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A comparison between GEBCO Sheet 5.17 and the International Bathymetric Chart of the Arctic Ocean (IBCAO) version 1.0

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Abstract

In 1979, the General Bathymetric Chart of the Oceans (GEBCO) published Sheet 5.17 in the Fifth Edition of its series of global bathymetric maps. Sheet 5.17 covered the northern polar region above 64° N, and was for long the authoritative portrayal of Arctic bathymetry. The GEBCO compilation team had access to an extremely sparse sounding database from the central Arctic Ocean, due to the difficulty of mapping in this permanently ice covered region. In the past decade, there has been a substantial increase in the database of central Arctic Ocean bathymetry, due to the declassification of sounding data collected by US and British Royal Navy nuclear submarines, and to the capability of modern icebreakers to measure ocean depths in heavy ice conditions. From these data sets, evidence has mounted to indicate that many of the smaller (and some larger) bathymetric features of Sheet 5.17 were poorly or wrongly defined. Within the framework of the project to construct the International Bathymetric Chart of the Arctic Ocean (IBCAO), all available historic and modern data sets were compiled to create a digital bathymetric model. In this paper, we compare both generally and in detail the contents of GEBCO Sheet 5.17 and version 1.0 of IBCAO, two bathymetric portrayals that were created more than 20 years apart. The results should be helpful in the analysis and assessment of previously published studies that were based on GEBCO Sheet 5.17.

Introduction

The scientific community's view of the Arctic Ocean seafloor has evolved considerably since the first real soundings were made in the deep Eurasian Basin during Fritjof Nansen's epic voyage from the New Siberian Islands towards Fram Strait, with his ship *Fram* frozen into the pack ice (Nansen, 1904). The soundings from this expedition were used to construct a bathymetric map that showed one deep, featureless central basin. Many years would pass before bathymetric maps of the Arctic Ocean began to show the ridges and basins structures that we know today. The reason it has taken so long for this knowledge to develop lies in the hostile operating conditions that are encountered in the central Arctic Ocean, where the perennial sea ice cover effectively precludes survey operations that rely on conventional research vessels. Nevertheless, each new published Arctic Ocean bathymetric map has increased our knowledge of the sea floor.

The General Bathymetric Chart of the Oceans (GEBCO) contour map series has provided information about the world's ocean floor ever since the First Edition was published in 1905 (see Scott et al., 2003). Unlike previous editions, Sheet 5.17 covered the Arctic region above 64° N on a single chart which was constructed on polar stereographic projection (Canadian Hydrographic Service, 1979). For many, this sheet also defined the extent of the Arctic Ocean, notwithstanding the fact that the International Hydrographic Organization (IHO) has a different and more complicated definition of this particular body of water.[1] This highlights the significant influence that GEBCO sheets have enjoyed through the course of their history.

The bathymetric contours of Sheet 5.17 were derived from publicly available soundings at the

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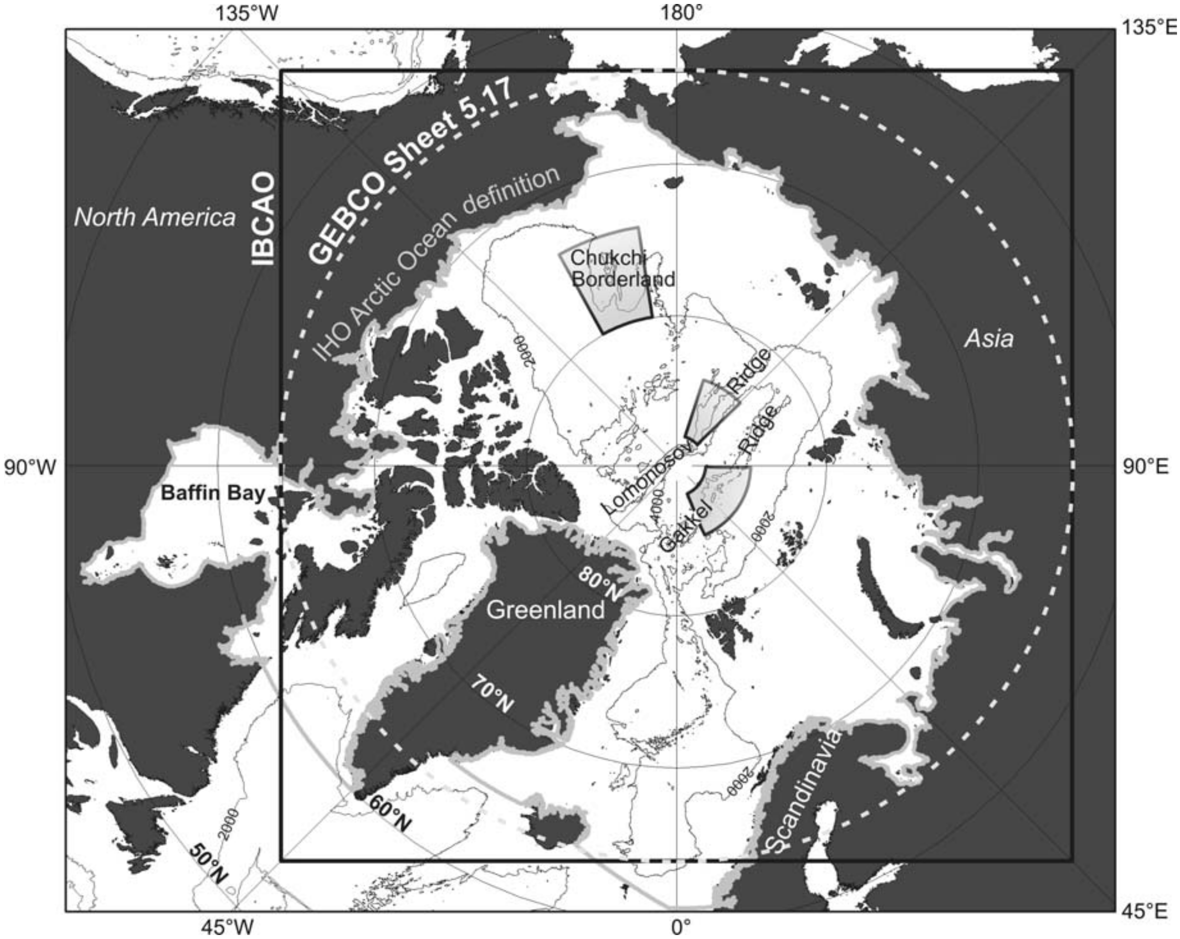


Figure 1. Map showing the IHO's formal definition of the Arctic Ocean (IHO, 2001) (bold gray line), the extent of GEBCO Sheet 5.17 (dashed light grey bold line), and the extent of the International Bathymetric Chart of the Arctic Ocean (IBCAO) digital bathymetric model (bold black line). The gray shaded areas of the Lomonosov Ridge, Gakkel Ridge, and Chukchi Borderland, show where the bathymetric portrayals of IBCAO and GEBCO Sheet 5.17 are displayed in side-by-side fashion in Figures 6–8. The main physiographic characteristic of the Arctic Ocean is shown by the 2000 and 4000 m contours, which have been derived from the IBCAO digital bathymetric model.

time of their construction, i.e. the late 1970s (Canadian Hydrographic Service, 1979). The sparseness of the bathymetric data only permitted the delineation of major seafloor features, so that following the publication of Sheet 5.17, evidence began to accrue from field expeditions that many of the smaller and some of the larger and significant features were poorly or wrongly defined (e.g. Macnab and Grikurov, 1997; Jakobsson, 1999). This situation posed problems not only for expedition planners but also for scientific investigators, who needed an accurate description of the sea floor to design field experiments and to link their research with processes affecting or affected by the shape of the seabed.

In 1991, the Swedish icebreaker *Oden* and German research vessel *Polarstern* reached the North Pole as the first conventionally driven surface ships (Anderson and Lönnroth, 1992; Fütterer, 1992). Shortly after, the US Coast Guard Cutter *Polarstar* carried out expeditions in the heavily ice covered areas of the Amerasian Basin (e.g. Grantz et al., 1993). This started a new era in Arctic research, demonstrating that the new-generation icebreakers were capable of exploring the central and perennially ice-covered Arctic Ocean. In addition, the Science Ice Exercise (SCICEX) was initiated in 1993, a program that deployed US nuclear submarines on mapping and research missions beneath the pack ice (Newton, 2000).

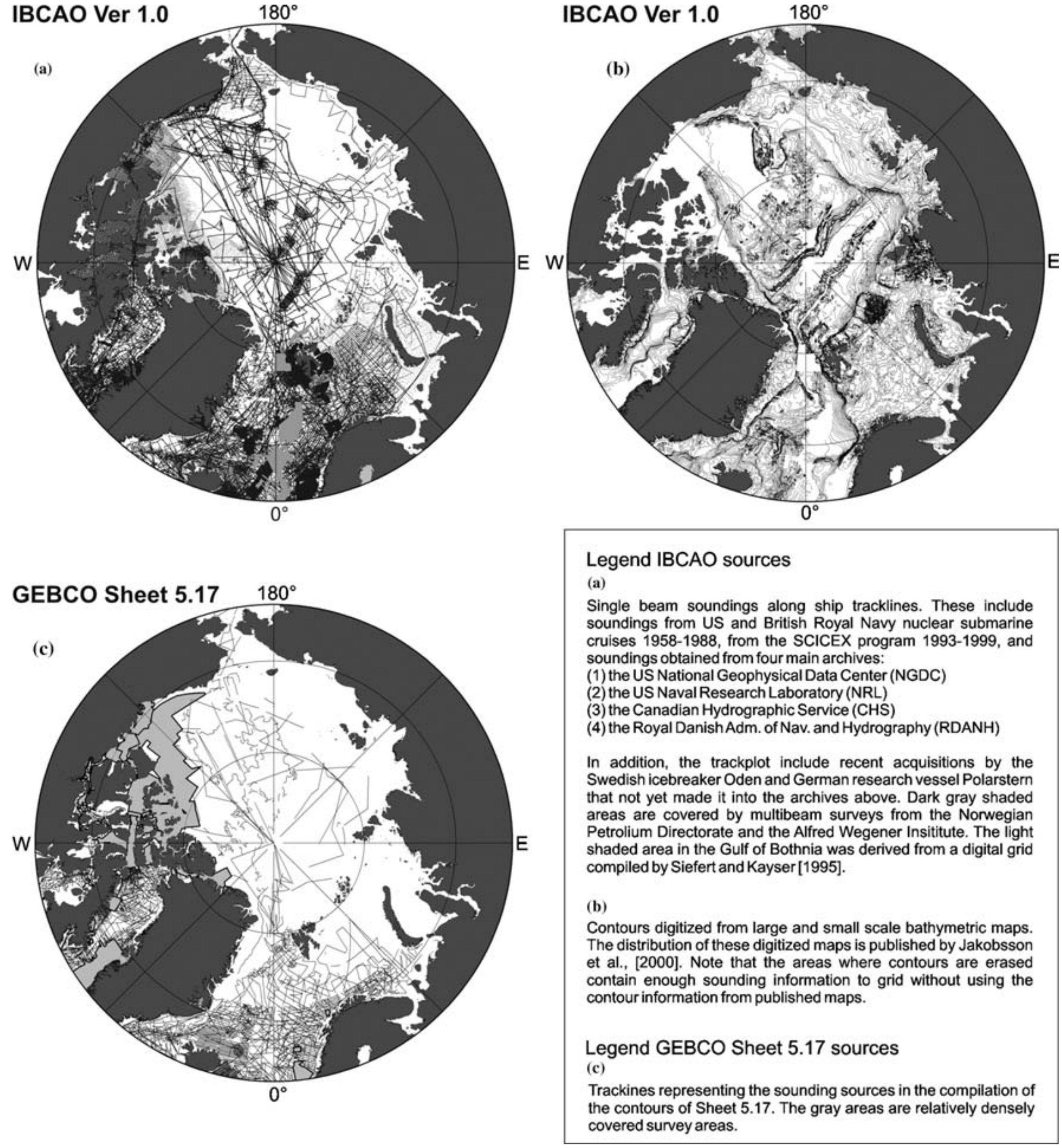
During these initiatives, new bathymetric data were collected that led to the discovery of further problems with existing maps of Arctic bathymetry. This included not only GEBCO Sheet 5.17, but other more recent compilations, such as one portrayed by the US Naval Research Laboratory (NRL) in its 1:4,704,075 scale map (Perry et al., 1986; for problems see Jakobsson, 1999). Eventually these problems came to the attention of the broader Arctic science community, including political decision makers. Therefore in September 1997 a workshop on Arctic Ocean bathymetry was organized in St. Petersburg, Russia (Macnab and Grikurov, 1997). This workshop led to the launch of International Bathymetric Chart of the Arctic Ocean (IBCAO). An Editorial Board was established that included representatives from the original five Arctic Ocean coastal states plus Iceland, as well as Germany and Sweden – two countries with strong scientific interests in the Arctic. The purpose of IBCAO was not only simply to make a new Arctic Ocean bathymetric map as a successor to Sheet 5.17, but also to construct a digital database containing all available bathymetric information north of 64° N. In addition to simplifying the construction of an up-to-date map, this database would provide a foundation for efficient updates as new data became available in the future. An accurate portrayal of the Arctic Ocean bathymetry has proved to be broadly sought after and IBCAO has been used in a variety of scientific as well as non-scientific applications. For example, the IBCAO digital bathymetric model has been included as a base layer in oceanographic modelling (Maslowski and Walczowski, 2002), in modelling of sea ice thickness and motion (Zhang and Rothrock, 2003), in studies of Arctic Ocean physiography and hypsometry (Jakobsson, 2002; Jakobsson et al., 2003), in the Arctic Gravity Project (ArcGP) (Kenon and Forsberg, 2000), and in studies related to the United Nations' Convention on the Law of the Sea (Macnab, 1999).

In this paper, we summarize briefly the compilation methods for GEBCO's Sheet 5.17 and IBCAO. We compare the general contents of both maps, as well as detailed contents within a set of selected areas, and we discuss the differences. This comparison highlights some major differences that should be taken into account when studying previously published studies based on GECBO Sheet 5.17.

The compilation of GEBCO Sheet 5.17

Techniques used in the construction of Sheet 5.17 are outlined in general terms in an information booklet that was issued with the GEBCO boxed set (IHO/IOC/CHS, 1984). All available soundings for the region were collected and manually plotted on master sounding sheets at a scale of 1:1 million. The contents of these master sheets represented an accumulation of data that had been collected over several preceding decades. There was considerable variation, both in depth and position, in the accuracy of the recorded observations on account of changes in sounding apparatus and navigational methods. Newer and better data sets were available, but they were insufficient to supplant all of the older soundings. Therefore over large portions of Sheet 5.17, the older information remained in use for interpretation by marine geologists and geophysicists who had an expert understanding of the geological processes that formed the topography of the seabed, and who transformed their understanding into hand-drawn contours that represented their best assessment of seabed morphology.

Depth values used in the construction of Sheet 5.17 were derived from a variety of sources. In addition to soundings from surface ships (icebreakers), the Sheet 5.17 source data consisted of observations collected from drifting ice islands, point soundings obtained along snow-mobile tracks or with air support, and depths extracted as isobaths from published and unpublished maps and reports. Nuclear submarines had been navigating beneath the polar pack ice since the late 1950s, so it was presumed that depth observations collected from these platforms, while remaining classified, might have been available to assist compilers in the construction of depth contours. Sounding lines were overprinted on Sheet 5.17 to illustrate the distribution of the Sheet's constituent data sets, but by their relative paucity, coupled with their total absence in large sections of the chart, they provided little specific information concerning the sources of the data or their quality (Figure 2c).



Legend IBCAO sources

(a)

Single beam soundings along ship tracklines. These include soundings from US and British Royal Navy nuclear submarine cruises 1958-1988, from the SCICEX program 1993-1999, and soundings obtained from four main archives:

(1) the US National Geophysical Data Center (NGDC)
(2) the US Naval Research Laboratory (NRL)
(3) the Canadian Hydrographic Service (CHS)
(4) the Royal Danish Adm. of Nav. and Hydrography (RDANH)

In addition, the trackplot include recent acquisitions by the Swedish icebreaker Oden and German research vessel Polarstern that not yet made it into the archives above. Dark gray shaded areas are covered by multibeam surveys from the Norwegian Petrolium Directorate and the Alfred Wegener Insititute. The light shaded area in the Gulf of Bothnia was derived from a digital grid compiled by Siefert and Kayser [1995].

(b)

Contours digitized from large and small scale bathymetric maps. The distribution of these digitized maps is published by Jakobsson et al., [2000]. Note that the areas where contours are erased contain enough sounding information to grid without using the contour information from published maps.

Legend GEBCO Sheet 5.17 sources

(c)

Trackines representing the sounding sources in the compilation of the contours of Sheet 5.17. The gray areas are relatively densely covered survey areas.

Figure 2. (a–c) Source data used in the compilation of IBCAO Version 1 and GEBCO Sheet 5.17.

The compilation of IBCAO database and Digital Bathymetric Model (DBM)

The current foundation of IBCAO is a digital Geographic Information System (GIS) database, formatted for access by Intergraph's GIS system Geomedia. This database contains an accumulation of bathymetric measurements collected during past and modern expeditions as well as digitized contours and depth soundings from published maps (Figure 2a and b). Compared to the Arctic data sets that were previously available to Western mapmakers including the GEBCO team, the information content of IBCAO has been substantially enhanced, particularly in the central Arctic Ocean. Here the previously nearly empty depth database has been significantly enriched by the addition of historic and modern bathymetric observations collected by US and British submarines (Newton, 2000), by Swedish and German icebreakers, and by depths derived from a new contour map prepared by the Russian Navy (Head Department of Navigation and Hydrography, 1999).

The database of the shallow shelves of the Laptev and East Siberian Seas has been enhanced as well, through the inclusion of contours derived from a quantity of depth soundings that were extracted from a suite of large scale navigational charts issued by the Russian Navy. Multibeam bathymetry from the Norwegian slope was contributed by the Norwegian Petroleum Directorate. Similar data sets collected in Fram Strait, north of Svalbard, and on the Lomonosov Ridge were obtained from the Alfred Wegener Institute in the form of 1×1 km grids (Klenke and Schenke, 2002).

More recently, additional multibeam data sets have been incorporated in the IBCAO database: from the Arctic Mid-Ocean Ridge Expedition (AMORE) (Thiede et al., 2002; Jokat et al., 2003; Michael et al., 2003), from cruises of the icebreaker USCGC *Healy* in the Amerasian Arctic Ocean, (Jakobsson et al., 2005), and from cruises of the German icebreaker *Polarstern* (Jokat et al., 2000). These soundings will be used in the preparation of the next version of the IBCAO digital bathymetric model.

The various steps involved to clean the IBCAO sounding database have already been described by Macnab and Jakobsson (2000). A large part of the process of mining and using data from various sources consisted of manually eliminating digitized bathymetric contours in places where the density of sounding data was sufficient for gridding. IBCAO may be described as a large quilt where original bathymetric sounding data take priority over digitized contours. In some areas where sparse track lines crossed digitized contours, track soundings were used to update the intersected contours where necessary.

Cleaned data consisted of various types of soundings, nodes from digitized contours, and in some areas points extracted from large-scale grids that had been derived from multibeam surveys. These were pre-processed with the block-median filter in Generic Mapping Tools (GMT, Wessel and Smith, 1991), using a block size of 2.5×2.5 km. Gridding at a cell size of 2.5×2.5 km was subsequently carried out with a continuous minimum curvature spline in tension, applying the algorithm in the GMT program *Surface* (Smith and Wessel, 1990) with the tension parameter set to 0.35. The X–Y coordinate system for the IBCAO digital bathymetric model was applied to a polar stereographic projection centred on the North Pole, with central meridian at 0° longitude, and true scale at 75° N. The horizontal datum selected was World Geodetic System 1984 (WGS 84). The final bathymetric model was portrayed in three dimensions using Fledermaus software, which facilitated visual inspection and comparison with the original data.

The IBCAO digital bathymetric model and isobaths derived from the grid are included in the latest release of the GEBCO Digital Atlas to represent the region north of 64° N (International Oceanographic Commission et al., 2003).

Methods of comparison between Sheet 5.17 and IBCAO

To enable a quantitative as well as visual comparison between the two bathymetric portrayals using computer technology, the depth contours of Sheet 5.17 were converted to a digital bathymetric model compatible with IBCAO. This process required the availability of the Sheet 5.17 contours in digital form, a requirement that was satisfied in a straightforward fashion because the necessary contours could be extracted from GEBCO Digital Atlas (IOC/IHO/BODC, 1997). These contours were used to create a digital bathymetric model that consisted of a 5×5 km grid, using map projection parameters that were compatible with IBCAO, along with the same continuous minimum curvature spline in tension algorithm that was used for IBCAO.

A color coded shaded relief was constructed from the Sheet 5.17 grid, and overlaid with the original contours to check that the result was satisfactory. This revealed undershooting and overshooting of the bathymetric surface, a problem that often occurs with the minimum curvature gridding algorithm (Smith and Wessel, 1990). To suppress this problem a higher spline tension of 0.99 was applied and, in some areas, steering contours were drawn at intermediate depths between the original Sheet 5.17 contours. It was possible to use a lower spline tension for constructing IBCAO grid because the increased data density provided a higher constraint for the minimum curvature surface. Even though the Sheet 5.17 and IBCAO digital bathymetric models were constructed with similar processing schemes, we acknowledge that the grid models have inherited certain artefacts introduced by the gridding process. However, for the purpose in this paper, such artefacts should not mask authentic differences between the bathymetric portrayals of the two models.

The two compatible bathymetric grid models may be compared visually by means of computer illumination techniques that shade and render the gridded bathymetric surfaces. Figure 3 shows side-by-side shaded relief images generated from the IBCAO and Sheet 5.17 digital bathymetric models. The use of digital grid models also facilitates quantitative comparison methods. For example, a difference model may be calculated by subtracting one model from the other. Descriptive statistics such as depth distribution may also be easily generated from analysis of the grids.

Results

A comparison between the seafloor portrayals of GEBCO Sheet 5.17 and IBCAO

When viewed in a side-by-side fashion, shaded relief images of the two bathymetric portrayals reveal some general differences (Figure 3). It can be clearly seen that the ridges, which are the largest and most dominant physiographic features in the central Arctic Ocean, appear very differently in IBCAO than in Sheet 5.17. The Lomonosov Ridge as portrayed in IBCAO has a far more complex morphology than in Sheet 5.17. Where Sheet 5.17 shows the ridge as a narrow, relatively straight feature that extends from a position near the North Pole (where it bends sharply in both maps) towards the Siberian and Greenland margins, in IBCAO it is broken into segments.

The morphology of the Gakkel Ridge is also more complex in the IBCAO portrayal than in Sheet 5.17. In the former, the deep axial valley may be followed for its full extent throughout the Eurasian Basin, whereas in the latter, it displays a less pronounced axial valley near 65° E. Similarly, the appearance of the Chukchi Borderland, which comprises the Northwind Ridge and the Chukchi Plateau, changes significantly from Sheet 5.17 to IBCAO. This is obvious even at the scale of Figure 3.

A comparison of the distribution of the depth values contained in the IBCAO and Sheet 5.17 digital bathymetric models readily indicates how the two differ over the shallow continental shelves (< 200 m depth) (Figure 3). It is evident from a visual examination that Sheet 5.17 contains very sparse bathymetric information over the shelves, which explains this difference.

A difference model generated by subtracting the IBCAO grid from the Sheet 5.17 grid reveals some prominent areas of bathymetric differences (Figure 4). The most striking differences are found along the Lomonosov and Gakkel Ridges, and on the Chukchi Borderland. This confirms differences that could be easily perceived through visual inspection of Figure 3. High values in the difference model, indicating depth differences between the two models, are also seen along stretches of the Arctic continental shelf slope and on Morris Jesup Rise.

Additional side-by-side comparisons of the seafloor morphology follow for selected areas of the Lomonosov and Gakkel Ridges, and the Chukchi Borderland. The locations of these areas are shown in Figure 1.

Lomonosov Ridge

The segment of the Lomonosov Ridge shown in Figure 5 has been selected for this bathymetric comparison because it displays the most dramatic change in appearance between Sheet 5.17 and IBCAO. Bathymetric profiles extracted from the two representations reveal that in IBCAO, that the center of the ridge crest has shifted by as much as 200 km towards the Makarov Basin. Furthermore, instead of being a narrow, slim ridge with a rounded crest as shown in Sheet 5.17, the Lomonosov Ridge features a flat-topped crest and a blocky nature with segments that line up in *en echelon* fashion. In IBCAO, the shallowest location in this area has a depth of 607 m, whereas in Sheet 5.17, the shallowest contour is 1000 m (Figure 5).

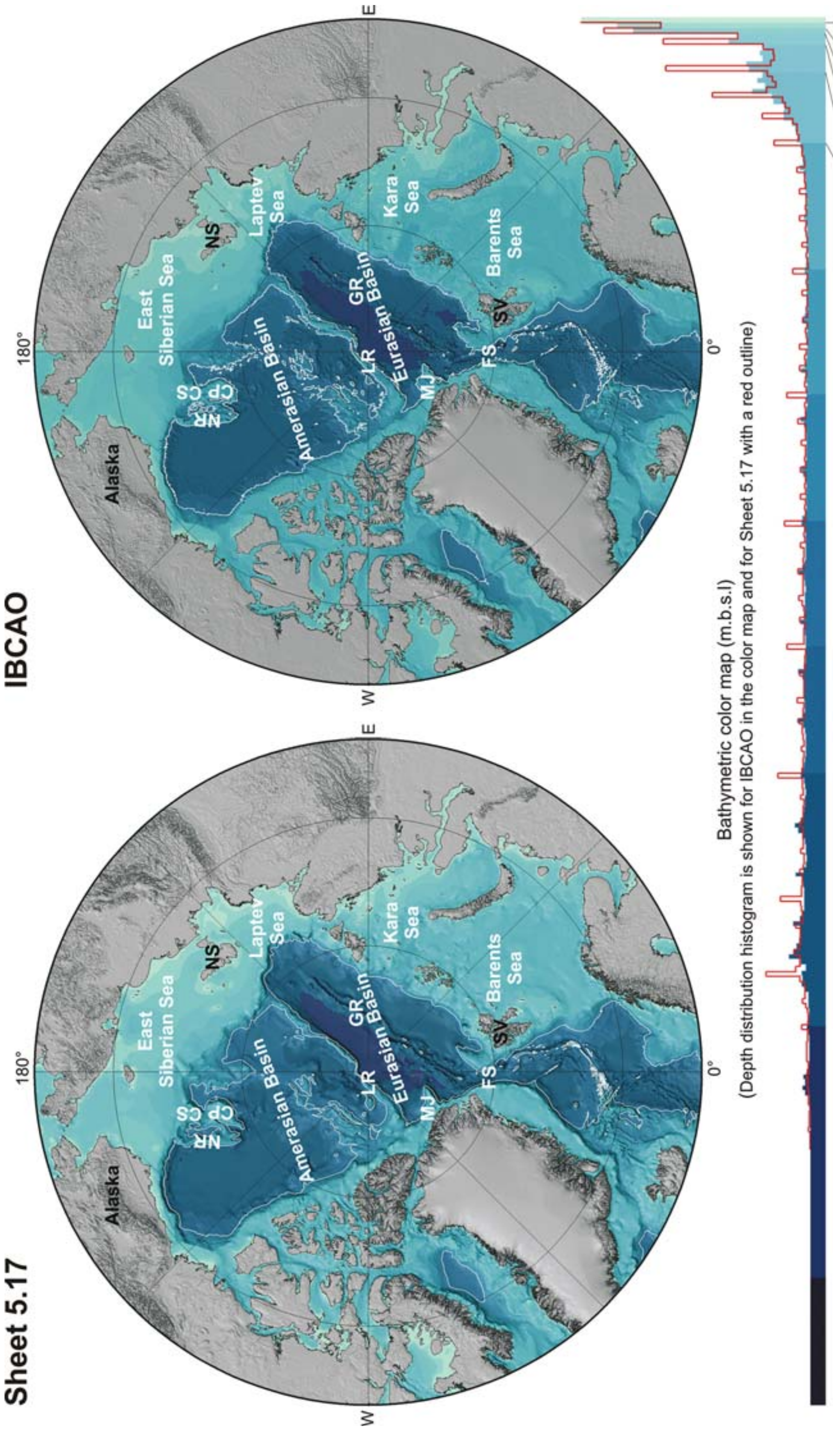


Figure 3. Shaded relief images of the GEBCO Sheet 5.17 (left) and the IBCAO (right) digital bathymetric model above 64° N. The 2000 m isobath is printed in white on both bathymetric maps. The bathymetric color scale also shows depth distribution histograms for both DBMs: the red outline is the histogram for Sheet 5.17, which features abundant depth ''spikes'' that are caused by depth biases toward the contour intervals. This is an artifact that results from using contours as the only source of information for constructing a grid. CP = Chukchi Plateau; CS = Chukchi Spur; FS = Fram Strait; GR = Gakkel Ridge; LR = Lomonosov Ridge; MJ = Morris Jesup Rise; NR = Northwind Ridge; NS = New Siberian Islands; SV = Svalbard. Chukchi Borderland is comprised of Northwind Ridge and Chukchi Plateau and Spur.

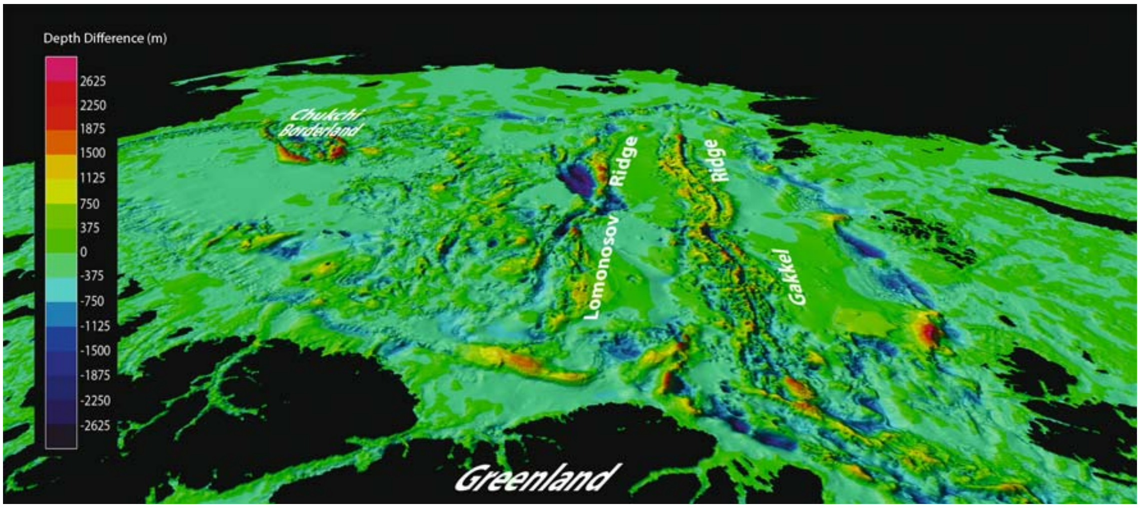


Figure 4. 3D image of difference model calculated by subtracting the IBCAO from the GEBCO Sheet 5.17 DBM. Note the large differences over sections of the Lomonosov Ridge, the Gakkel Ridge and the Chukchi Borderland. Figures 5–7 illustrate these physiographic features as they are portrayed in IBCAO and in Sheet 5.17, and which differ radically in appearance.

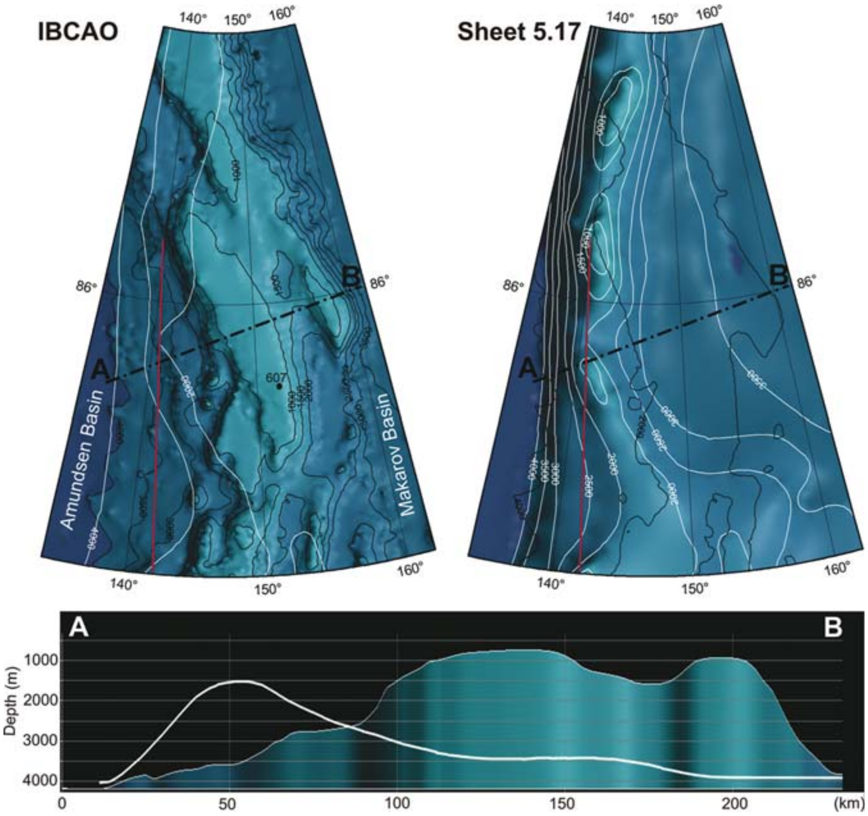


Figure 5. Comparison between IBCAO and GEBCO Sheet 5.17 over the Lomonosov Ridge (see Figure 1 for the location of the area). White bathymetric contours refer to depths on Sheet 5.17, black contours on IBCAO. The red line is the trackline indicated as the only source of information on the Sheet 5.17 data distribution plot. The bold white line in the in the lower part of the figure is a depth profile extracted from Sheet 5.17.

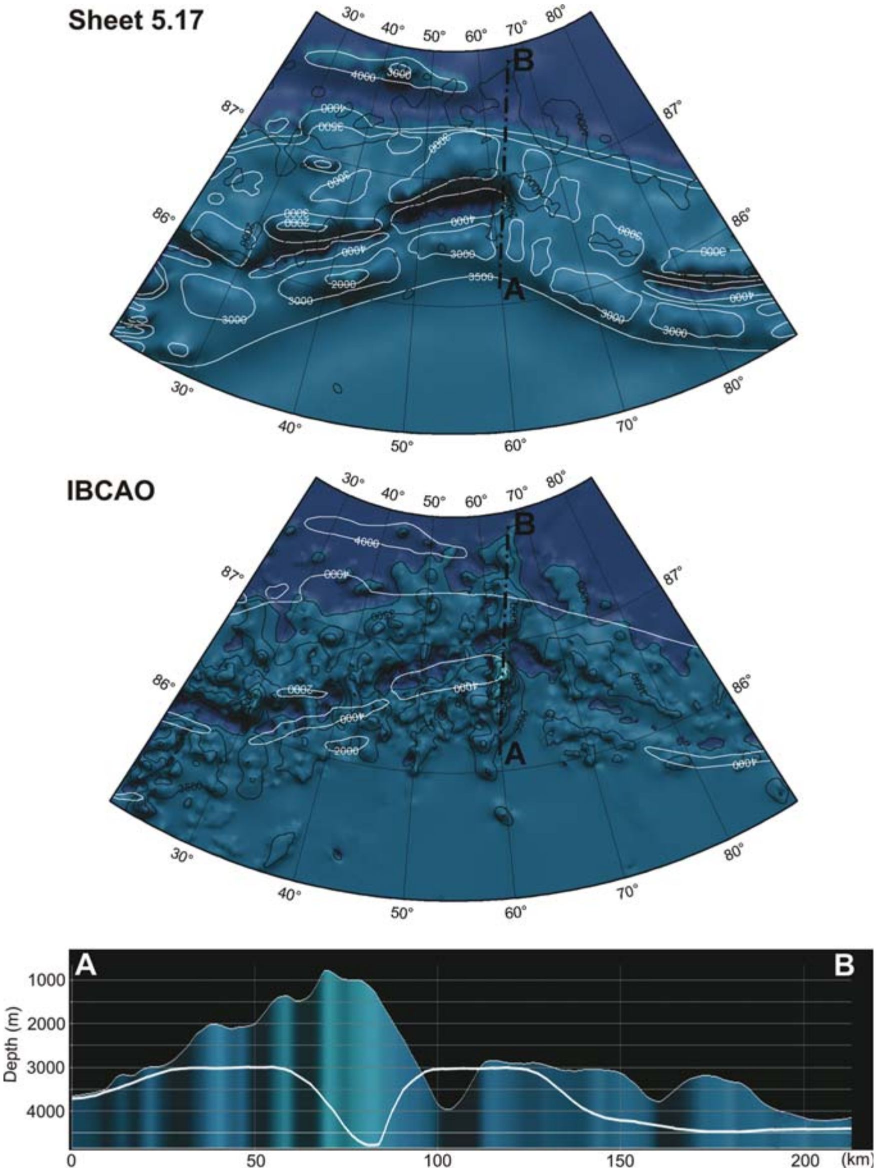


Figure 6. Comparison between IBCAO and GEBCO Sheet 5.17 over the Gakkel Ridge (see Figure 1 for the location of the area). White bathymetric contours refer to depths on Sheet 5.17, black contours on IBCAO. The bold white line in the lower part of the figure is a depth profile extracted from Sheet 5.17.

Gakkel Ridge

Due to the very sparse data that was available to Sheet 5.17 compilers over the area of the Gakkel Ridge in Figure 6, the map indicates smooth and highly generalized ridge morphology. In the IBCAO compilation, single beam echo soundings from the SCICEX cruises contribute substantially to a change in the Ridge's appearance. The new bathymetric model portrays ridge flanks with blocky structure, while the axial valley is not only nearly continuous, but it is more pronounced and deeper. Moreover, the entire axial valley is offset between the two bathymetric portrayals, as visible in the cross sections of Figure 6, which also shows a substantially higher ridge flank in the area on the south side of the axial valley.

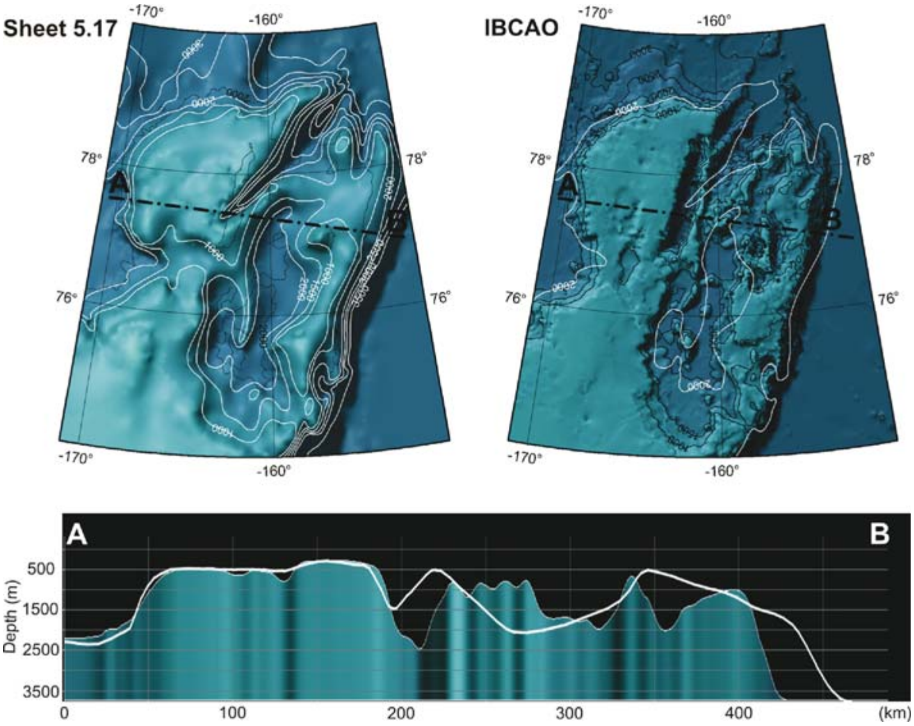


Figure 7. Comparison between IBCAO and GEBCO Sheet 5.17 over the Chukchi Borderland (see Figure 1 for the location of the area). White bathymetric contours refer to depths on Sheet 5.17, black contours on IBCAO. The bold white line in the lower part of the figure is a depth profile extracted from Sheet 5.17.

Chukchi Borderland

The bathymetric comparison in Figure 7 includes the Northwind Ridge and Chukchi Spur and Plateau, which together comprise the Chukchi Borderland. These features are today among the better mapped in the Arctic Ocean (Figure 2a), however, during the compilation of Sheet 5.17 bathymetric data was sparse (Figure 2c). This was particularly the case along the northeastern slope of Northwind Ridge and the northeastern tip of Chukchi Plateau, which resulted in an incorrect bathymetric definition in Sheet 5.17 (Figure 7). This is also evident from the difference model in Figure 4, which suggests depth variations between Sheet 5.17 and IBCAO that are several thousand meters in magnitude.

Discussion

More than 20 years have passed since the publication of Sheet 5.17. The deployment of a new generation of icebreakers and of nuclear submarines has significantly accelerated the exploration of the central Arctic Ocean and has resulted in a corresponding growth in the sounding database. In light of the fact that the IBCAO compilation team had access to substantially more bathymetric data than previous map makers, it is not unexpected that major discrepancies should be apparent between Sheet 5.17 and IBCAO. Not surprisingly, these discrepancies are situated mainly in the central ice-covered area over regions expressing a large bathymetric variation (ridges and other bathymetric highs) (Figures 4–7). The large, flat abyssal plains were already fairly well delineated in Sheet 5.17, and their appearance has not changed much between the two maps: where historical depth measurements are concerned, horizontal positioning represents the largest source of error, however their effect is naturally relatively minor over level and extensive abyssal plains (Jakobsson et al., 2002).

Perhaps the most striking difference between Sheet 5.17 and IBCAO is in the appearance of the Lomonosov Ridge near 86° N (Figure 5). In this area, the inaccuracy of Sheet 5.17 was noted during several expeditions, including a cruise of the Swedish icebreaker *Oden* during the Swedish Polar Research Secretariat's expedition *Arctic Ocean 96* (Jakobsson, 1999). When *Oden* headed towards the crest of the Lomonosov Ridge, a minimum depth of 607 m was observed in a location where Sheet 5.17 indicated a depth greater than 3000 m. The more recent map published by Naval Research Laboratory (Perry et al., 1986) indicated a depth that ranged between 1000 and 1500 m at this location.

As can be seen in the data distribution diagram in Figure 2C, it would appear that the only direct information that was available to the Sheet 5.17 compilers along this segment of the Lomonosov Ridge originated from a single track along the ridge crest. The straight nature of this track suggests that it could be associated with a submarine transit, which would not feature the frequent course and speed changes of an icebreaker navigating through heavy ice. However, a review of the IBCAO source database, which includes all declassified US and British Royal Navy submarine cruises between 1958 and 1988, reveals no track that perfectly matches the one shown in Sheet 5.17 over the Lomonosov Ridge. It is known that bathymetric data collected under the ice during early submarine cruises can sometime suffer from very large navigational errors (Jung et al., 2002), which could partially explain the incorrect position of the Lomonosov Ridge on Sheet 5.17.

The discovery of a major submarine feature crossing the deep Arctic Ocean has an interesting history, filled with remarkable postulations from scientists who had practically no access to real depth measurements. Harris (1904) analyzed tidal data and suggested that the Arctic Ocean was divided by a barrier into two basins characterized by different tidal oscillations. The actual discovery of such a barrier occurred much later, once Soviet scientists had carried out extensive investigations during high latitude expeditions in 1948. The following year, Yaakov Yaakovitch Gakkel compiled the first contour map showing the Lomonosov Ridge (Weber, 1983). However, the existence of the Lomonosov Ridge was not revealed outside the Soviet Union until 1954, when Soviet scientists decided to share their knowledge with the Western world (e.g. Gakkel, 1958).

The approximately 1700 km long Lomonosov Ridge is now considered to be a continental sliver that was separated from the Kara and Barents shelf and transported to its present position by seafloor spreading (e.g., Wilson 1963; Karasik, 1974; Vogt et al., 1979). The overall broken morphology apparent in the IBCAO digital bathymetric model provides additional support for the earlier hypothesis that the ridge consists of slightly tilted *en echelon* fault blocks (e.g., Weber and Sweeney, 1990; Jokat et al., 1992). Furthermore, the IBCAO DBM shows a flat-topped ridge crest that is very pronounced in several sections (Figure 5). This is explained by a pronounced erosional unconformity that was revealed in the stratigraphic column through seismic reflection surveys (Jokat et al., 1995). The unconformity in the Lomonosov Ridge stratigraphy is thought to have formed from subaerial and shallow marine erosion when the ridge first subsided below sea level about 50 million years ago (Jokat et al., 1995).

The existence of a spreading ridge in the Arctic Ocean was first suggested on the basis of earthquake epicenters and a small number of soundings (Heezen and Ewing, 1961). A few years afterwards, bathymetric profiles that had been collected during US Navy nuclear submarine cruises during the late fifties and early sixties were released and provided the first real support for the hypothesis of an extension of the mid-oceanic ridge (later called the Gakkel Ridge) system into the Arctic Basin (Johnson and Heezen, 1967). One of the primary objectives of the SCICEX program was to map the Gakkel Ridge, and systematic surveys were carried out in 1996, 1998 and 1999. The single beam soundings from these surveys have all been incorporated in the IBCAO database, and have substantially improved the current knowledge of the morphology and the behavior of the Gakkel Ridge (e.g. Coakley and Cochran, 1998; Cochran et al., 2003), which is the slowest spreading segment of the global mid-oceanic ridge system. During the recent Arctic Mid-Ocean Ridge Expedition (AMORE), the Gakkel Ridge was extensively mapped with multibeam bathymetric sonar (Thiede et al., 2002; Jokat et al., 2003; Michael et al., 2003). These observations are still being processed for inclusion in the next version of IBCAO, therefore they do not feature in the present comparison with Sheet 5.17. In addition, gravity and magnetic compilations from the Eurasian Basin of the Arctic Ocean have recently been published (Brozena et al., 2003) and may provide an additional aid for the next update of the IBCAO digital bathymetric model, in particular over areas with sparse bathymetric data.

The data source map for Sheet 5.17 in Figure 2 shows only a few tracks crossing the Gakkel Ridge. As in the case of the Lomonosov Ridge, the straightness of these tracks suggests they are associated with submarine transits. All but two are found to match the tracks of known US nuclear submarine cruises which are contained in the IBCAO database. Similarly, the offset of the Gakkel Ridge axial valley as seen in Sheet 5.17 compared to IBCAO (Figure 6) may be due to inaccuracies in the navigation of submarines operating beneath the ice.

The Chukchi Borderland extends from the Eastern Siberian and Western Alaskan shelves into the deep Amerasia Basin. Features of the Borderland are among the more extensively mapped in the Arctic Ocean (Hall, 1990), and the map published by Perry et al. (1986) is considered to provide a better bathymetric portrayal of this region than Sheet 5.17. New data from this area, which has been included in the development of the IBCAO model, further improves the image of the sea-floor morphology. The ridges appear more segmented than on previous maps, and the surfaces contain irregularities that likely reflect complex sea-floor processes. The largest differences between IBCAO and Sheet 5.17 are seen on the steep slopes of Northwind Ridge and Chukchi Plateau that lie farthest to the northeast. It is clear that the scarcity, of data during the compilation of Sheet 5.17 is behind these large differences.

Conclusion

This analysis has compared bathymetric portrayals from eras that are two decades apart. The GEBCO map featured a strong reliance on the cartographer's skill in developing hand-drawn contour maps from at times extremely limited data sets, in a manner that required informed geological speculation on the shape of the seabed and on the processes that influenced its development. The IBCAO map offers the advantage of superior data sets and powerful computer tools for their efficient manipulation and realistic visualization. GIS tools and digital databases have entered the ocean mapping arena, and will probably remain in the center for a foreseeable future. Nevertheless, the state of global ocean mapping has not yet advanced to the point where we can totally dispense with the geological speculation that informed the construction of earlier maps, especially not in inaccessible areas like the Arctic Ocean, which remains inadequately mapped. It will likely be several if not many years before mapmakers are able to avail themselves of well-populated databases and thereby take full advantage of their computer tools.

In addition to progress in the cartographic arena, this study also underscores the significant advances that have taken place in mapping the Arctic Ocean: where before the shape of the polar seabed remained imperfectly known on account of the opaque and permanent sea ice cover, we are now witnessing a constant improvement of knowledge through the deployment of icebreakers that feature new capabilities for mapping in ice-covered waters, and of submarines that collect unclassified observations while traveling beneath the ice.

The key lesson learned from this comparison is that to be truly informative, bathymetric maps cannot serve as static repositories of information, but that they must evolve constantly to incorporate new data sets and to capitalize on advances in data manipulation and visualization. While Sheet 5.17 served the needs of Arctic investigators for half a generation, its inherent inaccuracies eventually inspired an initiative to construct a modern and more reliable version, i.e. IBCAO. There is no doubt that the current version of IBCAO will soon be outdated, however in its design and implementation, provision has been made to develop successor versions with a minimum of time and effort.

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Note

[1] The International Hydrographic Organization's (IHO) definition of the Arctic Ocean includes all of Hudson Bay and Hudson Strait, and also extends south of Sheet 5.17 to 60° N in Davis Strait between Greenland and Baffin Island (IHO, 2001). Moreover, in defining the boundary between the Arctic Ocean and the North Atlantic Ocean, the IHO specifies rhumblines that join points on the coastlines of Greenland, Iceland, and Norway (Figure 1).

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