A consistent dataset of Antarctic ice sheet topography, cavity geometry, and global bathymetry

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Abstract

Sub-ice shelf circulation and freezing/melting rates in ocean general circulation models depend critically on an accurate and consistent representation of cavity geometry. Existing global or pan-Antarctic data sets have turned out to contain various inconsistencies and inaccuracies. The goal of this work is to compile independent regional fields into a global data set. We use the S-2004 global 1-minute bathymetry as the backbone and add an improved version of the BEDMAP topography for an area that roughly coincides with the Antarctic continental shelf. Locations of the merging line have been carefully adjusted in order to get the best out of each data set. High-resolution gridded data for upper and lower ice surface topography and cavity geometry of the Amery, Fimbul, Filchner-Ronne, Larsen C and George VI Ice Shelves, and for Pine Island Glacier have been carefully merged into the ambient ice and ocean topographies. Multibeam survey data for bathymetry in the former Larsen B cavity and the southeastern Bellingshausen Sea have been obtained from the data centers of Alfred Wegener Institute (AWI), British Antarctic Survey (BAS) and Lamont-Doherty Earth Observatory (LDEO), gridded, and again carefully merged into the existing bathymetry map. The resulting global 1-minute data set contains maps for upper and lower ice surface heights, bedrock bathymetry, and consistent masks for open ocean, grounded ice, floating ice, and bare land surface.

1 Introduction

Heat and salt fluxes at the base of any ice shelf, the properties of water masses within the cavity, and the exchange with the open ocean in numerical simulations strongly depend on an accurate and consistent representation of ice-shelf draft and sub-ice shelf bedrock topography. Early attempts to quantify the contribution of ice shelf water to the Southern Ocean's hydrography (e.g. Hellmer and Jacobs, 1995; Beckmann et al., 1999; Timmermann et al., 2001; Assmann et al., 2003) had to admit significant uncertainties due to partly crude assumptions about the geometry of ice shelf cavities. Local or regional simulations of individual cavities and the adjacent seas were able to use more detailed datasets but suffered from uncertainties arising from the choice of open or closed boundary conditions (e.g. Gerdes et al., 1999; Grosfeld et al., 2001; Williams et al., 2001; Thoma et al., 2006; Dinniman et al., 2007) and had no possibility to investigate larger-scale impacts and feedbacks.

An estimate of the rate of ice mass loss from the Antarctic ice sheet is an important component in the IPCC's Fifth Assessment Report. Given that most of the Antarctic ice sheet drains into floating glaciers or ice shelves, model estimates of sub-ice shelf melting rates are crucial to obtain a reliable estimate of the southern hemisphere's ice mass budget. In order to reduce error bars for high-resolution simulations of the coupled ocean–sea ice–ice shelf system in circumpolar or global ocean general circulation models, we compiled consistent maps for Antarctic ice and global ocean topography that combine available gridded data with independent high-resolution datasets and original multibeam echosounder surveys. To preserve as much as possible information from the source datasets and to ensure an easy interpolation to any model grid, we chose a resolution of 1 minute in zonal and meridional direction, although we are aware that large parts of the available information in high latitudes is less detailed than this grid spacing might suggest.

In this paper, we present the datasets used, discuss their spatial coverage and the preprocessing applied, the strategies followed for merging datasets, and the resulting maps of ice and bedrock topography. In contrast to the ongoing International Bathymetric Chart of the Southern Ocean (IBCSO) activities (e.g., Schenke and Ott, 2009), our main goal is not a remapping of bathymetric data in the region south of $50°$S, but a consistent representation of Antarctic ice sheet/shelf topography and global bathymetry in a dataset that contains enough detail for a wide range of regional and larger-scale studies. The main target group includes, but is not restricted to ocean modellers who aim at a realistic representation of Southern

Ocean ice shelf processes in ocean general circulation models.

2 Datasets and processing

2.1 Overview

The RTopo-1 dataset (see Figs. 1 and 2 for an overview) comprises global 1-minute fields for

- ocean bathymetry (including surface topography of continents; bedrock under ice sheets/shelves)
- Earth's surface height (zero for ocean; upper ice surface height for Antarctic ice sheet/shelves)
- topography of Antarctic ice sheet/ice shelf base (zero in the absence of ice)
- masks to identify open ocean, ice sheet, ice shelf, and bare land surface
- locations of coast and grounding lines (consistent with mask) for easy plotting

It should be noted that ice not connected to the Antarctic ice sheet, including glaciers on (sub-) Antarctic islands and the Greenland ice sheet, is not covered in our dataset; these areas are treated as bare land surface.

2.2 Data sources

2.2.1 World Ocean bathymetry

The nucleus of RTopo-1 is the S-2004 ocean bathymetry (Marks and Smith, 2006), which merges the gravimetry-based Smith and Sandwell (1997) map with the GEBCO 1-minute bathymetry. For the continental shelf regions of the Southern Ocean, where satellite gravity data are not available, this dataset features several uncertainties. Ice shelves are not represented at all; instead they appear as areas with zero surface height. For the Antarctic continent, S-2004 contains the (ice) surface elevation, but not the bedrock topography. For most of the World Ocean, however, S-2004 represents ocean bathymetry and continental bedrock topography with an impressive amount of detail. We therefore use this dataset as the global backbone bathymetry outside the immediate vicinity of Antarctica (see

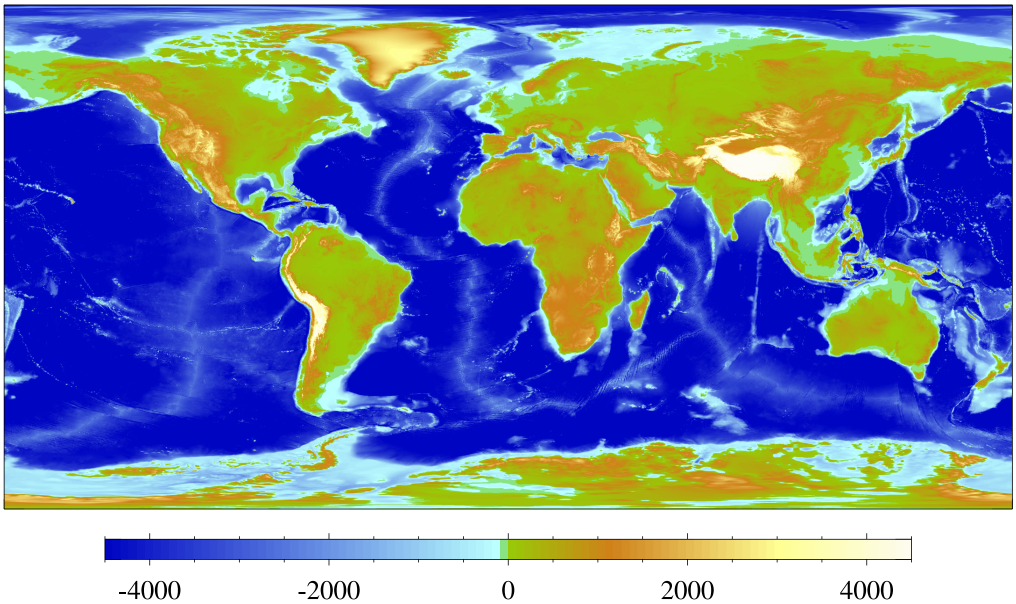

Figure 1: RTopo-1 global bedrock topography. On continents outside Antarctica, this represents the topography of the solid surface (e.g. bottom of lakes, surface elevation of glaciers and continental ice caps) and mirrors the S-2004 dataset.

Fig. 3 for the location of merging lines and the following section for a discussion of the reasoning for its location). We keep lakes and other features with a surface height below mean sea level and no connection to the world ocean, but mark them as continent in the surface type mask (see Section 2.3).

2.2.2 Antarctic ice and bedrock topographies

Surface topographies for the Antarctic ice sheet, some of the Antarctic ice shelves (see below for exceptions), and most of the Antarctic continental shelf is based on an improv endfor ed version of the BEDMAP (Lythe et al., 2001) dataset that has been compiled by Le Brocq et al. (2010) and will be refered to as ALBMAP hereafter. While the BEDMAP effort was mostly directed towards mapping the continental ice sheet (and its bed), ALBMAP features a greatly improved representation of sub-ice shelf cavities, which has been achieved mostly by using an improved interpolation scheme and carefully correcting (mostly increasing) bedrock depth towards the grounding line for many ice shelves ++Anne, please feel free to add/modify details of your work++. Maybe most important, ALBMAP ensures consistency of the different maps along the grounding lines and introduces a surface type mask for grounded ice, floating ice, and open water.

Like BEDMAP, ALBMAP uses a stereographic projection, which is very con-

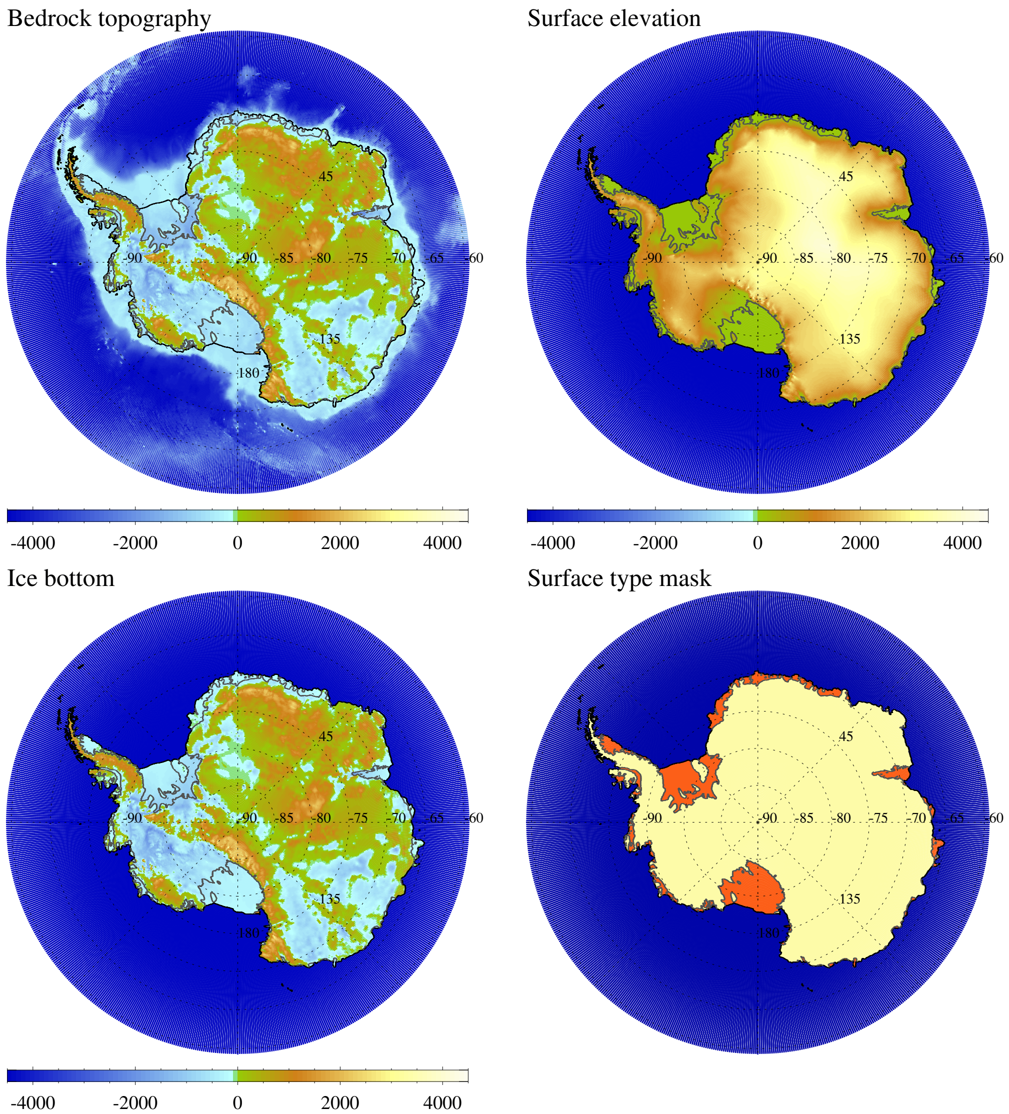

Figure 2: Antarctic subset of the RTopo-1 dataset. Top left: bathymetry (surface height of bedrock). Top right: surface elevation. Bottom left: ice bottom surface height (including ice shelf draft). Bottom right: surface type mask, blue = ocean, yellow = grounded ice, orange = floating ice, grey = bare bedrock (appears only on islands not attached to Antarctic Ice Sheet here). Grey line marks the grounding line, black line the ice shelf front or coast.

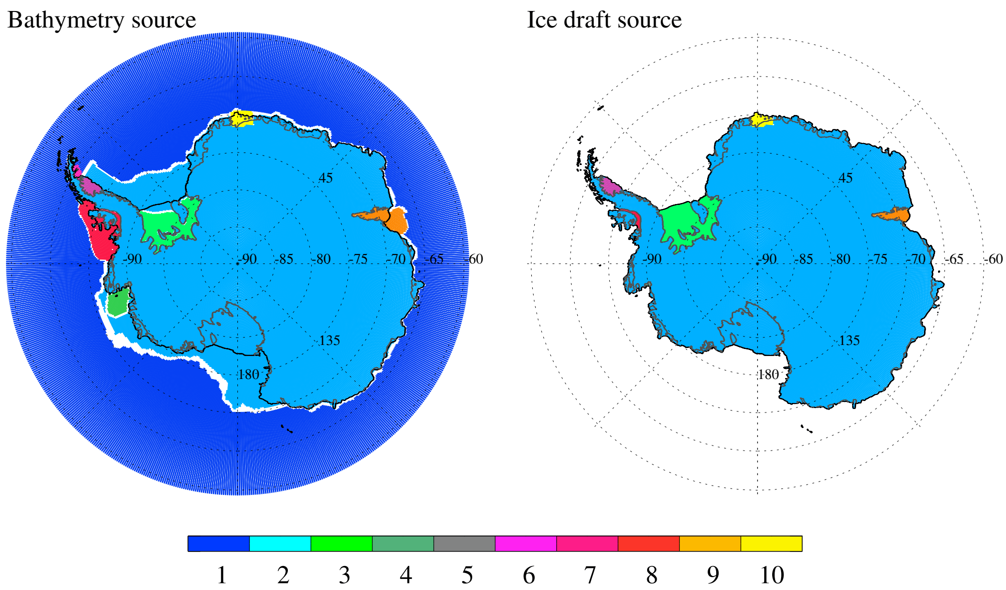

Figure 3: Data sources for ocean bathymetry (left) and ice sheet/shelf topography (right). See Table 1 for an explanation of numbers. White areas mark transition zones between the datasets.

venient for studies of the Antarctic ice sheet/shelf system, but much less so for circumpolar or global ocean models. We use spherical Delauney triangulation as a basis for linear interpolation to our regular 1-minute (lon,lat) grid.

To ensure a smooth continuation of bathymetry into the sub-ice shelf cavity, we merge the ALBMAP data into S-2004 not strictly along the ice-shelf edge, but at a line that has been carefully adjusted to keep the best out of both datasets (Fig. 3). In the East Antarctic and many other places, the transition follows the ice shelf front or Antarctic coast. In order to avoid the spurious signature of General Belgrano Bank, which has been reported to be only a minor rise (with an elevation of only 20 m above the surrounding flat bottom) by Nicholls et al. (2003), we use ALBMAP for the entire continental shelf in the southwestern Weddell Sea south of $66.15°$ S (which is the latitude between the Larsen B and C areas) with the transition occuring between the 1000 m and 2000 m isobaths. Similar arguments apply to the choice to use ALBMAP bathymetry in the Amundsen and Ross Seas with the transition to S2004 placed between 2000 and 4000 m water depth. Tangens hyperbolicus functions are used to ensure a smooth transition between the datasets without too much spurious blurring of gradients.

In order to use topographic information from surveys that have been conducted

Region	Data obtained from	Original data source(s)
1. World Ocean bathymetry	S2004 bathymetry (Marks and Smith, 2006)	1. GEBCO 1-minute bathymetry 2. Smith and Sandwell (1997)
2. Antarctic surface height, ice shelf draft, and bedrock topography	ALBMAP-v1 (Le Brocq et al., 2010)	BEDMAP (Lythe et al., 2001)
3. Filchner-Ronne Ice Shelf • draft and elevation • cavity bathymetry	 Lambrecht et al. (2007) Makinson and Nicholls (1999)	 radar and seismic sounding Vaughan et al. (1995) Johnson and Smith (1997) Mayer et al. (1995)
4. Amundsen Sea: • Pine Island Bay bathymetry	 Nitsche et al. (2007)	 AGASEA, ship data
5. Pine Island Glacier • ice draft and cavity bathymetry	 Jenkins et al. (2010)	 orig. AUTOSUB data
6. Larsen C Ice Shelf • surface height and draft • cavity bathymetry	 Jansen et al. (2010)	 BEDMAP + ICESat altimetry estimate using grouding line depth and bathymetry at ice shelf front
7. former Larsen B Ice Shelf cavity bathymetry	Eugene Domack (pers. comm.) AWI database	*Nathaniel B. Palmer* multibeam data *Polarstern* multibeam data
8. Bellingshausen Sea • bathymetry • George VI sub-ice bathymetry • George VI ice shelf topography	 Tara Deen (pers. comm. 2009) Rottmann et al. (1996) / AWI database Potter and Paren (1985) Humbert (2007)	 BAS archived multibeam data *Polarstern* multibeam data radar, plumb-line, seismics BEDMAP + ICESat laser altimetry
9. Amery Ice Shelf • ice draft and cavity bathymetry	 Galton-Fenzi et al. (2008)	 radar, seismics, tidal modelling
10. Fimbul Ice Shelf • ice draft and cavity bathymetry	 Smedsrud et al. (2006)	 Nøst et al. (2004)

Table 1: Data sources for individual regions of the Southern Ocean, as merged into RTopo-1. Numbers in the Region column correspond to the source flag in Fig. 3.

after the BEDMAP dataset had been published, we replace ice and ocean topographies by newer, regional datasets in several places outlined in the following sections. Again we use spherical triangulation as a basis for interpolation and tangens hyperbolicus functions of the ratio between ”new” and ”background” data in a data window of typically 1° width for the transition between datasets. In places where inconsistencies between ice shelf draft and ocean bathymetry yield negative water column thickness we modify the bathymetry (and to a smaller extent the ice shelf draft) to obtain a minimum water column thickness of 10 m.

2.2.3 FRIS

Filchner-Ronne Ice Shelf surface height and draft have been derived from the ice thickness datasets of Lambrecht et al. (2007) using their Eq. (2) with the proposed densities and parameter values. The position of Ronne Ice Shelf front has been carefully redrawn, now representing a more recent location. Given their small-scale and transient nature, the inlets downstream from Hemmen Ice Rise have been filled with interpolated values.

Bathymetry in the Filchner-Ronne Ice Shelf cavity is derived from the dataset compiled by Makinson and Nicholls (1999). In order to maintain floating conditions in the embayment with the inflow of Support Force Glacier, we deviate from the ALBMAP grounding line here and apply the grounding line of Rignot and Jacobs (2002) instead, which is consistent with grounding line locations suggested by Makinson and Nicholls (1999) and Lambrecht et al. (2007).

Inconsistencies between the two datasets (ice thickness and bathymetry) are addressed by applying a minimum water column thickness of 10 m in the area of floating ice. In contrast to all other ice shelves (where ice shelf draft is assumed to be well-known and only bathymetry is adjusted), both the draft and bathymetry are modified here, with the depth adjustment split across the draft (25% of depth adjustment) and bathymetry (75% of depth adjustment). Corrections can be as high as 200 m for bathymetry (and accordingly less for ice shelf draft), but occur localized mostly along the grounding line; in particular at places where the grounding line has been relocated.

2.2.4 Amundsen Sea ice shelves and Pine Island Glacier

As can be seen in Fig. 3, ocean bathymetry in most of the Amundsen Sea is derived from ALBMAP, with the transition to S2004 occuring between 2000 and 4000 m water depth. Open ocean bottom topography in Pine Island Bay, however, utilizes the dataset from Nitsche et al. (2007), which is a combination of ship data with the *Airborne Geophysical Survey of the Amundsen Embayment* (AGASEA) and BEDMAP datasets. This dataset has already been included in ALBMAP, but to preserve its fine resolution we decided to use the original Nitsche et al. (2007) data here.

For surface height/draft and cavity bathymetry of most ice shelves in the Amundsen Sea we retain the data from ALBMAP, which in turn uses AGASEA data (Vaughan et al., 2006; Holt et al., 2006) for Thwaites Glacier Tongue, and Crosson and Dotson Ice shelves.

An important exception is Pine Island Glacier, where the geometry of the sub-ice cavern (including ice-shelf draft) is interpolated from the very recent AUTOSUB data of Jenkins et al. (2010). While BEDMAP and S-2004 do not contain any meaningful information for the sub-PIG cavity, ALBMAP suggests a trough with a depth of about 900 m at the glacier front and a sill of about 100 m height at about two thirds of the distance between ice shelf front and grounding line. The AUTOSUB survey now reveals that the trough is more than 1000 m deep at the ice front; the sill is located halfway between glacier front and grounding line, and its height is about 300 m (see Fig. 6 below). Water column thickness in the cavity thus varies from about 700 m near the glacier front to only 275 m at the sill, but then again increases to a maximum of 360 m towards the grounding line.

2.2.5 Larsen C Ice Shelf

For Larsen C ice shelf topography (surface elevation and draft) and grounding line location, we use data from Jansen et al. (2010), who combined BEDMAP data with surface heights obtained from ICESat altimetry. The grounding line location in this dataset has been picked from interferometry from the ERS-1/ERS-2 tandem mission in the north, and from MODIS imagery in the south. It is a rather conservative estimate in a sense that for all areas denoted as ice shelf we can be sure that the ice is really floating. Differences from BEDMAP draft occur mainly along the ice shelf front, where the ice is thinner now, and towards the grounding line, where the depth of the ice shelf base increases to about 550 m below sea level (Fig. 4, left).

Bottom topography in the cavity below Larsen C ice shelf is based on ALBMAP, but has been modified in order to ensure a minumum water column thickness of 10 m near the grounding line and a gradual rise to the bottom depth found near the ice shelf front. Bathymetry now features a depth between 500 and 600 m under most of the ice shelf with deep troughs towards the grounding line (Fig. 5). The existance of such deep troughs in immediate vicinity to the mountains of the Antarctic Peninsula might seem doubtable at first glance; multibeam bathymetry surveys in Antarctic Sound and the former Larsen B cavity (Gavahan and Domack, 2006), however, show that indeed troughs of very similar depth and horizontal scale have been carved out where ice streams interfered with the ocean bottom. In any case it should be kept in mind that bathymetry in the Larsen C cavity in our dataset is hardly more than an educated guess.

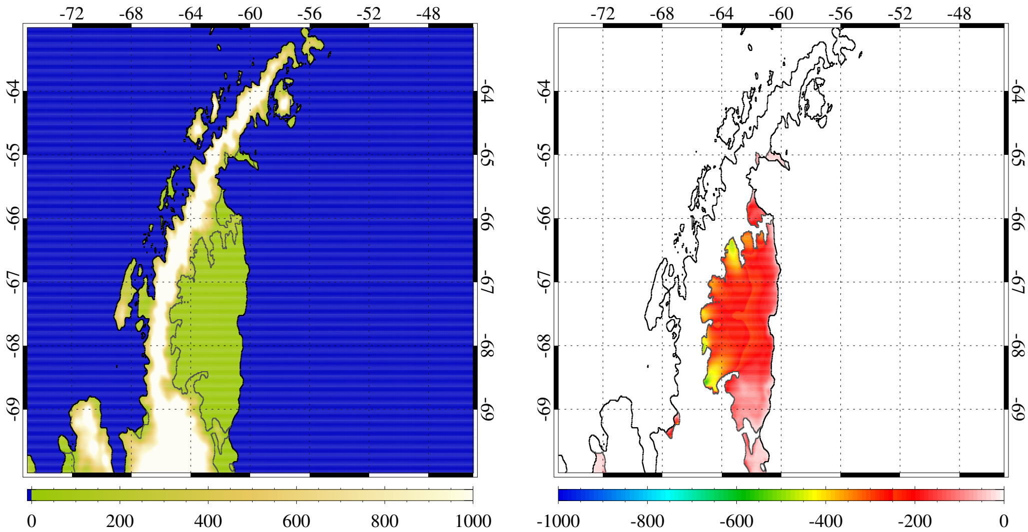

Figure 4: Surface height (left) and ice shelf draft (right) for the Antarctic Peninsula, including Larsen C ice shelf and the remnants of Larsen B ice shelf. Ice shelf front is marked with a black line, grounding line location with a grey line.

2.2.6 Larsen A and B Ice Shelves

The disintegration of Larsen A and B Ice Shelves in January 1995 and February 2002 left the former cavities as open water embayments. For the bathymetry in this area, we combine original data from *Polarstern* cruise ANT-XXIII/8 (Pugacheva and Lott, 2008) with digitized maps of along-track multibeam data from the *Nathaniel B. Palmer* NBP0107 and NBP0603 cruise reports (E. Domack, pers. comm.). Again spherical triangulation is used as a basis to fill the gaps between cruise tracks (Fig. 5). The coastline of the Larsen B embayment has been carefully corrected wherever the existance of ships tracks suggests the presence of open water instead of ice or continent.

2.2.7 Bellingshausen Sea and George VI Ice Shelf

For the eastern Bellingshausen Sea shelf area (i.e. the area shallower than 1000 m in the sector east of 90°W and south of 67°S), bathymetry is constructed from multibeam swath data from the BAS bathymetry database (Deen, pers. comm. 2009) augmented with original data from R/V Polarstern cruise ANT-XI/3 (Rottmann et al., 1996) in the area near Ronne Entrance (Fig. 6). Bottom topog-

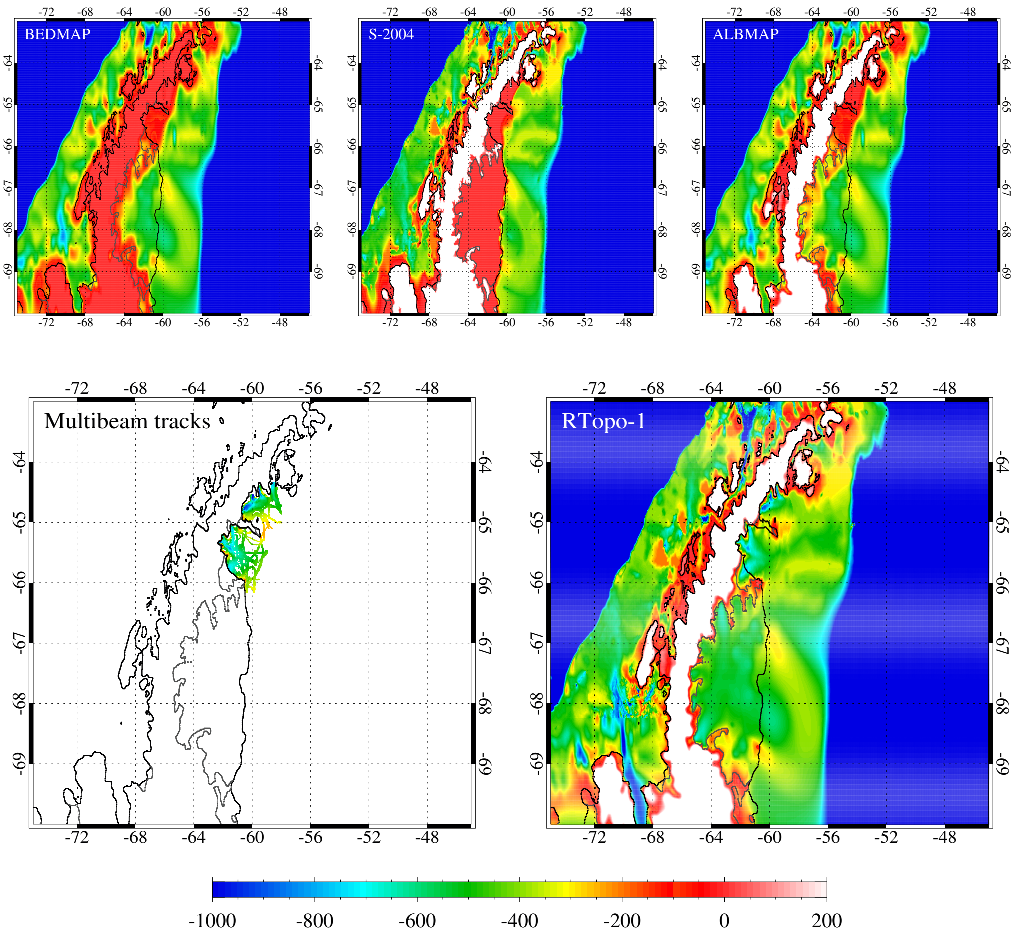

Figure 5: Different representations of bathymetry (bedrock topography) in the area of the Larsen ice shelf. Top row: BEDMAP (left), S-2004 (middle), and ALBMAP (right). Bottom row: Multibeam track data (left), and the RTopo-1 product (right). Ice shelf front is marked with a black line, grounding line location with a grey line.

raphy underneath George VI Ice Shelf follows the sections of Potter and Paren (1985). In contrast to the representations in BEDMAP, ALBMAP and S-2004 (Fig. 6, top row), these data clearly indicate the existance of a 700-900 m deep trough that extends all the way from Marguerite Bay through George VI Sound (i.e. the cavity under George VI Ice Shelf) to Ronne Entrance. Form here, further channels provide connections to the continental shelf break. Note that we had to make assumptions for bathymetry in the data gap in the northern part of George VI Sound, but these are fully consistent with the Potter and Paren (1985) plumb line profile along the northern ice shelf front.

Surface height and draft of George VI Ice Shelf is derived from the Humbert (2007) thickness dataset. Given that George VI ice shelf is covered with melt ponds and a real firn layer is virtually absent, we convert thickness to draft assuming an ice density of 910 kg m^{-3} and do not apply any firn correction.

2.2.8 Amery Ice Shelf

For Amery Ice Shelf, we use the ice draft and ocean bathymetry data of Galton-Fenzi et al. (2008), who combine radar and seismic surveys, ice thickness estimates from satellite altimetry, borehole and ship-based observations, and insight obtained from tidal modelling. Compared to BEDMAP and ALBMAP, this dataset features a much deeper cavity (3000 m instead of 1800 m), introduces fives ice rumples, and yields substantial corrections for grounding line and ice edge location.

2.2.9 Fimbul Ice Shelf

For Fimbul Ice Shelf draft and sub-ice shelf bathymetry we use the topography dataset of the regional model of Smedsrud et al. (2006), which is based on the data from Nøst et al. (2004) with an educated guess for the deep cavity near the grounding line. While we retain ALBMAP's grounding line location here, ice extent has been carefully reduced to match the more recent data.

2.3 Water column thickness, masks and coastline

As already discussed, we provide a global mask that discriminates between grounded and floating ice, open ocean, and bare bedrock (Fig. 7). For Antarctica, the mask largely follows ALBMAP but, as already mentioned, has been corrected based on ship tracks in the former Larsen B area and independent grounding line

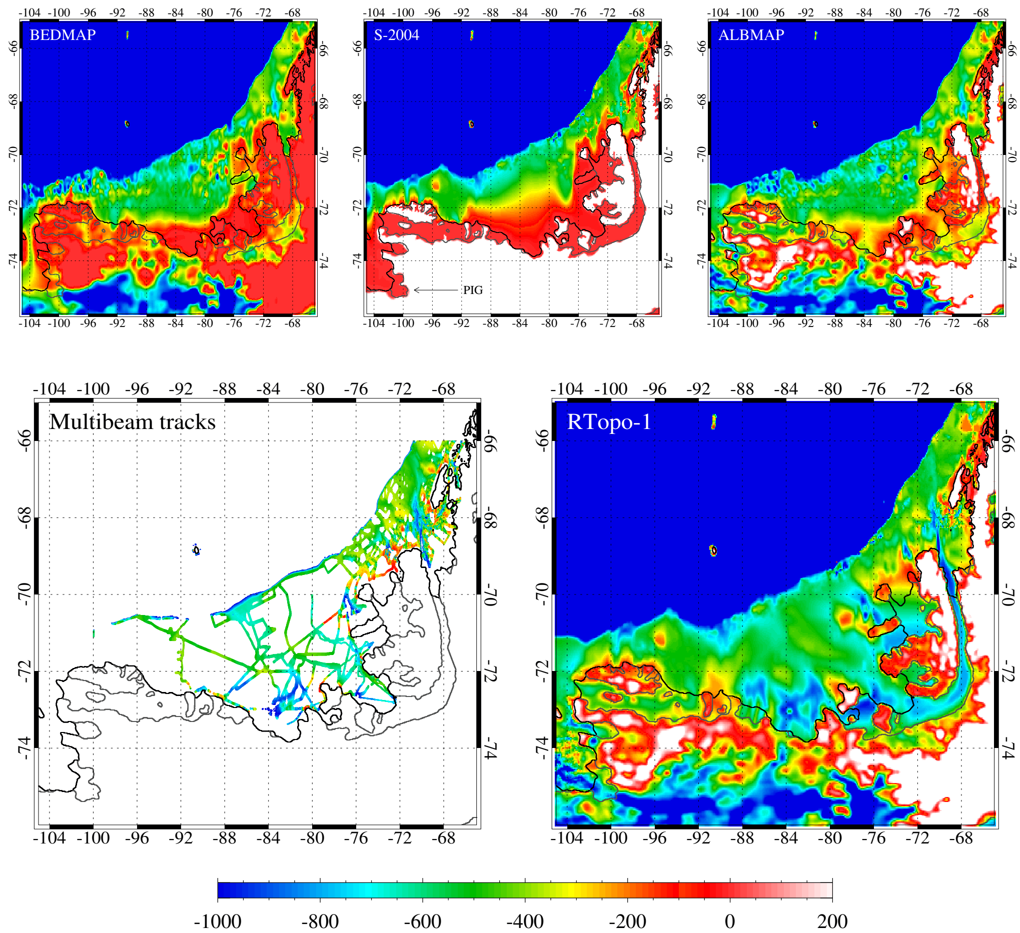

Figure 6: Different representations of bathymetry (bedrock topography) in the Bellingshausen Sea. Top row: BEDMAP (left), S-2004 (middle), and ALBMAP (right). Bottom row: Multibeam track data (left), and the RTopo-1 product (right). Also note the differences for Pine Island Glacier (PIG) and George VI sub-ice bathymetries. Black line represents the coastline, dark grey line the grounding line.

locations for, e.g., Support Force Glacier (Filchner IS region), and the Amery Ice Shelf. Ice caps not connected to the Antarctic ice sheet have been removed from the mask and are now classified as bedrock (with the ice surface height adopted as the bedrock surface height). Subglacial lakes are ignored.

While lakes and enclosed seas outside Antarctica are still present in the bathymetry dataset (adopted from S-2004), they are marked as “continent” in the mask. Using the topography map(s) together with the mask thus allows for an easy generation of global or regional ocean model grids without the need to manually remove features with a topography below mean sea level and no connection to the world ocean.

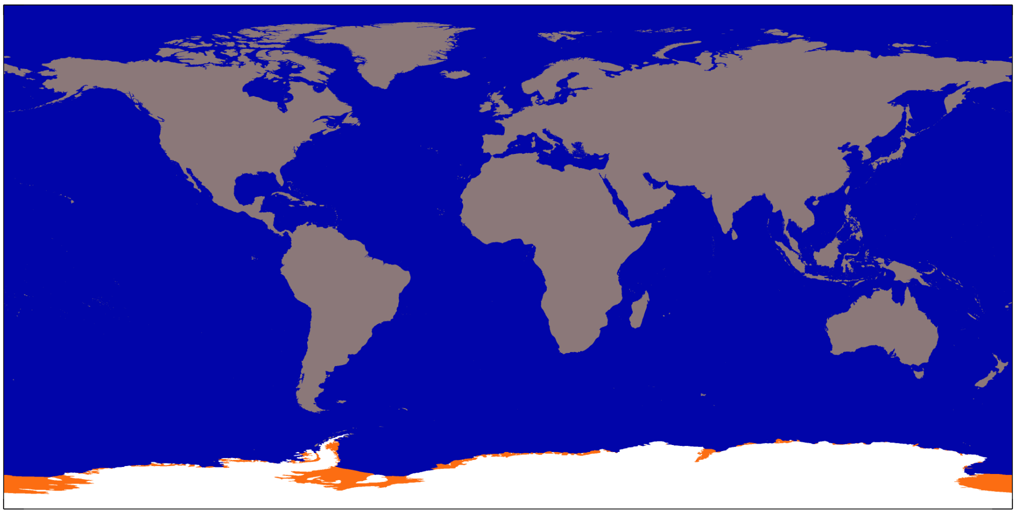

Figure 7: Global surface type mask in RTopo-1. Blue = ocean, white = grounded ice, orange = ice shelf, grey = bare land surface.

Water column thickness needed for the generation of grids for ocean models with a terrain-following coordinate can be computed as the difference between ice bottom surface height (which is zero in the absence of ice shelves) and ocean bedrock topography (Fig. 8). Locations of nonzero entries in the resulting field are consistent with the area denoted as “ocean” in the mask.

Last but not least, the dataset contains position data for coast- and grounding lines that are consistent with the mask and all other datasets. These can be used for an easy and overlap-free plotting of maps in any desired projection (and have been used for all the maps in this paper).

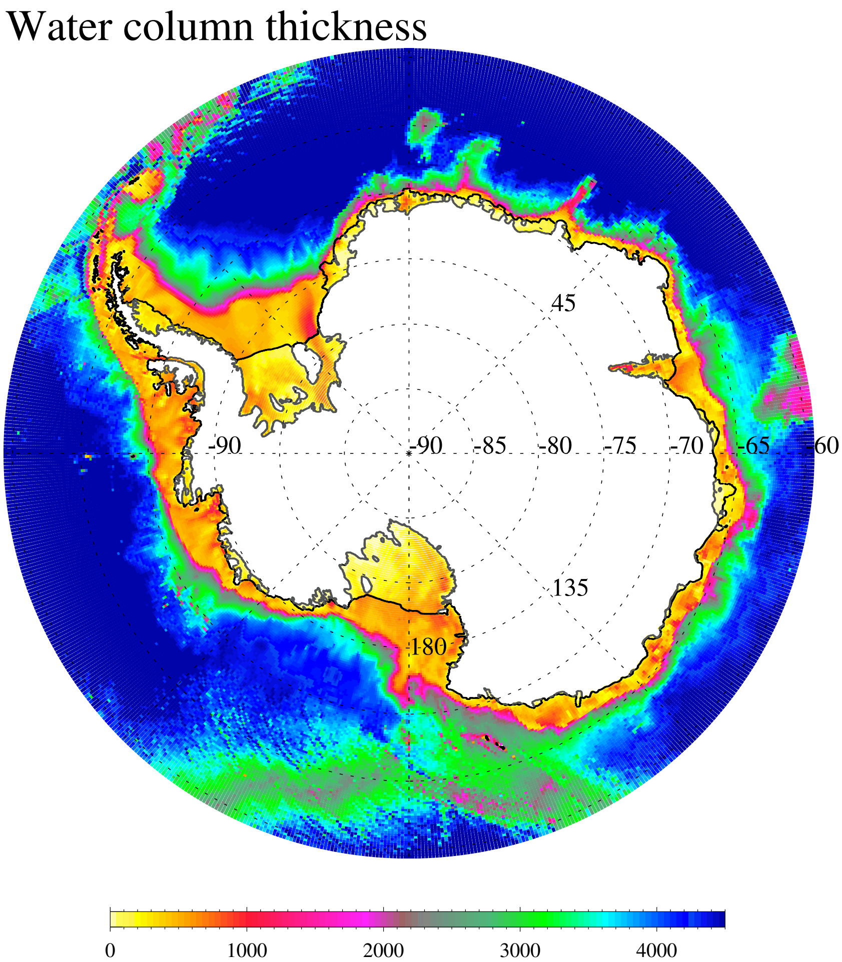

Figure 8: Water column thickness in the Southern Ocean sector of RTopo-1.

3 Summary and Outlook

We have presented a global 1-minute data set for World Ocean bathymetry and Antarctic ice sheet/shelf topography that compiles high-resolution data for the Amery, Fimbul, Filchner-Ronne, Larsen C and George VI Ice Shelves, and for Pine Island Glacier into a synthesis of the S-2004 global 1-minute bathymetry with a BEDMAP-derived panantarctic topography dataset. Wherever fields were derived from original bathymetry surveys (namely in the Larsen A/B area and the southeastern Bellingshausen Sea), we presented data coverage and the resulting gridded fields. Next to maps for bedrock topography and the upper and lower surface heights of the Antarctic ice sheet/ice shelf system, the dataset contains consistent masks for open ocean, grounded ice, floating ice, and bare land surface.

Naturally, this kind of dataset can hardly be complete. We already mentioned that bathymetry under Larsen C ice shelf is not more than an educated guess; contributions to this topic are more than welcome. Other developments in the future might be related to using alternative interpolation schemes to fill the data gaps in Antarctic bedrock topography maps, like for example the streamline-following interpolation scheme presented by Warner and Roberts (2010). Any other input regarding local ice shelf/cavity geometry will be more than welcome and used to update the dataset as soon as possible.

4 Data access

The RTopo-1 dataset is available in NetCDF format in two flavours at doi:10.1594/pangaea.xxxxxx:

1. The complete global 1-minute dataset has been split into two files:
   - RTopo_<version>_data.nc (2.8 GB file size) contains the digital maps for bedrock topography, ice bottom topography, and surface elevation.
   - RTopo_<version>_aux.nc (700 MB file size) contains the auxiliary maps for data sources and the surface type mask.
2. A regional subset that covers all variables for the region south of 50°S is available in RTopo_<version>_50S.nc (780 MB file size).

Datasets for the location of grounding line (RTopo_<version>_gl.asc, 1.7 MB) and coast line (RTopo_<version>_coast.asc, 17.5 MB) are prepared in ASCII format and simply contain two columns for longitude and latitude, separated by blanks.

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