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An improved bathymetric portrayal of the Arctic Ocean: Implications for ocean modeling and geological, geophysical and oceanographic analyses

Martin Jakobsson,[1] Ron Macnab,[2,3] Larry Mayer,[4] Robert Anderson,[5] Margo Edwards,[6] Jörn Hatzky,[7] Hans Werner Schenke,[7] and Paul Johnson[6]

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[1] A digital representation of ocean floor topography is essential for a broad variety of geological, geophysical and oceanographic analyses and modeling. In this paper we present a new version of the International Bathymetric Chart of the Arctic Ocean (IBCAO) in the form of a digital grid on a Polar Stereographic projection with grid cell spacing of 2 × 2 km. The new IBCAO, which has been derived from an accumulated database of available bathymetric data including the recent years of multibeam mapping, significantly improves our portrayal of the Arctic Ocean seafloor. **Citation:** Jakobsson, M., R. Macnab, L. Mayer, R. Anderson, M. Edwards, J. Hatzky, H. W. Schenke, and P. Johnson (2008), An improved bathymetric portrayal of the Arctic Ocean: Implications for ocean modeling and geological, geophysical and oceanographic analyses, *Geophys. Res. Lett.*, *35*, L07602, doi:10.1029/2008GL033520.

1. Introduction and Background

[2] The International Bathymetric Chart of the Arctic Ocean (IBCAO) was first released in provisional form following its introduction at the American Geophysical Union (AGU) fall meeting in 1999 [*Jakobsson et al.*, 2000]. This first release consisted of a Digital Terrain Model (DTM) on a Polar Stereographic projection with a grid cell spacing of 2.5 × 2.5 km. The DTM was compiled from an accumulated database that contained all available bathymetric data at the time including soundings collected during past and modern expeditions as well as digitized isobaths and depth soundings from published maps. Compared to previous bathymetric maps of the Arctic Ocean, the first released IBCAO was based upon a substantially enhanced database, particularly in the central Arctic Ocean [*Jakobsson and Macnab*, 2006]. De-classified echo soundings acquired during US and British submarine cruises between 1958 and 1988 [*Edwards and Coakley*, 2003; *Newton*, 2000] were included as well as soundings from icebreaker cruises conducted by Sweden and Germany at the end of the twentieth century.

[3] Despite all the bathymetric soundings that became available in 1999, there were still large areas of the Arctic Ocean where publicly accessible depth measurements were completely absent. Some of these areas had been mapped by agencies of the former Soviet Union, but their soundings were classified and thus not available to IBCAO. Depth information in these areas was acquired by digitizing the isobaths that appeared on a bathymetric map which was derived from the classified Russian mapping missions, and which was published by the Department of Navigation and Oceanography (DNO) in 1999 [*Naryshkin*, 1999].

[4] Version 1.0 of the IBCAO DTM was introduced at the AGU fall meeting in 2001 [*Jakobsson et al.*, 2000]. The improvements, compared to the provisional version consisted of several small corrections as well as the incorporation of multibeam data from the Norwegian continental slope contributed by the Norwegian Petroleum Directorate, and multibeam data from the Lomonosov Ridge and the Fram Strait obtained from the Alfred Wegener Institute onboard *R/V Polarstern*.

[5] Since the first release, IBCAO has been widely used by scientists and non-scientists for a wide range of applications. It has served as the base bathymetry in numerous ocean circulation modeling experiments [e.g., *Maltrud and McClean*, 2005; *Maslowski and Walczowski*, 2002; *Padman and Erofeeva*, 2004] and it has been incorporated as the standard bathymetry representing the Arctic Ocean in the global 1-minute bathymetric grid assembled by the General Bathymetric Chart of the Oceans (GEBCO) [*Jones*, 2003] as well as in the 2-minute grid ETOPO2 [*U.S. Department of Commerce et al.*, 2006].

[6] Since the beginning of the twenty-first century, several multibeam mapping missions with the *USCGC Healy*, *R/V Polarstern* and *I/B Oden* have been completed that significantly improved our knowledge of the seafloor morphology beneath the perennially ice covered central Arctic Ocean. These surveys include the extensive multibeam mapping of the Gakkel Ridge axial valley during the Arctic Mid Ocean Ridge Expedition (AMORE) [e.g., *Michael et al.*, 2003], several cruises with *USCGC Healy* off the Alaskan margin and in the central Arctic Ocean [e.g., *Gardner et al.*, 2006; *Jakobsson et al.*, 2005], and multibeam surveys of the Fram Strait [*Klenke and Schenke*, 2002]. The multibeam data from these mapping missions have now been made available and, together, all the used multibeam data cover approximately 6% of the new IBCAO DTM area. In addition, cross track analysis between data from the previously de-classified US

[1]Department of Geology and Geochemistry, Stockholm University, Stockholm, Sweden.
[2]Geological Survey of Canada, Dartmouth, Nova Scotia, Canada.
[3]Retired.
[4]Center for Coastal and Ocean Mapping, University of New Hampshire, Durham, New Hampshire, USA.
[5]Science Applications International Corporation, Poulsbo, Washington, USA.
[6]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, Hawaii, USA.
[7]Alfred Wegener Institute, Bremerhaven, Germany.

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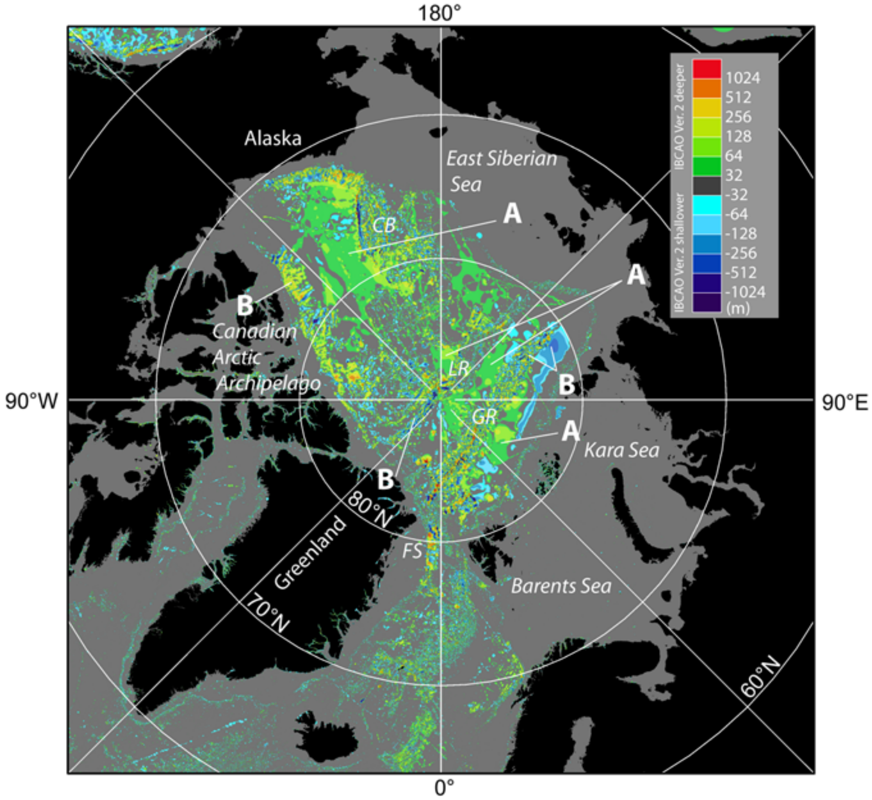

Figure 1. Map showing the differences between IBCAO Version 2.0 and 1.0 calculated in meters by subtracting the version 2.0 DTM from the version 1.0. As the depths are represented with negative values in the IBCAO DTM, negative values in this difference map show areas where version 2.0 is shallower. A indicates abyssal plains that are systematically deeper by 50–60 m (see discussion on US Navy submarine data); B indicates areas where contours from the 1999 DNO map have been replaced by isobaths extracted from the later more detailed version published 2001. CG = Chukchi Borderland; FS = Fram Strait; GR = Gakkel Ridge; LR = Lomonosov Ridge.

Navy submarine cruises and single and multibeam data from icebreaker tracks in the flat Canada Abyssal Plain revealed systematic depth errors of the submarine soundings due to erroneous assumptions of sound speed in the time-depth conversion. The new multibeam data together with applied corrections of the time-depth conversion scheme of the US Navy submarine soundings warranted a new IBCAO compilation. The morphological portrayal of several submarine ridges such as the Lomonosov Ridge, Gakkel Ridge, Northwind Ridge, the Chukchi Plateau and Morris Jessup Rise are enhanced in the new version as well as the oceanographically critical Fram Strait. The application of a proper time-depth conversion of the US Navy submarine soundings resulted in a significant reduction of visible track line artifacts and systematic depth changes of the Arctic Ocean deeper abyssal plains. This paper presents the new IBCAO Version 2.0 and discusses some of the potential implications of the improved portrayal of the Arctic Ocean seafloor for geological, geophysical and oceanographic analyses.

2. Methods

[7] The main work of mixing and blending historical and contemporary bathymetric data consists of checking the depth soundings for inconsistencies (remove outliers etc.) and deciding where digitized contours from bathymetric maps are required due to lack of soundings. The IBCAO compilation process relies on GIS tools to investigate how the individual bathymetric data sets optimally can be “stitched” together. Filtering and gridding algorithms are subsequently used to create a coherent grid from the assimilated bathymetric data. The methods applied to assemble the final IBCAO grid on Polar Stereographic projection with grid cell spacing of 2 $\times$ 2 km and source distribution maps are shown in the auxiliary material.[1]

3. Results and Discussion

3.1. General Comparison Between IBCAO Version 2.0 and 1.0

[8] It is not easy to create a general overview that visualizes the improvements in IBCAO Version 2.0 compared to Version 1.0. The enhancements are best shown by zooming in on selected regions. However, before doing so we will briefly investigate a map showing the depth differences between Version 1.0 and 2.0 expressed in meters (Figure 1). Four striking points may be highlighted:

[9] 1. The deep abyssal plains are systematically ca. 50–60 m deeper in the new IBCAO.

[10] 2. The largest differences between the new and old IBCAO are mainly associated with the incorporation of multibeam data (compare Figure 1 and Figure S1 in the auxiliary material).

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033520.

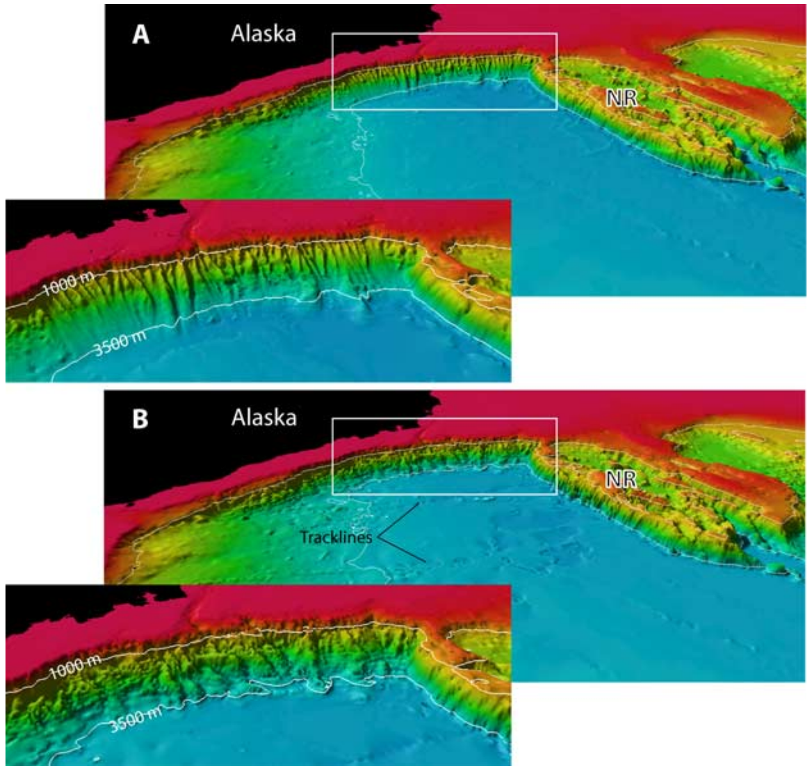

Figure 2. 3D-view of the Canada Slope and Northwind Ridge. (a) The new IBCAO which has been significantly improved through the use if multibeam data; (b) The old IBCAO based on single beam soundings and digitized contours. The improvements are clearly seen in the zoomed in area. For example, note the superior definition of regular erosional gullies carved into the slope of the northern Alaskan Continental Margin. A comparison between the full resolution multibeam data and IBCAO Version 2.0 is shown in Figure S3 in auxiliary material. NR = Northwind Ridge.

[11] 3. The continental slope of the Canadian Arctic Archipelago and the Lomonosov Ridge flanks on the Greenland side show large depth differences.

[12] 4. The rise off the Kara Sea Margin is more pronounced as shown by a bias towards shallower depths in the new IBCAO.

[13] The deeper abyssal plains are explained by the discovery of erroneous sound speed corrections applied to the U.S. Navy submarine data. This will be discussed further below as well as some of the more important regional changes. The depth differences clearly noticeable along the margin of the Canadian Arctic Archipelago and Lomonosov Ridge are associated with the removal of contours from the DNO map published in 1999 [*Naryshkin*, 1999] in exchange for contours from the later updated DNO map published in 2001 [*Naryshkin*, 2001]: the contours from the new map were a much better match to single beam soundings from these regions. The incorporation of contours from the DNO 2001 map also explains the depth changes along the Gakkel Ridge in the eastern sector of the Eurasian Basin outside of the AMORE survey area, as well as the more pronounced rise off the Kara Sea margin.

3.2. US Navy Submarine Data Revisited

[14] Echo soundings collected prior to 1988 by US Navy nuclear submarines were digitized from analogue Precision Depth Recorder's (PDR) records. The bathymetric data acquisition was done differently during the later nuclear submarine cruises within the SCICEX program that started 1993: more modern PDRs had automated digital bottom trackers that allowed the depth soundings to be saved directly to disk (D. Bentley, U.S. Arctic Submarine Laboratory, personal communication, 2004). When all these submarine data were included in the first version of IBCAO, the information provided to the compilers was that all depths referred to a nominal sound speed of 1500 m/s. Therefore, Carter's tables were applied in the IBCAO processing scheme to convert depths to "corrected meters" assuming that all data were referred to 1500 m/s. Cross-over errors were detected, but assumed to be the result of the known, poorly constrained navigation of submarines under ice. The observed cross-over differences in the flat Canada Abyssal Plain were on the order of 3 %, not a particularly large difference considering that older deep water echo sounders are accurate to approximately 1–2% of the depths. However, as additional single and particularly multibeam data from the icebreakers were added to the IBCAO database in the process of updating the Beta version, the cross-over errors were found to be systematic. This led to a thorough metadata analysis which gave the following results:

[15] 1. U.S. Navy submarine data from 1957–1982 were in fact collected using 800 fath/sec (about 1463 m/s as 1 fathom = 1.8288 m)

[16] 2. The U.S. Navy SCICEX cruises were also found to be collected using 800 fath/sec.

[17] 3. U.S. Navy submarine data from 1983–1988 were collected using 820 fath/sec (about 1500 m/s)

[18] Soundings from the *USCGC Polar Star* were first used in the cross over analysis with the submarine data. However, to complicate the matter further, we found that

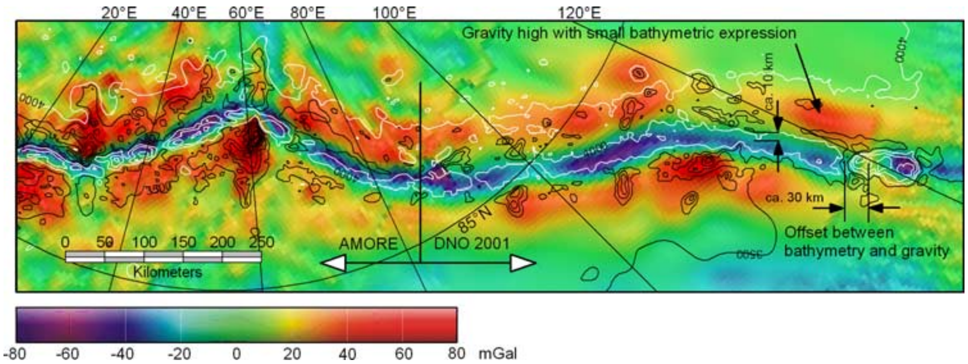

Figure 3. Free air gravity compared with bathymetric contours derived from IBCAO Version 2.0. Depth contours deeper than 4000 m are shown in white while shallower are shown in black. There are 500 m depth intervals between contours.

the *USCGC Polar Star* depths retrieved from the USGS Infobank, which had a sound speed of 1500 m/s listed, in fact were referred to a sound speed of 1463 m/s! When all the erroneous assumptions of applied sound speeds were sorted out, a significant reduction of cross-over errors was achieved. Instead of using Carter's tables, all the submarine data have been recalculated so that the depths are referred to a harmonic mean sound speed of 1463 m/s. This is generally in close agreement with harmonic mean sound speeds calculated from CTD stations from the central Arctic Ocean. Figure 2 compares shaded relief renditions of the Canada Abyssal Plain and northern Alaskan Continental Slope based on new and old versions of IBCAO.

3.3. Beaufort Sea

[19] One striking improvement of the Arctic Ocean sea floor morphological portrayal is found on the continental slope off northern Alaska. The systematic multibeam surveys by *USCGC Healy* and *R/V Palmer* here together reveal regular erosional gullies and down-slope deposition of sediments even after the multibeam data have been reduced to the IBCAO grid resolution of 2 $\times$ 2 km (Figure 2). It is most likely that this characteristic slope morphology continues further to the east of the multibeam mapped areas until the slope changes its characteristics due to the vast sediment deposition from the Mackenzie River area [*Grantz et al.*, 1990]. The grid derived in this area from sparse single beam soundings and hand-drawn bathymetric contours hints that this is the case, although the lack of detail makes for a blurred image (Figure 2).

[20] The slope of the Northwind Ridge of the Chukchi Borderland has been mapped with multibeam over the last five years. This is primarily due to the systematic *USCGC Healy* surveys for the purpose of delineating the foot of the slope for a potential US extension of the continental shelf definition under the United Nations Convention of the Law of the Sea (UNCLOS) Article 76 [*Gardner et al.*, 2007]. The new multibeam data show that Northwind Ridge's slope towards the deep Canada Abyssal Plain is extremely steep; several sections have an inclination of >10° over a depth difference of 3000 m.

3.4. Lomonosov Ridge

[21] The Lomonosov Ridge stretches across the central Arctic Ocean dividing it into the Amerasian and Eurasian Basins. The ridge's bathymetry has long been discussed among oceanographers, given its impact on the circulation and water mass properties of the Arctic Ocean [e.g., *Aagaard*, 1981]. In the Amerasian Basin, the deep bottom waters close to the Lomonosov Ridge have been found to be slightly colder and less saline than the corresponding waters near the Alaskan Continental Margin. A deep water overflow across the central Lomonosov Ridge has been suggested as an explanation for the observed water mass differences [*Jones et al.*, 1995] and the previously released IBCAO versions contained a pronounced channel at about 88°25′N, 150°E with a sill depth of about 2500 m. However, the bathymetry of IBCAO was here based on the Russian bathymetric contour map published in 1999 [*Naryshkin*, 1999] as there were at the time no soundings available from the apparent sill area. In 2005, the critical area was mapped with multibeam during the Healy-Oden Trans-Arctic Expedition (HOTRAX) [*Darby et al.*, 2005]. The new bathymetric data showed a maximum sill depth of about 1870 m and the hypothesized deep water exchange from the Eurasian Basin side to the Amerasian could not be confirmed [*Björk et al.*, 2007]. Instead, a flow of deep water from the Amerasian to the Eurasian Basin was observed across the 1870 m passage [*Björk et al.*, 2007]. The new IBCAO Version 2.0 contains the HOTRAX multibeam bathymetry acquired from *USCGC Healy* as well as the swath bathymetry from the SCICEX 1999 cruise with *USS Hawkbill* [*Edwards and Coakley*, 2003].

3.5. Gakkel Ridge and Fram Strait

[22] Gravity anomalies measured over the World oceans have been shown to correlate with the seafloor topography in the longer wavelengths of about 15 to 200 km [*Smith and Sandwell*, 1997]. This correlation is not always straight forward due to, for example, variation in sediment cover and crustal density. However, prominent features like seamounts, oceanic ridges and spreading ridge's axial valleys generally show strong correlations with gravity anomalies. The Arctic Gravity Project (ArcGP) released a gravity compilation of the Arctic Ocean assembled from airborne, surface, submarine and satellite measured gravity [*Kenyon and Forsberg*, 2001]. The free air 5-minute grid, updated by the ArcGP in 2006, has been used in the IBCAO compilation process to check for potentially unmapped features or offsets of mapped features, specifically in regions with sparse bathymetric data coverage. This approach is particularly valuable when the gravity data source is completely independent from the bathymetric mapping, e.g. airborne or satellite gravity. The Gakkel Ridge axial valley, from the Fram Strait's northern part to approximately 86°E, was mapped with multibeam

during the AMORE 2001 expedition [*Michael et al.*, 2003]. There are very few available bathymetric soundings eastward of 86°E and, thus, IBCAO in this area relies on contours and spot soundings from the DNO map published 2001 (Figure S1, auxiliary material). The IBCAO bathymetry of the Gakkel Ridge generally shows a good fit with the ArcGP free air gravity (Figure 3). However, there are some sections where the gravity hints at potential problems; specifically where the DNO map has been used (Figure 3). Between about 110°E and 120°E, the axial valley appears to be offset approximately 10 km to the north compared to the pronounced gravity low. The gravity high at 120°E 81°40′N does not correlate with the bathymetric ridge-like feature crossing and interrupting the axial valley about 30 km further to the west (Figure 3). These examples pinpoint some areas of the Arctic Ocean where future mapping could significantly improve our bathymetric database.

4. Conclusions

[23] We have compiled a new improved version of the International Bathymetric Chart of the Arctic Ocean (IBCAO) DTM: Version 2.0. Even if the new IBCAO is far superior compared to its predecessors, it is not flawless: it retains certain errors such as track line artifacts, terracing from the use of contours, and in areas where there are no available soundings, it relies on contours from maps with sometimes no source information, etc. Only when the entire area has been mapped with multibeam will it be possible to create a near-perfect bathymetric model of the Arctic Ocean. Products based on the new IBCAO Version 2.0, such as the digital grid in various projections, maps and derived isobaths, may be downloaded from www.ibcao.org.

[24] **Acknowledgments.** We thank all contributors to IBCAO. Multibeam surveys with the USCGC HEALY on cruises HEALY0302, HEALY0405, and HEALY0703 and with the R/V KILO MOANA in the Gulf of Alaska were funded through the National Oceanic and Atmospheric Administration grant NA0NOS4001153. Alfred Wegener Institute (AWI) is thanked for the continued logistic and financial support of conducting multibeam surveys with the research icebreaker "Polarstern". The icebreaker Oden multibeam cruises were organized by the Swedish Polar Research Secretariat and financial support was received from the Swedish Research Council (VR), the Swedish Royal Academy of Sciences through grants by the Knut and Alice Wallenberg Foundation, and the Swedish Maritime Administration. This article is a contribution from the Bert Bolin Centre for Climate Research at Stockholm University.

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R. Anderson, Science Applications International Corporation, 26279 Twelve Trees Lane, Poulsbo, WA 98370, USA.

M. Edwards and P. Johnson, Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, 1680 East-West Road, POST 815, Honolulu, HI 96822, USA.

J. Hatzky and H. W. Schenke, Alfred Wegener Institute, Van-Ronzelen-Straße 2, D-27568 Bremerhaven, Germany.

M. Jakobsson, Department of Geology and Geochemistry, Stockholm University, Svante Arrhenius väg 8c, SE-106 91 Stockholm, Sweden. (martin.jakobsson@geo.su.se)

R. Macnab, Geological Survey of Canada, 11 Lyngby Avenue, Dartmouth, NS, Canada B3A 3T6.

L. Mayer, Center for Coastal and Ocean Mapping, University of New Hampshire, 24 Colovos Road, Durham, NH 03824, USA.