche et al.*, 2007; *Schenke et al.*, 1997], and there have been some attempts to integrate those into the available global bathymetric models [e.g., *Timmermann et al.*, 2010], to date, no equivalent regional bathymetric compilation to IBCAO exists for the Southern Ocean. This issue has been raised frequently over the last decade due to the increasing demand for DBMs, in particular, to serve as a base for oceanographic models and ice sheet reconstructions.

[4] In 2006, IBCSO was initiated as a General Bathymetric Chart of the Oceans (GEBCO) regional mapping project with the goal to create a DBM covering the entire Southern Ocean using all available bathymetric data. This project was endorsed by GEBCO and its parent organization, the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the International Hydrographic Organization (IHO), and the Scientific Committee on Antarctic Research (SCAR). The IBCSO Steering Committee is an expert group of the Geoscience Standing Scientific Group of SCAR and works in collaboration with the IHO Hydrographic Commission on Antarctica. An IBCSO Editorial Board was established consisting of experts in Antarctic bathymetry from nations that acquire data in the Southern Ocean. This expert group collectively

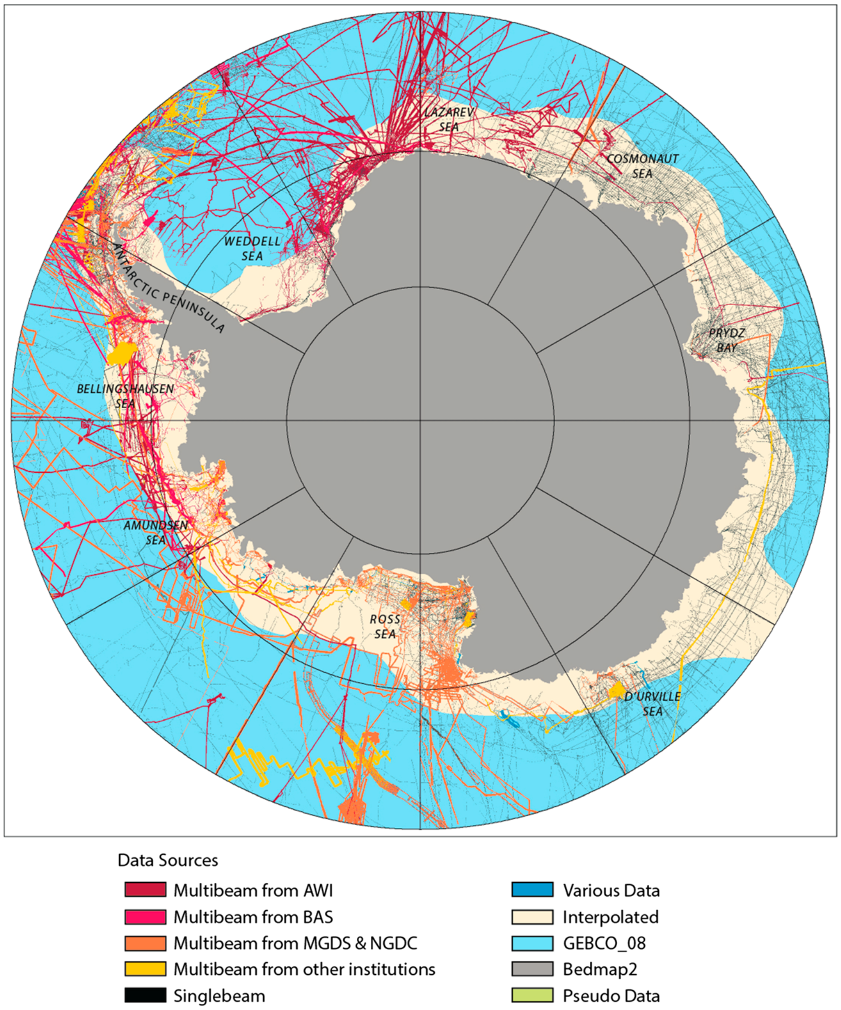

Figure 1. Source Identification grid (AWI = Alfred Wegener Institute, BAS = British Antarctic Survey, MGDS = Marine Geoscience Data System, NGDC = National Geophysical Data Center) and geographic names mentioned in the text.

gathered bathymetric data from more than 30 institutions in 15 different countries.

[5] **Here** we present the first IBCSO Version 1.0 DBM covering the area south of 60°S with a resolution of 500 × 500 m based on a polar stereographic projection with true scale at 65°S referenced to the WGS84 ellipsoid. In addition to the DBM, an IBCSO digital bathymetric chart for printing has been assembled as a second major product of the project. The DBM and the digital chart are available for download from the project website (www.ibcso.org) and at http://dx.doi.org/10.1594/PANGAEA.805736. In this paper, we describe the data sources as well as how the IBCSO DBM was compiled. We also compare the new IBCSO Version 1.0 with previously available bathymetric compilations of the Southern Ocean to illustrate the differences.

2. Methods

2.1. Bathymetric Data

[6] IBCSO is compiled using bathymetric data from hydrographic offices, scientific institutions, and data centers, including single-beam and multibeam echo sounding data, regional DBMs, digitized soundings from printed nautical charts, and satellite-based predicted bathymetry in the deep sea, where sounding data are sparse. The resulting IBCSO Version 1.0 database comprises more than 4200 million data points.

2.1.1. Multibeam Data

[7] Multibeam echo soundings are the core of this compilation. Although just a few research vessels (RVs) equipped with multibeam echo sounding systems are operating in the Southern Ocean, 98.7% of the soundings in the IBCSO database are multibeam data. In total, 177 multibeam cruises are included in the IBCSO database (Figure 1). These range from large-scale systematic survey areas to data collection along single transit lines. Surveys of the RVs NB Palmer, Polarstern, and JC Ross generated the majority of multibeam data. The quality of the multibeam data sets varies substantially, depending on acquisition date, multibeam system, and processing status. The spatial distribution of the multibeam surveys is heterogeneous with a higher concentration in the Ross Sea, around the Antarctic Peninsula, in the eastern Weddell Sea, in the Lazarev Sea, and in the southern parts of the Amundsen Sea, Bellingshausen Sea, and D'Urville Sea (Figure 1). Some contributed data sets contain multibeam and single-beam data in merged files, and these files are referred to as various data (Figure 1). A full list of the incorporated multibeam surveys is given in the auxiliary material.

2.1.2. Single-Beam Data

[8] In addition to the multibeam data, the IBCSO database includes approximately 50 million depth soundings from single-beam surveys (Figure 1). Several institutions provided their single-beam soundings in merged files without distinguishing individual surveys or other metadata included, such as, for example, information about echo sounding and positioning systems. This made it impossible to count the exact number of individual single-beam cruises and assess their individual quality. The spatial distribution of single-beam soundings is heterogeneous with a higher concentration in the same areas as multibeam soundings. In addition, single-beam cruise data are densely available in Eastern Antarctica offshore of permanent research stations, i.e., in Prydz Bay or in the Cosmonaut Sea (Figure 1).

2.1.3. Soundings Digitized From Nautical Charts

[9] Soundings from nautical charts published by the National Geospatial Intelligence Agency from 1995 to 1997 were digitized and integrated into the database in areas where no other data exist. With no available metadata describing these soundings, it was not possible to fully assess their quality. However, their positional accuracy values are probably on the lower end, since most of them were collected prior that GPS satellite navigation became common in the early 1990s. This is evident in some areas, where the digitized soundings from nautical charts differed up to several hundred meters from multibeam and single-beam data. In other areas, no obvious differences were observed.

2.1.4. Regional Compilations

[10] Several regional bathymetric compilations of Antarctic waters have been published [e.g., *Beaman et al*., 2011; *Bolmer et al*., 2004; *Davey*, 2004; *Graham et al*., 2011; *Leon*, 2008; *Nitsche et al*., 2007; *Rebesco et al*., 1998; *Schenke et al*., 1997; *Sexton and Tully*, 2004; *Stagpoole et al*., 2004]. Most of these are located in rather densely surveyed areas close to or on the continental shelf. These regional compilations have been assembled using different gridding methods and vary in age and quality. In most cases, the source data used for these compilations are part of the IBCSO database. Consequently, only small parts of the Bellingshausen Sea compilation [*Graham et al*., 2011] and the George V margin compilation [*Beaman et al*., 2011] were directly integrated into the IBCSO database. In all other areas where regional compilations existed, the new IBCSO Version 1.0 database yielded a better result when gridded directly using the source data with the algorithm described below.

2.1.5. Predicted Bathymetry

[11] Although more than 4200 million data points have been gathered, approximately 83% of the offshore 500 × 500 m grid cells of the IBCSO DBM are left unconstrained by depth data. Some data gaps up to 200 km in diameter exist. Most of these large gaps are located in the deep-sea areas of the Indian and the Pacific Oceans. Predicted bathymetry taken from the GEBCO_08 data set [*BODC on behalf of the IHO and the IOC*, 2008] has been used to fill these gaps in the deep ocean as described below.

[12] However, the accuracy of gravity determination by altimetry is low for waters with year-round sea ice conditions, which directly lower the quality of the derived predicted bathymetry in these areas [*Schöne and Schenke*, 1998]. Especially near and on continental shelves, GEBCO_08 and other data sets using predicted bathymetry contain artifacts associated with undulations in the gravity field that are not related to bathymetry. Therefore, we did not use predicted bathymetry for areas of the continental shelf, where visual inspection indicated that the quality is too low (Figure 1, "interpolated" areas).

2.1.6. Database

[13] The IBCSO database was generated in a generic ASCII XYZ data format, including weighting factors and unique source identification (SID) codes as point attributes. All contributed data sets were transformed into this ASCII XYZ data format. The weighting factor was determined by the quality of the data, which is mainly defined by age and acquisition system. The source identification code is a six-character integer that identifies the type of sounding source (e.g., multibeam or single-beam sounding), the contributing institution, and individual cruises or contributed files. The source identification code is used to create the source identification (SID) grid (Figure 1) that provides information about the data source for each grid cell of the DBM. A complete list of data sets and its source identification codes that are incorporated in the IBCSO Version 1.0 database is available in the auxiliary material.

2.2. Continental Data

[14] We consider that bedrock elevation is the logical continuation of bathymetry in an ice-covered region such as Antarctica. Therefore, the Bedmap2 [*Fretwell et al*., 2013] subglacial bedrock elevation model was used to generate the land representation in IBCSO Version 1.0. Bedmap2 is a set of digital elevation models describing surface elevation, ice thickness, and subglacial bedrock elevation for the entire Antarctic continent. It has a resolution of 1 km and is available in polar stereographic projection with true scale at 71°S referenced to the WGS84 ellipsoid. As reference for elevation, the GL04C geoid was used. Although depth data in the IBCSO database are referenced to mean sea level, no systematic discrepancies were observed, and Bedmap2 could be integrated without any vertical adjustment. The spatial area where Bedmap2 is used is shown in Figure 1.

2.3. Gridding Algorithm

[15] The IBCSO Version 1.0 DBM was compiled using an iterative process consisting of gridding the depth data stored in the database, visualizing the result, identifying and cleaning bad data points, and regridding until satisfactory results were achieved. All cleaning was done directly on the ASCII XYZ data using QPS Fledermaus. Native Fledermaus Pure File Magic files were created from the ASCII XYZ data, cleaned in the 3D Editor, and then exported back to the IBCSO ASCII XYZ format. To handle the large accuracy and density differences between high-resolution multibeam data and widely spaced single soundings and large data gaps, we applied a suite of techniques. First, the cleaned depth data were gridded at 2000 × 2000 m cell size resolution using the surface splines in the tension algorithm of the Generic Mapping Tools (GMT) [*Wessel and Smith*, 1995]. This was followed by adding high-quality data gridded at 500 × 500 m cell size resolution by applying a method similar to the remove-restore method used for IBCAO Version 3.0 [*Hell and Jakobsson*, 2011; *Jakobsson et al*., 2012; *Smith and Sandwell*, 1997]. In order to make use of predicted bathymetry from satellite altimetry used in the GEBCO_08 grid in areas where our IBCSO database

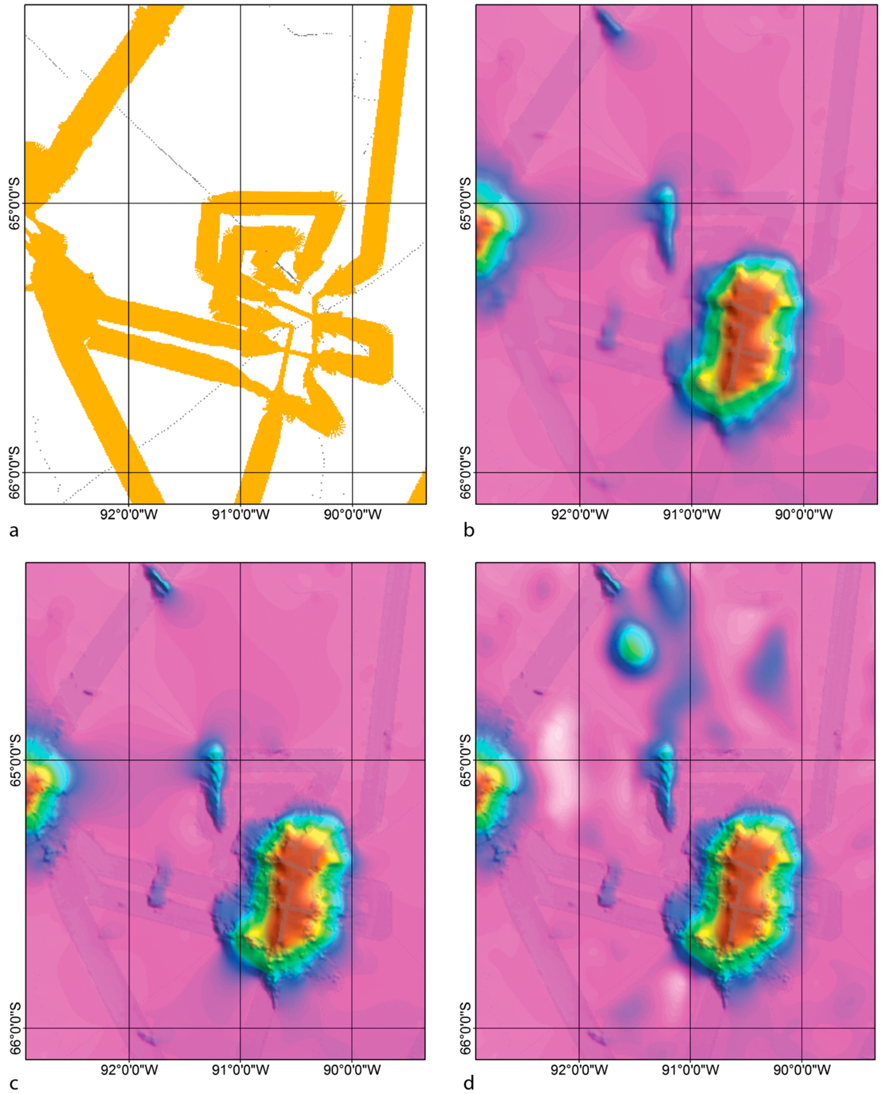

Figure 2. Gridding steps to create the IBCSO DBM. (a) Available single-beam (black) and multibeam (orange) soundings. (b) Raw surface gridded at 2000 m resolution. (c) Surface with restored multibeam data gridded at 500 m resolution. (d) Final IBCSO DBM after integration of predicted bathymetry with the gap-fill method.

does not contain depth data, we developed a method that we refer to as "gap-fill" (see section 2.3.3).

[16] At some locations, inferred pseudo observations were needed for the gridding algorithm to generate a realistic portrayal of the bathymetry. For example, around the Antarctic Peninsula and along the western shore of the Ross Sea, it was necessary to steer the DBM to stay below mean sea level close to the coastline. These observations were manually inferred after inspection of the nearby DBM surface and the SCAR Antarctic Digital Database Version 6.0 coastline data set [*Scientific Committee on Antarctic Research*, 2012]. Underneath some ice shelves, pseudo observations were added to prevent unrealistic interpolation within the transition to continental data. In addition, it was necessary to infer topographic heights on some islands for which no elevation data were available to keep them above mean sea level. The locations of pseudo observation data can be obtained from the SID grid.

2.3.1. Gridding at Two Resolutions

[17] To maintain a maximum of the seafloor morphology details where data density and quality are sufficient and, at the same time, to prevent the occurrence of artifacts in areas with sparse data, we generated separate low- and high-resolution grids and merged those with a specific bending algorithm (see Figures 2b and 2c).

[18] In order to create the low-resolution 2000 × 2000 m grid, a weighted block median filter with the block size set to 2000 m was applied to the entire IBCSO database using the GMT program "blockmedian." The block median filtered points were subsequently gridded using the GMT splines in tension program "surface" with a 0.35 tension factor. The resulting grid was then smoothed using a 6000 × 6000 m cosine filter of GMT's program "grdfilter" and subsequently resampled to 500 × 500 m resolution using GMT's "grdsample".

[19] The high-resolution 500 × 500 m grid was compiled using a weighted block median filter with the block size set to 500 m resolution. This was only applied on spatially dense and high-quality data of the IBCSO database. These block median filtered points were gridded using GMT's program "nearneighbor" at 500 × 500 m resolution. Using this approach, the high-resolution grid is limited to areas where high-quality data exist, while other parts of this grid contain

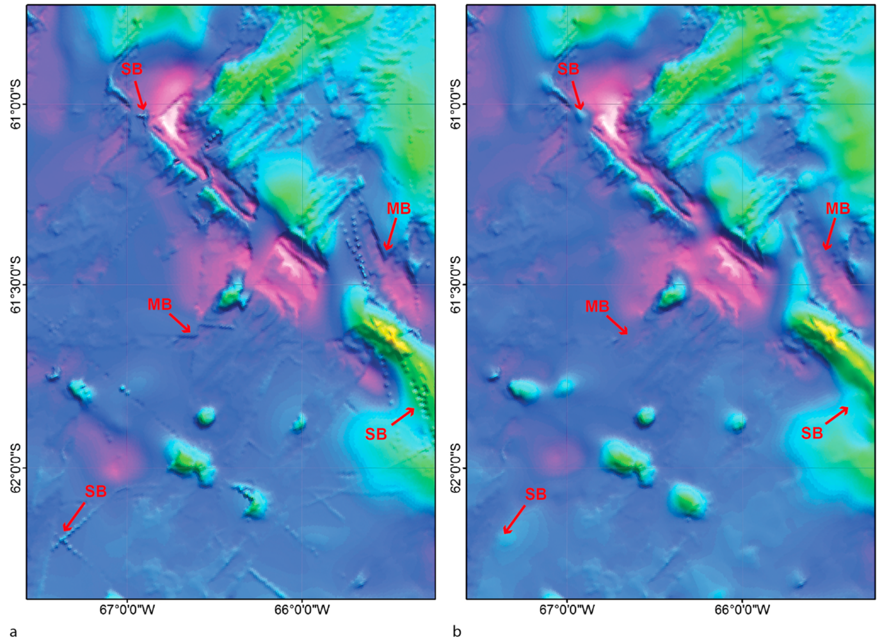

Figure 3. (a) Test area showing samples of artifacts from single-beam (SB) and multibeam (MB) data if no transition zone is used. (b) Result for a 10 km transition zone in the gap-fill method.

no data. The low-resolution grid, in contrary, is a continuous surface interpolating in areas without soundings.

2.3.2. Merging Grids With the Bending Algorithm

[20] Where high-resolution grid cell values were present, we used these to replace the grid cell values of the low-resolution grid using the remove-restore concept. To minimize artifacts at the boundary between these grids, we defined a 1000 m transition zone inside the high-quality data where we applied a so-called bending algorithm using a combination of tools available in ArcGIS.

[21] With the bending algorithm, a new surface is calculated at the intersection of two grids—in this case, the low- and high-resolution sounding grids. The tool uses the hyperbolic weighting function $1/d^2$, with d representing the distance to the next high-quality data constrained cell or the next cell outside the transition zone, respectively. As a result, grid cells close to high-quality data were less influenced by depth values from the low-resolution grid than grid cells further away from high-quality data. Grid cells directly constrained by high-quality data and depth values of the low-resolution grid outside the transition zone remained unchanged.

[22] This minimized the occurrence of edge effects caused by the different grid resolutions. The bending algorithm can be used universally for merging overlapping grids in conjunction with individually defined transition zones.

2.3.3. Integration of Predicted Bathymetry

[23] Areas away from the continental shelves where no soundings constrained the gridding were filled with adjusted predicted depths based on satellite altimetry from the GEBCO_08 data set using the new "gap-fill" method as described below (Figure 2d).

[24] First, the GEBCO_08 grid was adjusted to the soundings of the IBCSO database to minimize the difference to the interpolated grid derived only from soundings in the previous steps. For this, the vertical difference between sounding data and GEBCO_08 was calculated using GMT's "grdtrack." On these difference points, a 10 km block median filter was applied. A difference grid was subsequently created from the filtered points with the splines in tension algorithm. Adding the difference grid to the GEBCO_08 grid adjusted the predicted bathymetry grid to the sounding data of the IBCSO database.

[25] Artifacts in the transition zone between depth data and predicted bathymetry were smoothed with the bending algorithm described above (section 2.3.2). To do so, the transition zone for the bending algorithm was defined by a 10 km distance buffer around depth data of the IBCSO database. In this transition zone, the influence of the adjusted predicted bathymetry depth values increased with increasing distance to depth data. Grid cells directly constrained by depth data and adjusted predicted bathymetry outside the transition zone remained unchanged. This method successfully prevented unrealistic discontinuities in the seafloor shape, caused by the higher resolving ability of direct measurements compared to predicted bathymetry while integrating the predicted bathymetry smoothly into the resulting surface where data gaps exist (Figure 3).

3. Results and Discussion

[26] Figure 4 presents results of the IBCSO Version 1.0 DBM. The developed gridding algorithm has created a smooth bathymetric portrayal over areas with sparse data while providing the detailed seafloor features mapped with multibeam bathymetry.

[27] In total, around ~17% of the offshore grid cells at 500 × 500 m resolution are directly constrained with data. Of these, ~15.4% are constrained by multibeam bathymetry and only ~1.4% by single-beam soundings. The remaining 83% of the grid cells do not contain any direct measurements and have been determined by interpolation between measurements or by integrating predicted bathymetry. While this

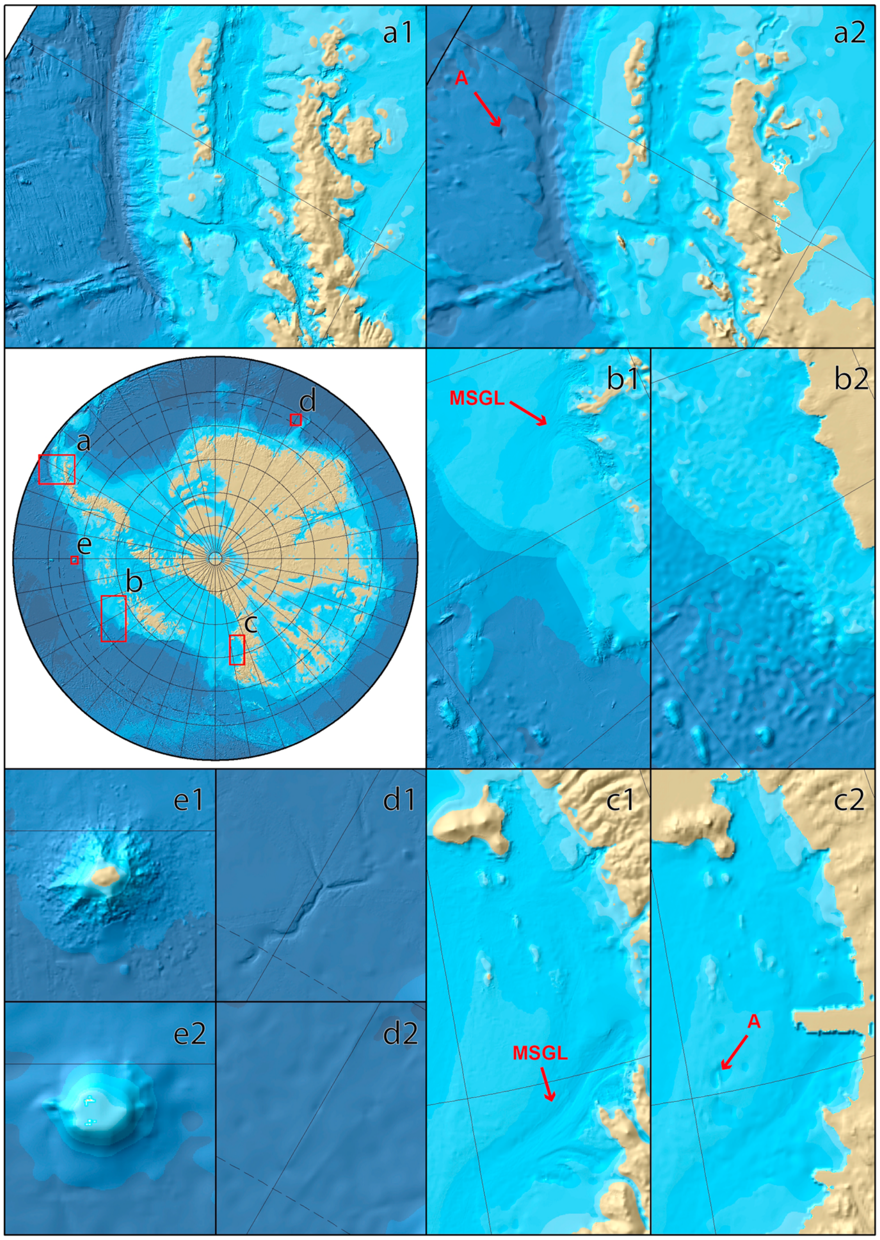

Figure 4. Results of IBCSO (1) and comparison to GEBCO_08 (2) in (a) the region around South Shetland Islands, (b) western Amundsen Sea, (c) western Ross Sea, (d) northern part of Ritscher Canyon, and (e) Peter I Island. MSGL are megascale glacial lineations, and A are artifacts.

is slightly better than for the Arctic Ocean, which has been mapped by multibeam over ~11% of the area [*Jakobsson et al.*, 2012], it highlights that the main part of the Southern Ocean seafloor remains unmapped. The choice of larger grid cell size would reduce the percentage of interpolated cells, but larger grid cells would at the same time make it impossible to resolve any of the detailed features mapped by multibeam sonars. The accompanying IBCSO SID grid helps the user in identifying the source for each grid cell and should prevent misinterpretation and misusage of the DBM in poorly surveyed areas.

[28] Before IBCSO, only global bathymetric data sets covered the entire Southern Ocean, e.g., ETOPO1 [*Amante and Eakins*, 2009], GEBCO_08 [*BODC on behalf of the IHO and the IOC*, 2008], and SRTM30_PLUS [*Becker et al.*, 2009]. Comparing the IBCSO Version 1.0 DBM with the GEBCO_08 DBM (Figure 4) shows that the higher grid resolution in combination with more data, specifically from multibeam surveys, has led to a significantly improved and more detailed representation of the seafloor around Antarctica. For example, in IBCSO, it is possible to identify intermediate-scale seabed features such as channels (Figure 4d) and larger megascale glacial lineations (Figures 4b and 4c) that were not visible in the previous global bathymetric compilations. In areas with sparse data coverage, the cleaning of single-beam soundings in combination with the lower-resolution gridding has reduced the amount of artifacts (Figures 4a and 4c). It should be mentioned, however, that there are still areas where data density and quality are so poor that artifacts most likely remain and will be identified only with additional surveys.

[29] Areas with particular difficulties are located along the coast of Antarctica for the most part has no coastline defined

by sea level but by the termination of ice fronts of glaciers and ice shelves. Consequently, in many places, the "coastlines" are dynamic and constantly changing. Therefore, sub-ice bedrock elevation is the logical continuation of bathymetry and the best approach to solve the coastline issue. Although the bedrock elevation is often poorly determined, the results for the transition zone between bathymetry and continental data showed good, realistic results by using the Bedmap2 bedrock elevation layer [*Fretwell et al*., 2013] for continental Antarctica. The different accuracy values and resolutions between Bedmap2 and IBCSO Version 1.0, however, required adjustments in some areas.

[30] Overall, the continental shelves are the areas where most improvements are made in IBCSO version 1.0 compared to GEBCO_08. Unrealistic bumps are abundant in the GEBCO_08 predicted bathymetry resulting from undulation in the gravity field that is not related to bathymetry. These undulating areas are now replaced by a more realistic smooth surface resulting from interpolation between measurements (Figure 4b).

[31] The increased quality of the IBCSO Version 1.0 DBM has furthermore required the repositioning of some undersea features included in the GEBCO Sub-Committee on Undersea Features Gazetteer (www.gebco.net). For example, the position of the Anashkin Seamount in the northern part of the Ross Sea had to be shifted by more than 150 km westward to agree with the new bathymetry. In other cases, the generic term of undersea features will have to be revised because the new DBM reveals the features' true shape.

4. Conclusions and Outlook

[32] IBCSO Version 1.0 covers the entire Southern Ocean south of 60°S and comprises a substantial improvement compared to previously available bathymetric portrayals. The publicly available DBM and digital chart will be of benefit in various fields of Antarctic research. Among others, the DBM can be used for benthic habitat mapping using GIS analysis in biology, interpretation of seafloor morphology in geology, modeling of ocean circulation more accurately in oceanography, and modeling of ocean-ice sheet interactions in glaciology. These scientific applications can now be also implemented for the entire Southern Ocean and no longer will be limited to regions. While neither the IBCSO DBM nor the chart should be used for navigation, we envision that both products and the established bathymetric database are useful sources of information when the next generations of nautical charts will be developed for safe navigation in Antarctic waters. IBCSO may serve as a basis for cruise planning. In addition, the SID grid may be used to identify data holdings of institutions or data centers. This facilitates full-resolution data identification and access.

[33] The cooperation between international and national organizations has made it possible to obtain the majority of bathymetric data from the Southern Ocean. While the result is an improvement compared to previous compilations, it also shows that more than 80% of the Southern Ocean seafloor is not yet mapped even at a resolution of 500 × 500 m. However, new data collected by an increasing fleet of icebreaking research vessels with multibeam bathymetry capabilities will improve future versions of IBCSO. Finally, we like to emphasize that IBCSO is a collaborative effort built around the concept of data sharing. The DBM and the digital version of the printable chart are publically available from the IBCSO homepage (www.ibcso.org) and at http://dx.doi.org/10.1594/PANGAEA.805736.

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