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The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0

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[1] The International Bathymetric Chart of the Arctic Ocean (IBCAO) released its first gridded bathymetric compilation in 1999. The IBCAO bathymetric portrayals have since supported a wide range of Arctic science activities, for example, by providing constraint for ocean circulation models and the means to define and formulate hypotheses about the geologic origin of Arctic undersea features. IBCAO Version 3.0 represents the largest improvement since 1999 taking advantage of new data sets collected by the circum-Arctic nations, opportunistic data collected from fishing vessels, data acquired from US Navy submarines and from research ships of various nations. Built using an improved gridding algorithm, this new grid is on a 500 meter spacing, revealing much greater details of the Arctic seafloor than IBCAO Version 1.0 (2.5 km) and Version 2.0 (2.0 km). The area covered by multibeam surveys has increased from ∼6% in Version 2.0 to ∼11% in Version 3.0. **Citation:** Jakobsson, M., et al. (2012), The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0, *Geophys. Res. Lett.*, *39*, L12609, doi:10.1029/2012GL052219.

1. Introduction

[2] For generations there was only speculation as to what lay beneath the frozen sea ice of the high Arctic. Even towards the end of the 19th century, maps of the region depicted large continental land-masses beneath the ice. Then, from a handful of lead line soundings acquired during the *Fram Expedition* 1893–1896, Fridtjof Nansen compiled a bathymetric map that portrayed the central Arctic Ocean as a single deep featureless basin [*Nansen*, 1907]. While Nansen's map still represents the single largest step forward in Arctic Ocean bathymetric mapping, subsequent maps successively revealed a much more complex bathymetric landscape formed from the tectonic evolution of the Arctic Basin, ocean currents and glacial history [e.g., *Atlasov et al.*, 1964; *Johnson et al.*, 1979; *Perry et al.*, 1986]. In 1997, one century after the *Fram Expedition*, the International Bathymetric Chart of the Arctic Ocean (IBCAO) project was initiated in St Petersburg, Russia. The project had a single major objective: to collect all available bathymetry data for the compilation of the most up-to-date bathymetric portrayal of the Arctic Ocean seafloor. An Editorial Board was established consisting of representatives from the circum-

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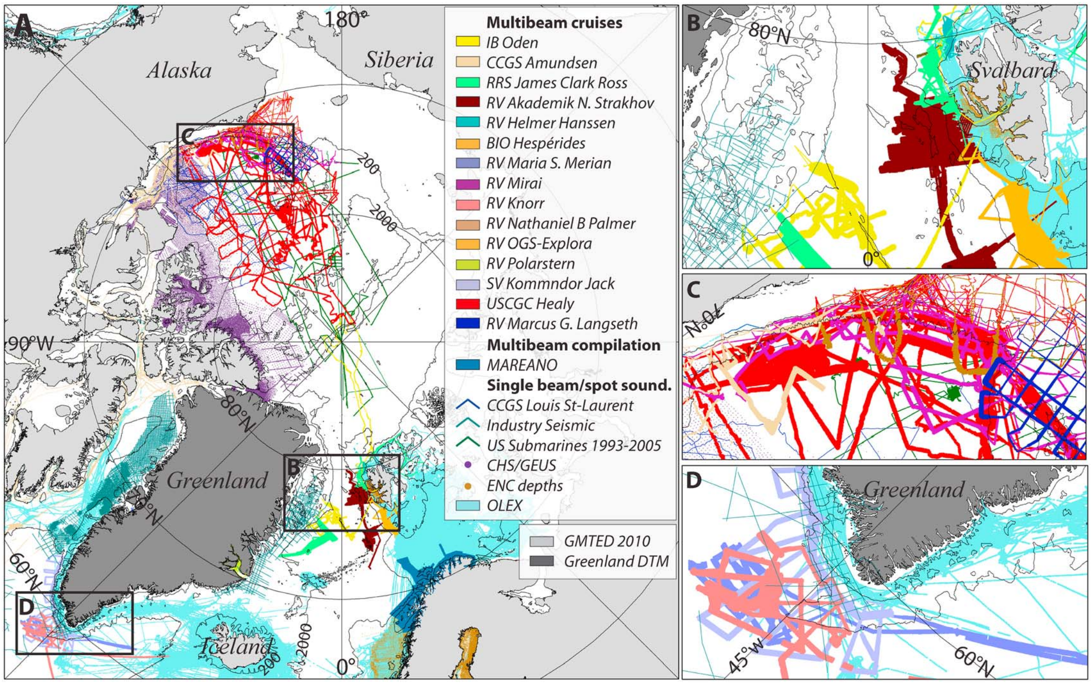

Figure 1. (a) Bathymetric data new to the IBCAO 3.0 compilation. A complete list with references to each multibeam survey or set of surveys is found in the auxiliary material. (b–d) Close-up maps of the areas where the newly included multibeam surveys are most concentrated.

Arctic Ocean nations plus Germany and Sweden. Three years later, the first bathymetric compilation from IBCAO was released to the public after an introduction at the AGU Fall Meeting in 1999 [*Jakobsson et al.*, 2000]. This first compilation consisted of a Digital Bathymetric Model (DBM) with grid cell spacing of 2.5 × 2.5 km on a polar stereographic projection. In 2008, Version 2.0 of the IBCAO DBM was completed at a finer grid spacing of 2 × 2 km [*Jakobsson et al.*, 2008]. This version was compiled from an expanded bathymetric database. In addition to the soundings acquired from submarines, icebreakers and from the pack ice, and depth contours digitized from published maps that were used in Version 1, Version 2.0 also included some multibeam sonar datasets. In IBCAO Version 2.0, only about 6% of the area was compiled using multibeam data.

[3] During the *First Arctic-Antarctic Seafloor Mapping Meeting* held at Stockholm University in May 2011, it became obvious that a wealth of new bathymetric data had become available since the 2008 compilation of IBCAO 2.0 (Figure 1). Numerous bathymetric mapping campaigns in the Arctic Ocean have recently been carried out for scientific purposes and as a result of Arctic coastal states' interests in establishing extended continental shelves under the United Nations Convention on the Law of the Sea (UNCLOS) Article 76 [*Marcussen and Macnab*, 2011; *Mayer et al.*, 2010]. Vast amounts of single beam data have also been collected in the Arctic region using the *Olex* seabed mapping system (www.olex.no). Furthermore, since the release of IBCAO Version 2.0, single beam echo soundings from US nuclear submarine cruises between 1993–2005 have been declassified and the Geological Survey of Denmark and Greenland has released soundings from industry seismic surveys around Greenland for IBCAO use (Figure 1).

[4] Given the availability of these new data sources, a new IBCAO Editorial Board was established for the purpose of compiling IBCAO Version 3.0. Here we describe the compilation of IBCAO 3.0, the new bathymetric data, and the major improvements that have implications for geological, geophysical and oceanographic analyses as well as for numerical modeling applications. IBCAO 3.0 will be the new standard bathymetric data set for the Arctic Ocean. Applying an enhanced gridding algorithm, the IBCAO 3.0 DBM is gridded from a substantially enlarged source database. While the base grid is still compiled at a resolution of 2 × 2 km on a polar stereographic projection, the higher resolution source data (primarily multibeam and Olex) are merged on to the base grid at a resolution of 500 × 500 m in a final step using the remove-restore method [e.g., *Hell and Jakobsson*, 2011; *Smith and Sandwell*, 1997]. This approach develops a final 500 × 500 m size grid that does a much better job of preserving details in regions where source data are denser than in previous versions of IBCAO. On a broader scale, IBCAO 3.0 is likely to contribute to substantially improved insight on the geological processes responsible for the formation of the Arctic Ocean basin. The higher resolution data resolve canyons along the continental slopes as well as some of the more prominent glacial features that were not visible in previously released versions. While the area covered by multibeam surveys has increased from ∼6% in Version 2.0 to ∼11% in Version 3.0, there are still huge areas of the Arctic Ocean remaining to be mapped before we reach the same level of

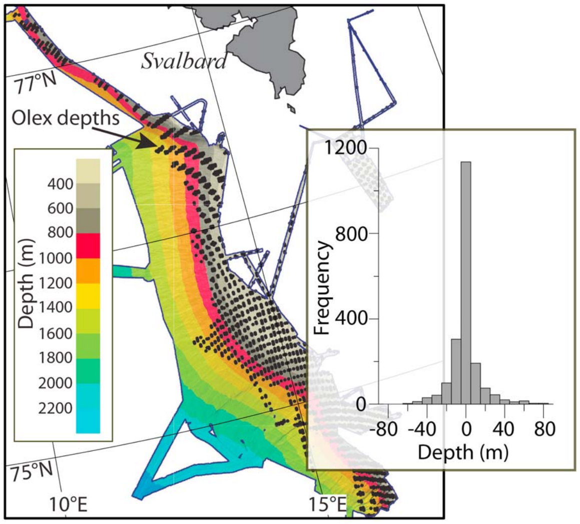

Figure 2. (a) Map showing the area south of Spitsbergen where depths from the multibeam survey of Italian *RV OGS-Explora* and Spanish *BIO Hespérides* are compared with depths from the *Olex* sounding database. The black dots are the soundings from *Olex* selected for comparison as they are located closer than 50 m from nodes of the 200 × 200 m resolution multibeam grid. (b) Histogram showing the calculated depth differences.

topographic characterization as that of the Moon or Mars [*Mazarico et al.*, 2012].

2. Methods

2.1. Bathymetric Source Data

[5] The bathymetric data new to IBCAO 3.0 are shown in Figure 1 and references to each of the multibeam surveys, or group of surveys, are found in the auxiliary material.[1] There are only a handful of research icebreakers with multibeam systems capable of operating within the heavy pack-ice-covered central Arctic Ocean. Along the edges of the pack ice, however, several multibeam surveys by ice strengthened research vessels have made substantial contributions [e.g., *Dowdeswell et al.*, 2010; *Hogan et al.*, 2010; *Pedrosa et al.*, 2011; *Rebesco et al.*, 2011; *Westbrook et al.*, 2009; *Zayonchek et al.*, 2010].

[6] In addition, there is now an additional set of declassified bathymetric soundings acquired by U.S. Navy submarines released from cruises between 1993–2005 (Figure 1). These soundings provide depth information in several sparsely mapped areas but are only partly used in the Canada Basin. The reason for this is that U.S. and Canadian surveys conducted with the icebreakers *USCGC Healy* and *CCGS Louis St-Laurent*, carried out to establish the limits of the extended continentals shelf, are dense enough to constrain the flat abyssal plain of the Canada Basin.

[7] The seafloor mapping, navigation, and fishery system *Olex* (http://www.olex.no) is manufactured to interface with both single and multibeam echo sounders. Depths are collected by the system and merged into a locally stored depth database. Many *Olex* users share their data through *Olex* which hosts a continuously growing depth database. Because the majority of *Olex* users are fishermen there is a strong bias in the database coverage towards good fishing areas on the continental shelves (Figure 1). For IBCAO 3.0, a snapshot of the *Olex* database was captured in October 2011. Depths were retrieved as median values on a 0.12 × 0.12 arc minute grid. Fishermen rarely calibrate their echo sounders (by measuring speed of sound in the water column). Instead, a nominal sound speed based on experience is commonly applied in the conversion between the echo travel-time to depth. This implies that there is an uncertainty in the *Olex* depth database regarding the applied sound speeds, though typically the sound speed used is between 1460 and 1480 m/s (O. B. Hestvik, *Olex*, personal communication, 2011).

[8] To investigate travel time to depth issues, we compared depth values from the *Olex* sounding database in the area off the Storfjorden Trough, south of Spitsbergen, where the Italian *RV OGS-Explora* and Spanish *BIO Hespérides* carried out collaborative multibeam surveys [*Pedrosa et al.*, 2011] (Figure 2). This area was chosen for the comparison because the multibeam surveys are of high quality and carried out with regular sound speed control [*Pedrosa et al.*, 2011]. Individual depths from the *Olex* database were paired with depths from the provided 200 × 200 m multibeam grid for comparison. The criteria used to form a pair of depth values was that the two must be located closer than 50 m from each other. The map in Figure 2 shows the *Olex* depths paired with multibeam depths; 1999 depth values were selected for comparison. The mean difference $(\frac{1}{n}\sum_{i=1}^{n}(D_{Olex} - D_{multibeam})$; *depths are negative numbers*) is -4.9 m, suggesting a slight bias towards deeper *Olex* depths. However, considering that the mean depth of the compared values is 640 m, the mean difference is less than 1% of the water depth, which is better than the accuracy expected from a standard non-survey type single beam echo sounder. The distribution of depth differences does not show a clear bias above what can be considered outside of the accuracy of standard single beam echo sounders (Figure 2). Therefore, we left the *Olex* depth database as originally extracted.

[9] Numerous seismic reflection profiles have been collected by industry along Greenland's eastern and western continental margins for oil and gas exploration. Through the Geological Survey of Denmark and Greenland (GEUS), single beam soundings acquired along with the seismic reflection profiles have been released to be used in IBCAO 3.0 (Figure 1). For all surveys the metadata describes whether the echo sounding depths are in corrected meters, i.e., depths derived using a measured sound velocity profile of the water column, or referred to a nominal sound speed. In the latter case, 1500 m/s was used as a standard. Of the 43 surveys used, 18 contained uncorrected depths that were recalculated to refer to a harmonic mean sound velocity of 1463 m/s; a velocity that adjusted the depth values to fit well with sound speed corrected surveys as determined from track line cross-overs.

[10] Additional bathymetry were collected as part of the Norwegian MAREANO mapping program (http://www.mareano.no). The high quality MAREANO multibeam

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL052219.

compilation has been provided to IBCAO at a uniform resolution of 25 × 25 m on a Universal Transverse Mercator (UTM) projection. As will be shown in the result section, these data make a huge improvement in the depiction of the Norwegian shelf as compared to the previously released IBCAO 2.0.

[11] Depths extracted from Electronic Navigational Charts (ENCs) have been provided by several countries' hydrographic offices to the International Hydrographic Organization (IHO) for use in regional mapping projects affiliated with the General Bathymetric Chart of the Oceans (GEBCO). Because IBCAO is one of GEBCO's affiliated regional mapping projects all the ENC extracted depths within the compilation area have been used in Version 3.0.

2.2. Land Topography

[12] Narrow fjords, bays, or islands that only are slightly wider than the final IBCAO DBM resolution, in our case 500 m, are often difficult to preserve. This may, to some extent, be helped by including land topography in the full gridding process as it guides the gridded surface. The recently released Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) [*Danielson and Gesch*, 2011] has been used in IBCAO 3.0, replacing the GTOPO30 [*U.S. Geological Survey*, 1997] used in IBCAO 2.0. Over Greenland the approximately 2000 × 2000 m resolution Digital Elevation Model (DEM) published by *Ekholm* [1996] is still used.

2.3. Gridding Algorithm and Source Identification

[13] The gridding algorithm used in IBCAO 3.0 is a further improvement of that developed to compile IBCAO 2.0 [see *Jakobsson et al.*, 2008]. The main improvement consists of adding the source data with a spatial horizontal resolution approximately equal to, or better than, 500 m in a final step using the remove-restore method [e.g., *Hell and Jakobsson*, 2011; *Smith and Sandwell*, 1997]. Further details about the gridding algorithm are described in the auxiliary material. Along with the IBCAO Version 3.0 DBM, a source identification grid (SID) has been compiled (auxiliary material). At a resolution of 2000 × 2000 m, this SID allows the user to identify the grid cells that are constrained by source data and not interpolated. The SID contains six codes distinguishing between data sources categorized as land, multibeam, single beam, Olex, contours from digitized maps, and other gridded bathymetric compilations (auxiliary material).

3. Results and Discussion

[14] The IBCAO 3.0 DBM is, from several perspectives, best described by comparison to the preceding Version 2.0. One general, but striking, difference with 3.0 is the higher resolution of 500 × 500 m in all areas where the source data density permits compilation at this scale. This is the case in the shelf regions around the North Atlantic where *Olex*, MAREANO, and the released single beam soundings from industry seismic data add substantially to the bathymetric source database (Figure 1). For example, it is possible in Version 3.0 to distinguish seafloor imprints from the paleo-ice streams draining the Scandinavian Ice Sheet during past glacial periods (Figure 3). Glacigenic features now visible that were barely seen in 2.0 include mega-scale glacial lineations (Figure 3), lateral and terminal moraines, and large iceberg plow marks. The full resolution MAREANO multibeam grid with 25 × 25 m cells provides an additional level of detail and can be requested directly from the MAREANO project (http://www.mareano.no).

[15] Denmark, the U.S., and Canada all agreed to contribute their Arctic Ocean UNCLOS Article 76 bathymetric surveys to IBCAO 3.0. The continental slope along southern Greenland, the Barrow Margin and the perimeter of the Chukchi Cap is, for this reason, better mapped in Version 3.0 (Figure 1). In Version 2.0, depths of the deeper parts of Canada Basin were corrected after it was found that several of the declassified single beam datasets from nuclear submarines had not been treated properly due lack of metadata information regarding applied sound speeds [*Jakobsson et al.*, 2008]. Yet another change, albeit smaller than the previous correction, is imposed in Version 3.0 owing to the UNCLOS surveys by icebreakers *USCGC Healy* and *CCGS Louis St-Laurent.* GPS-based navigation on the icebreakers is better than the inertial navigation on submerged nuclear submarines. The submarine soundings were thus removed from the gridding procedure in the deep Canada Basin, but only after being investigated for previously unmapped shoals. As a result of this update, the flat Canada Basin seafloor deeper than 3500 m is, on average, approximately 64 m deeper in Version 3.0 than in 2.0 (auxiliary material). However, the average depth adjustment due to the new data in the region deeper than 3500 m is less than 2%, estimated along a bathymetric profile across the entire basin (auxiliary material). Canyons formed in the slopes offshore of the Arctic continental shelves are usually not precisely captured in DBMs gridded from randomly oriented sparse single beam tracklines and/or digitized bathymetric contours. This became evident along the continental slope of northern Alaska when IBCAO 1.0 was updated by incorporation of multibeam surveys from this area [*Jakobsson et al.*, 2008]. Cartographers who specialized in compiling bathymetric maps commonly interpret slope-canyon systems from sparse depth soundings using their geological knowledge and conceptually drawn depth contours in order to illustrate the canyons' anticipated morphology. IBCAO 3.0 is still gridded from digitized depth contours where no other data are available. One should keep in mind that, in these regions, the precise locations of portrayed bathymetric features, such as canyons, may deviate from reality. Contours are used from six published maps [*Cherkis et al.*, 1991; *Intergovernmental Oceanographic Commission et al.*, 2003; *Matishov et al.*, 1995; *Naryshkin*, 1999, 2001; *Perry et al.*, 1986], although large areas relying on contours in Version 2.0 can now be gridded directly from single or multibeam data (see SID in the auxiliary material). The overall IBCAO goal is to minimize the use of digitized bathymetric contours in the gridding process.

[16] The approach of first gridding all the data while constraining output values to not exceed 0.1 m depth, and subsequently adding the topography in a separate step, in combination with the higher resolution GMTED2010, improved the coastline constraint dramatically in Version 3.0 compared to 2.0 (Figure 3). This makes IBCAO much more useful for nearshore applications ranging from simple

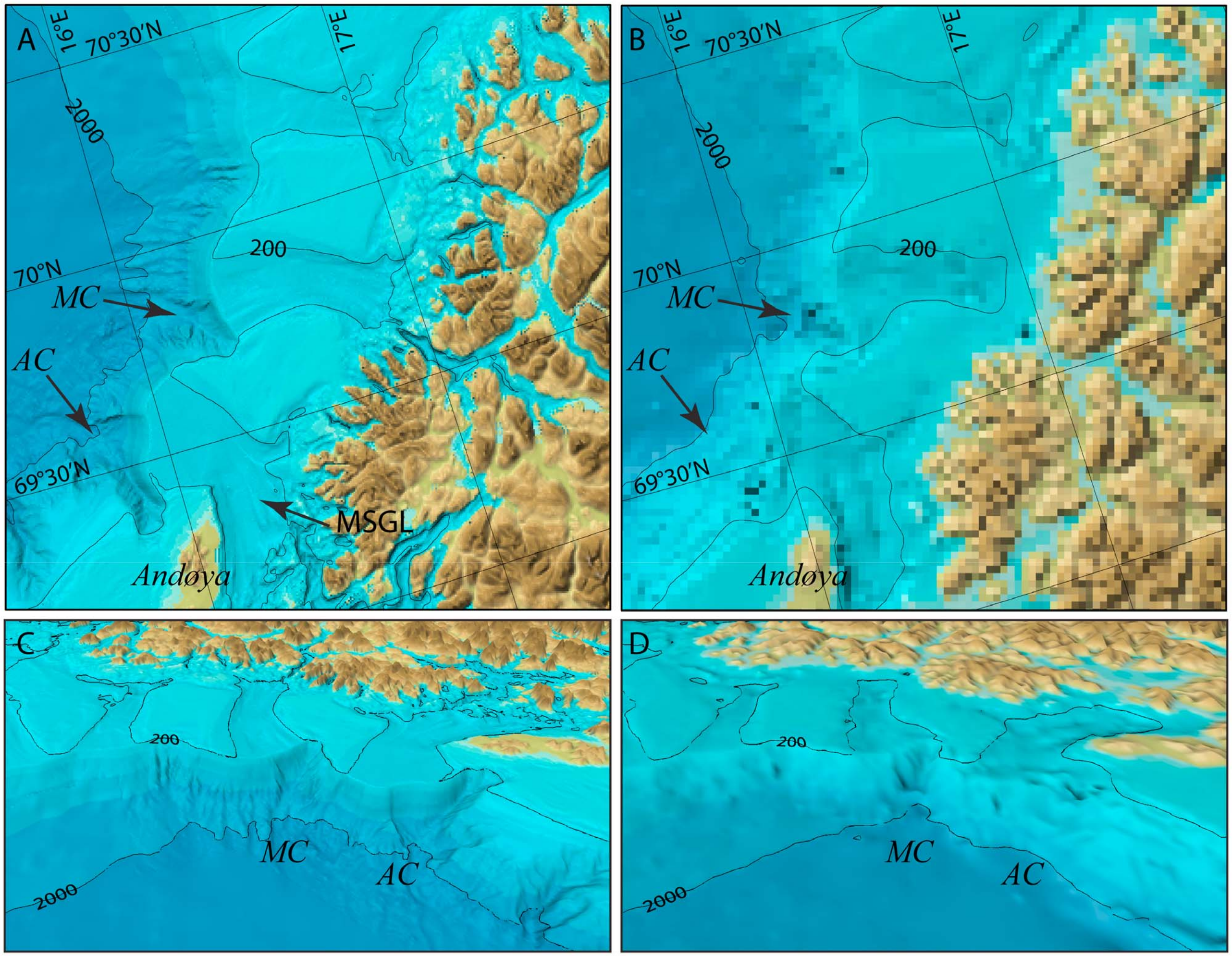

Figure 3. Comparison between IBCAO (a) 3.0 and (b) 2.0 in the area of northwestern Norwegian continental margin where the MAREANO multibeam data makes a significant difference. Note the difference in portrayal of canyons along the slope; even the large Andøya Canyon (AC) and Malangen Canyon (MC) are barely visible (d) in IBCAO 2.0 compared to (c) in IBCAO 3.0. MSGL = Mega Scale Glacial Lineations.

map making to regional ocean circulation modeling [e.g. *Lu et al.*, 2010].

4. Conclusions and Outlook

[17] Mapping of the world oceans' seafloor has resulted in some of the major breakthroughs in our understanding of earth system processes. The mapping of oceanic rift zones by *Heezen* [1960] led *Hess* [1962] directly to the formulation of the concept now known as seafloor spreading. Similarly, it was after submarine ridges and basins appeared on Arctic Ocean maps towards the end of the 1950s that geological provinces could be defined, allowing evaluation of hypotheses concerning the opening of the Arctic Basin [*Dietz and Shumway*, 1961; *Heezen and Ewing*, 1961].

[18] Nuclear submarines have collected echo sounding data ever since they began to explore the Arctic Ocean during the Cold War. In 1993 the U.S. Navy delighted the scientific community by committing to a trial cruise for what would become the Science Ice Exercise Program (SCICEX) [*Edwards and Coakley*, 2003; *Newton*, 2000]. Bathymetric mapping by nuclear submarines and our most powerful icebreakers have been instrumental in producing our current view of the perennially sea ice covered central Arctic Ocean seafloor. In addition, new innovative methods to map in severe pack ice are beginning to emerge, such as echo sounding from hovercraft and the deployment of autonomous drifting echo sounding buoys [*Hall and Kristoffersen*, 2009].

[19] As new data comes in we will continue to update the view of the Arctic Ocean seafloor through IBCAO, however, the pace at which its central part is currently mapped is much too slow for the scientific community's need for a better bathymetric portrayal so critical for oceanographic, geological, geophysical and biological research and applications. The seafloor has a profound influence on numerous processes not obvious at a first glance. Its role in sea ice formation and evolution, which recently has been shown using IBCAO 2.0, may serve as one such example [*Nghiem et al.*, 2012]. Even considering a scenario where sea ice continues its declining trend that may eventually lead to sea-ice free summers [*Wang and Overland*, 2009], the short Arctic summer period (and possibility of some ice hazard) will severely limit the pace of Arctic mapping. Large coordinated

efforts as well as new innovative mapping methods adapted to the harsh Arctic Ocean environment are therefore needed. The IHO contribution with depths extracted from ENCs serve as one good example of such coordinated effort. The "crowd source" data from *Olex* have shown that a collective is capable of producing results far beyond what could be imagined by the mapping community!

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