

Analysis of the Under-Ice Topography in the Arctic Basin as Recorded by the USS *Nautilus* during August 1958

ALFRED S. MCLAREN¹

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ABSTRACT. The USS *Nautilus* (SSN-571) was the first vessel to cross the Arctic Basin via the North Pole in early August 1958. During this expedition almost continuous acoustic under-ice thickness distribution profiles were recorded. This article presents an overall statistical analysis of the under-ice draft measurements obtained during this historic cruise. Geographic areas found to have distinct under-ice characteristics and ice compositions are identified.

Principal findings are: (1) *Nautilus* recorded an overall mean under-ice draft of 3.68 m across the Arctic Basin; (2) the under-ice topography becomes progressively more severe when proceeding from the Canadian to the Eurasian side of the Arctic Basin; (3) the Canada Basin was observed to contain the most moderate under-ice topography and the greatest number of open water and refrozen polynyas and leads along the transpolar route taken by *Nautilus*; (4) *Nautilus* encountered the most severe under-ice topography of the voyage over the Arctic Mid-Ocean Ridge; and (5) an overall Arctic Basin mean of 2.6% open water/new ice (<30 cm) was encountered during her voyage beneath the sea ice cover of the Arctic Ocean.

Key words: sea ice, under-ice thickness distribution, sonar, Canada Basin, Central Arctic, Eurasian Basin, arctic submarine

RÉSUMÉ. Le sous-marin *Nautilus* (SSN-571) fut le premier bâtiment à traverser le bassin arctique via le Pôle Nord, au début d'août 1958. Au cours de l'expédition, on réalisa, de dessous la glace et de façon presque ininterrompue, des enregistrements acoustiques de la distribution de l'épaisseur de la glace. Cet article présente une analyse statistique générale des mesures du tirant d'eau de la glace prises lors de ce voyage historique. On a identifié les zones géographiques qui ont montré des caractéristiques distinctes du dessous de la glace ainsi que des compositions différentes de la glace.

Les résultats principaux sont les suivants: 1) le *Nautilus* a enregistré un tirant d'eau moyen de la glace de 3,68 m dans tout le bassin arctique; 2) la topographie du dessous de la glace devient de plus en plus accidentée quand on se déplace du côté canadien au côté eurasiatique du bassin arctique; 3) on a observé que le bassin canadien possédait la topographie du dessous de la glace la plus uniforme ainsi que le plus grand nombre de polynies et de chenaux d'eau libre ou regelés, le long de la route transpolaire empruntée par le *Nautilus*; 4) le *Nautilus* a rencontré la topographie du dessous de la glace la plus accidentée de tout le voyage, au-dessus de la dorsale du milieu de l'océan Arctique; et, 5) il a relevé une moyenne de 2,6% d'eau libre et de glace nouvelle (< à 30 cm) dans le bassin arctique au cours de son voyage sous la couverture de glace de l'océan Arctique.

Mots clés: glace de mer, distribution de l'épaisseur de la glace mesurée par dessous, sonar, bassin canadien, centre de l'Arctique, bassin eurasiatique, sous-marin arctique

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INTRODUCTION

In July 1958, the USS *Nautilus* cruised through the largely uncharted Chukchi Sea on her third attempt to make the world's first transpolar voyage. After searching unsuccessfully for a deep-water route, she proceeded eastward along the Alaskan coast via the Barrow Sea Valley in hopes of finding sufficiently deep water to submerge safely beneath the vast polar ice pack. *Nautilus* finally reached a point north of Point Franklin, Alaska, early on 1 August from which she was able to head directly for the valley's mouth. Deeper water was encountered within hours, and *Nautilus* was at last able to proceed beneath the polar ice pack and gradually increase depth and speed as she left the North American Continental Shelf and entered the deep Canada Basin. Upon reaching the 155th meridian, her captain, William R. Anderson, ordered her course changed to north (Anderson, 1959). The rest is history, for within the next 96 hours, *Nautilus* passed beneath the North Pole some 2026 km distant and safely emerged from beneath the polar ice pack, northeast of Greenland (Fig. 1). Although some preliminary analysis was accomplished on the data (Lyon, 1961), this article presents the first in-depth statistical analysis, based on complete digitization of the profile records, of the under-ice topography recorded by the USS *Nautilus* in 1958.

THE DATA

Nautilus 1958 continuous analog under-ice thickness recordings, together with supporting navigational logs, were obtained

from the Arctic Submarine Laboratory, U.S. Naval Ocean Systems Center, San Diego.

The under-ice topography was measured by a Navy Electronics Laboratory variable frequency (20-200 kHz) upward-beamed acoustic profiler. The received return echoes from this sonar were fed into a signal processor, which generated a resultant distance to the underside of the ice pack. This derived distance was based on an assumed sound velocity through the intervening water column. A standard intensity level for the reflected pulse was used. The depth of the under-ice profiling sonar transducer, as measured by a pressure sensor, was then subtracted from the measured distance determined above. The resultant electrical signal was used to trace continuously the under-ice topography above the submarine, in the form of ice draft beneath the surface, on a curvilinear recording chart (Fig. 2).

Nautilus used frequencies of either 50 or 180 kHz almost exclusively. The signal beam width for the 180 kHz signal, used 47% of the time, was 3°, while the 50 kHz signal, used 52.7% of the time, had a 10° beam width. *Nautilus* briefly experimented with other frequencies the remaining 0.3% of the time. Both frequencies and beam widths were experimental, with the higher frequency and narrower beam width proving, during the analysis, to yield the more accurate data (McLaren, 1986). A beam width correction factor of 0.836, similar to that derived by Wadhams (1981) and McLaren (1986), was applied for comparison purposes to the overall mean ice drafts only of those segments of the *Nautilus* record that had been recorded at 50 kHz. Such a correction is necessary since *Nautilus*'s wide-beam

¹Cooperative Institute for Research in Environmental Sciences (CIRES) and Department of Geography, Campus Box 449, University of Colorado, Boulder, Colorado 80309, U.S.A.

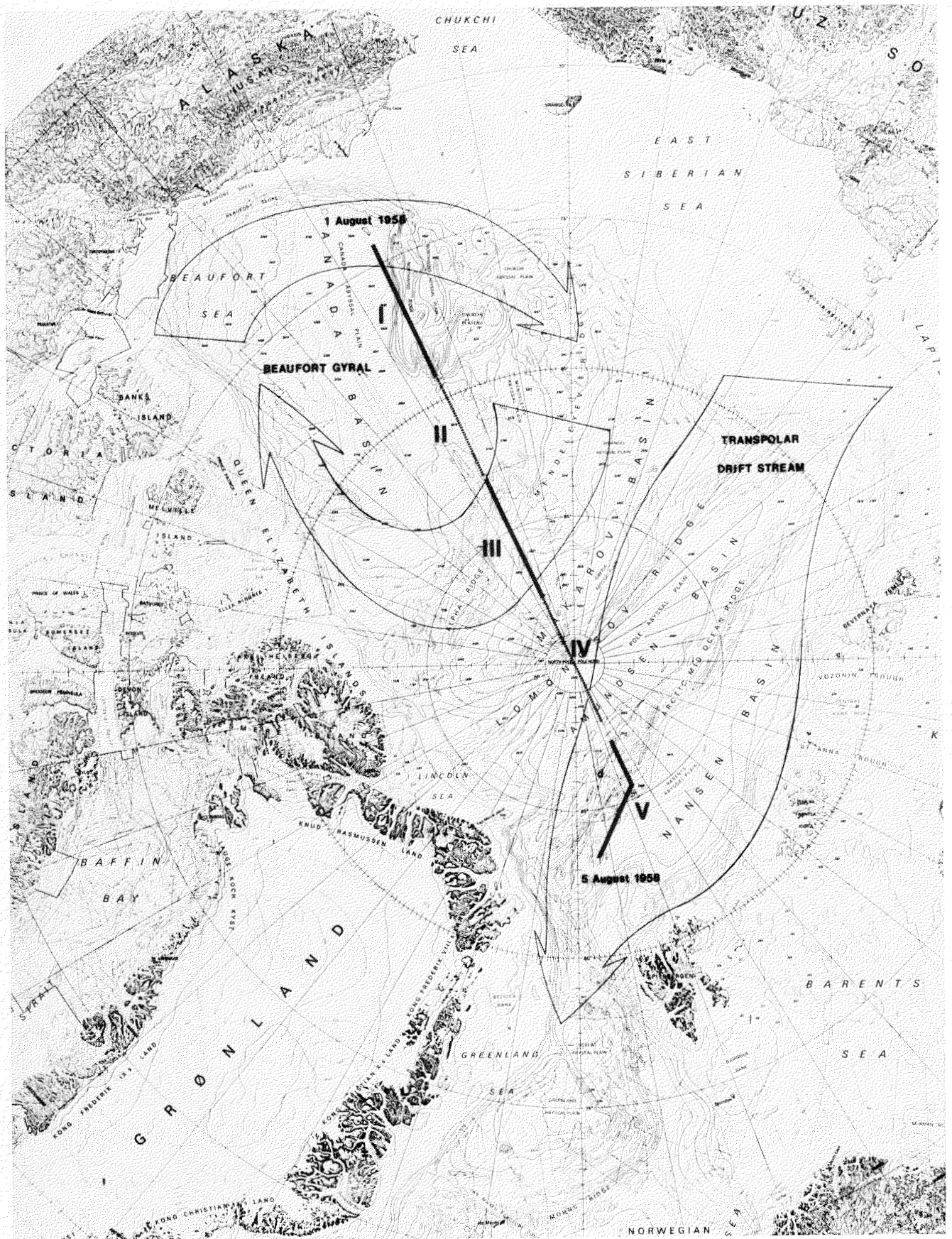


FIG. 1. Map (adapted from Canadian Hydrographic Service) showing USS *Nautilus*'s route across the Arctic Basin and the five distinct ice regions encountered during early August 1958.

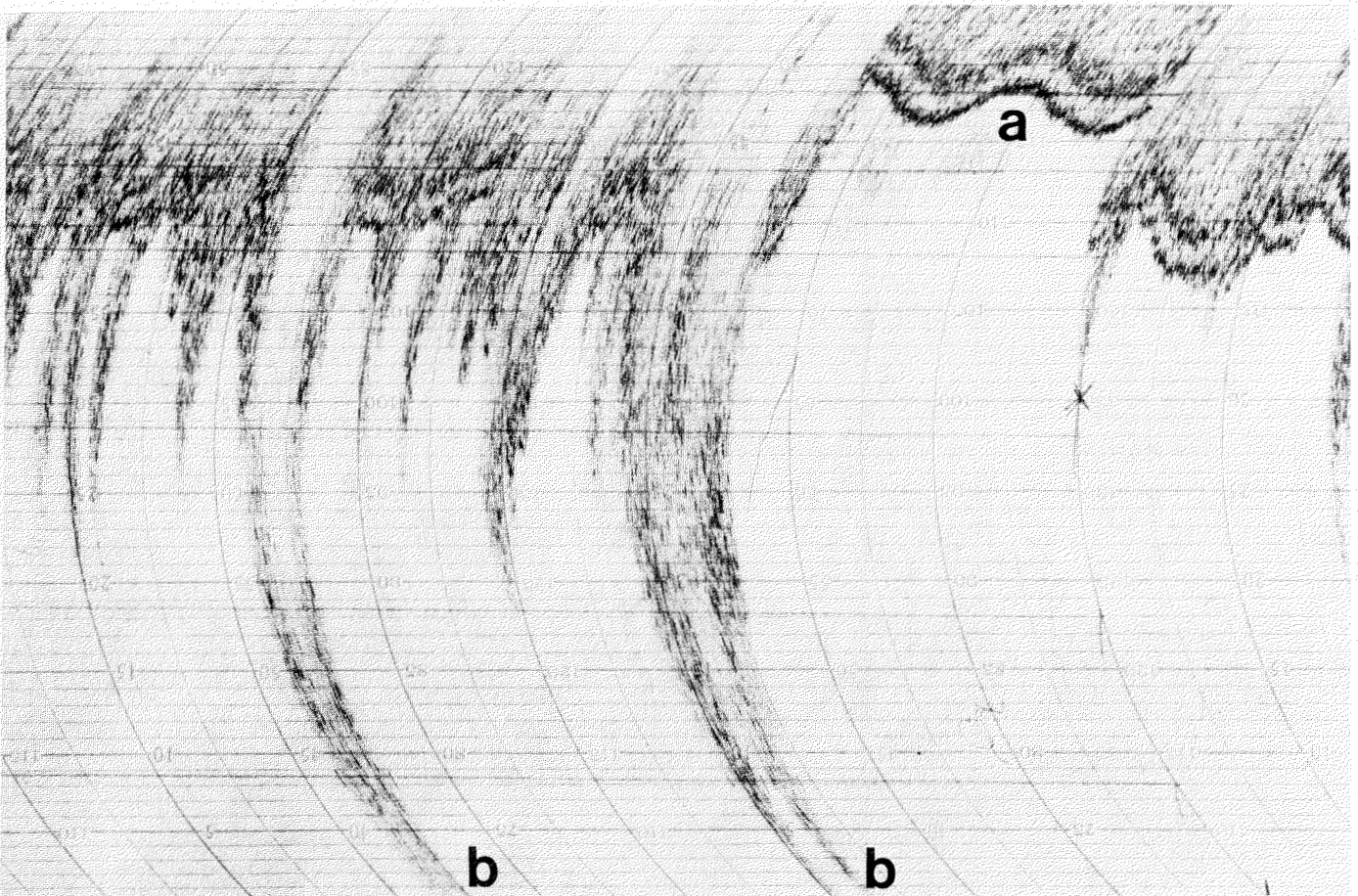


FIG. 2. Typical under-ice topography acoustic recording of approximately 3 km in length (vertical scale 0-55 ft/0-16.8 m) obtained by *Nautilus* during her 1958 transit beneath the polar ice pack. (a) Open lead/polynya of approximately 680 m in length. (b) Heavy deep draft keels (source: U.S. Navy).

acoustic signal tended to smooth the finer detail, such as troughs between closely spaced keels, with the following results: (1) overestimation of mean ice draft; (2) underestimation of the slopes of individual deep draft keels; and (3) a general distortion/rounding of their shapes. The absolute drafts of independent deep draft keels greater than 5.0 m, however, were considered, as Wadhams (1981) determined, accurately measured.

PROCESSING OF THE DATA

The under-ice thickness data recorded on the analog recordings were manually digitized by the author using a curve follower and a digitizer tablet that produced one data point every 0.002 in (0.05 mm) of a recording chart. Over two million data points were obtained for subsequent statistical analysis. The basic reference for under-ice draft should be actual sea level. Since no independent measurement of sea level was available, to maintain accuracy sea level had to be determined through frequent reference (every 3-4 km) to indications of open water on the data profiles and inserted during the digitization process. Since ship's speed variations and manual digitization can both produce variable spacing between individual ice draft data points, the data were initially put through an interpolation

process to ensure that individual data points were equally spaced at 1.7 m intervals, thus assuring a more balanced representation of under-ice thickness.

It is important to note that all results are subject to: (1) the accuracy of the submarine's under-ice acoustic profiler (estimated to range from ± 15 cm, when open water is clearly evident on the analog record, to ± 50 cm in the case of *Nautilus* 1958 data); (2) the accuracy with which the under-ice topography recordings are digitized and sea level is estimated; and (3) the precision of the interpolation routine (estimated to be ± 1 cm).

Data gaps due to ship's recording equipment malfunction were encountered throughout the entire voyage. These ultimately totaled some 373.6 km, or 14.7% of the total route taken by *Nautilus* across the Arctic Basin.

The digitized data were edited and analyzed statistically using a data-processing and statistics software package program, written in Fortran, and derived from an Algol C version developed by Wadhams and Horne (1978). The distributional characteristics of the data points within the overall track and smaller evaluation segments of these tracks were determined as simple frequencies. Ice draft data were screened and sorted in order to generate mean statistics and standard deviations (an indication of under-ice roughness) for the overall ice draft profile, level ice, deep draft keels, and open/refrozen leads and polynyas.

Probability density plots and histograms were also produced and used for analysis and evaluation of each major statistical analysis category and track evaluation segment.

STATISTICAL RESULTS

Overall Under-Ice Profile

Overall mean under-ice thickness (or draft) is determined to be 3.68 m with a standard deviation of ± 2.77 m. Table 1 presents an overview of ice type percentages recorded by *Nautilus* across the Arctic Basin. This is followed by a discussion of the overall statistical results. Figures 3-6 present probability density plots of overall statistical results.

TABLE 1. Ice type overview

Type ^a	Draft (cm)	%
Open water/young ice	0-29.9	2.6
Thin ice	30-69.9	4.4
Medium ice	70-119.9	6.7
Thick first-year ice	120-199.9	14.1
Second-year ice	200-299.9	21.3
Multi-year ice	300-399.9	18.3
Deformed ice	400-4599.9	32.6

^aArctic sea ice terminology is after Weeks, 1976, and Stringer, *et al.*, 1984. The thicknesses are to be considered approximations only and not absolute limits.

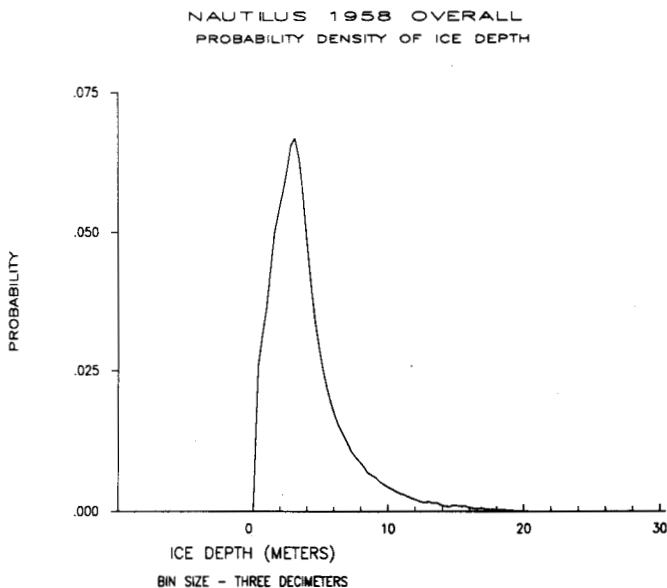


FIG. 3. Overall under-ice thickness probability density recorded by *Nautilus* across the Arctic Basin (after: McLaren, 1986).

Level ice. The percentage of level or undeformed ice (based on 1 in 40 gradient, as used by Wadhams, 1981) was 55.2%, with a mean draft of 2.85 m and a standard deviation of ± 2.52 m.

Independent keels. The mean draft of independent keels was 5.68 m, with a standard deviation of ± 3.04 m. For consistency and comparison purposes, the author uses a definition originating with Williams *et al.* (1975), which was subsequently refined by Wadhams (1981). That is: a keel is independent if its point of maximum draft is bracketed by points of minimum draft

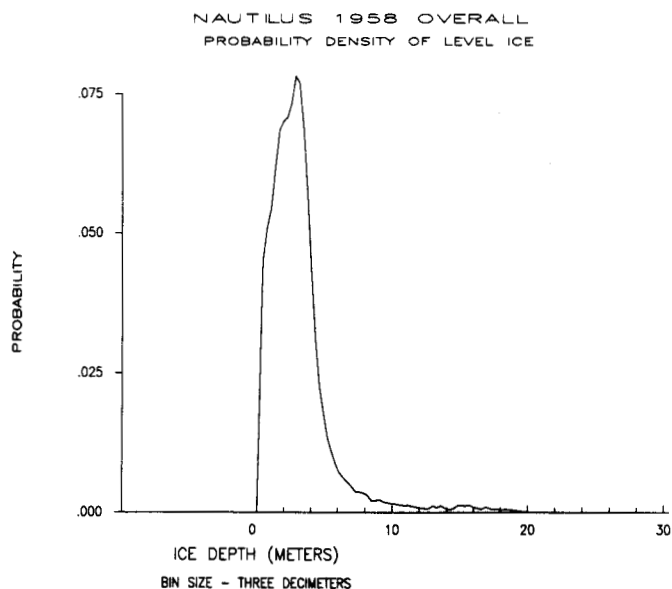


FIG. 4. Overall probability density of level ice recorded by *Nautilus* across the Arctic Basin (after: McLaren, 1986).

whose depths below the local undeformed ice bottom or underside is less than half of the keel's deepest point. Since a "local level ice bottom" is difficult to find in areas of heavily deformed ice, it is arbitrarily defined as being at a draft of 2.5 m. This is similar to the Rayleigh criterion for resolving spectral lines. Of the 16 055 independent keels measured, 7462, or 46.5%, were found to be greater than 5.0 m in draft (mean: 8.17 m); or 14.2%, to be greater than 9.0 m in draft (mean: 11.62 m); and the deepest draft keel recorded was 20.47 m. This last figure is certain to be too shallow. A close visual inspection of all ten

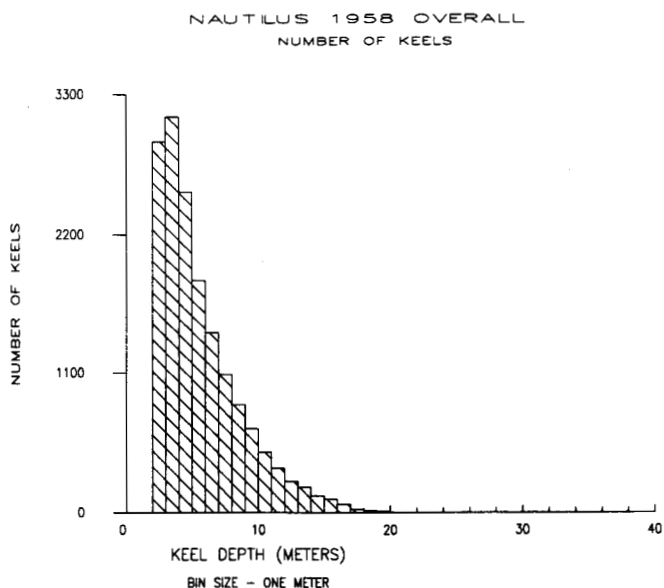


FIG. 5. The number and size of independent keels recorded by *Nautilus* across the Arctic Basin (after: McLaren, 1986).

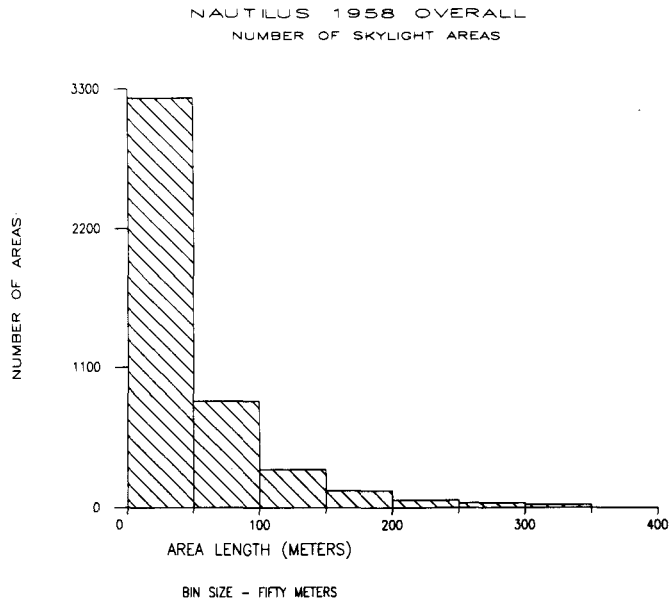


FIG. 6. The number and size of refrozen polynya/lead areas of thicknesses up to 1.0 m (skylights) recorded by *Nautilus* across the Arctic Basin (after: McLaren, 1986).

profile rolls revealed over 260 occasions where a deep draft keel went completely off the 0-55 feet (0-16.8 m) scale in use. Since the captain of *Nautilus* observed that the ice pack in the central Arctic Basin was running between 8 and 80 feet (2.4-24.4 m) thick, with keels down to 100 or 125 feet (30.4-38.1 m) (Anderson, 1959), the actual ice draft passed beneath can only be estimated. The deepest draft keel recorded by USS *Queenfish* in 1970 along the same route extended 36.5 m beneath the sea (McLaren, 1986).

The distribution of deep draft independent keels (see Fig. 5) appears to follow the same negative exponential functions described by Hibler *et al.* (1972), Rothrock and Thorndike (1980) and Wadhams (1983).

Refrozen leads and polynyas. Along the route 1613 measurable sections of what is probably open water or young ice (<30 cm thick) were revealed. Their mean length was 35.6 m; 203 of these were 50-100 m in length, and another 113 exceeded 100 m. The longest, an impressive 1474 m, was encountered by *Nautilus* at approximately 80°N latitude. The overall percentage of open water/young ice in the form of leads and polynyas was determined to be 2.6%.

When thin and medium ice (up to 100 cm thick) and inclusive of the open water/young ice category is included, some 4670 refrozen "skylights" are noted, with a mean length of 50.4 m; 835 of these were 50-100 m in length, and an additional 604 exceeded 100 m. The overall percentage of measurable "skylights" underrun by *Nautilus* was 10.6% of the total track.

A final refrozen lead/polynya category examined, inclusive of the above two categories, was what an arctic submariner would call a potentially "surfaceable area" (up to 200 cm thick) (McLaren, 1986). *Nautilus* passed beneath 9120 such areas, having a mean length of 67.3 m; 1871 were between 50 and 100 m in length and an additional 1757 exceeded 100 m in length. The overall percentage of measurable "surfaceable

areas" encountered between 1 and 5 August 1958 was 27.8% of the total route traveled.

Regional Variations

Close examination of under-ice draft statistics, probability density plots and histograms for smaller evaluation segments across the Arctic Basin revealed at least five distinct ice regions (see Fig. 1). The statistical results for each of these regions, which are presented in Table 2, show significantly different under-ice thickness characteristics and ice type compositions. Several of these regions and their general characteristics were noted by Captain William Anderson and by the voyage's chief scientist, Waldo Lyon, during *Nautilus's* journey beneath the polar ice pack (Anderson, 1959; Lyon, pers. comm. 1984).

Region I. This region extends approximately 536 km from the southern edge of the Canada Abyssal Plain (74°22.5'N, 155°04.0'W), where *Nautilus* first began recording the under-ice topography, to just past the northern edge of the Northwind Ridge (approximately 79°12.1'N, 155°04.0'W).

Region II. This region extends from 79°17.9'N, 155°04.0'W approximately 403 km to 82°55.0'N, 155°04.0'W, at the northern edge of the Canada Basin. This moderate ice region not only contained five large (510-1322 m in length) open/newly frozen-over leads or polynyas, but also over 16% of the area consisted of ice "skylights" up to 1.0 m in thickness, and approximately 38% of the region was spanned by refrozen "surfaceable areas" of up to 2.0 m in thickness.

Region III. This region extends approximately 491 km across the Alpha Ridge from 83°03.2'N, 155°04.0'W to 87°28.2'N, 154°00.0'W. The under-ice topography of this and the next region were all recorded using a 50 kHz signal. This region also was found to contain five more very large (517-1558 m in length) open/newly refrozen leads or polynyas.

Of particular interest within this region was the detection of two smaller, uncharacteristic sub-regions approximately 38 and 57 km in length. The first, located directly above one of the shallowest (500 m) sections of the Alpha Ridge, was composed of almost (85%) second, multi-year and deformed ice, of which approximately 48% was deformed or heavily rafted/hummocked ice over 4.0 m in draft. An overall mean draft of 4.78 m, with a standard deviation of ± 3.32 m, indicates it to be an area of extreme under-ice roughness. The second sub-region was located, interestingly, above a deep (3000 m) trough within the Alpha Ridge. It was composed of almost (50%) young through thick first-year ice and had an overall mean draft of 2.91 m with a standard deviation of ± 2.53 m. Over 47% of this area was covered by refrozen leads and polynyas of up to 2.0 m thick.

Region IV. With this region, the under-ice topography recorded by *Nautilus* in 1958 became thicker and rougher as the route passed beneath the North Pole en route the Arctic Mid-Ocean Ridge. This transpolar region extended approximately 506 km from 87°28.2'N, 155°00.0'W across the Makarov Basin, North Pole and Amundsen Basin to 87°58.6'N, 025°00.0'E.

Approximately 100 km separate Regions IV and V. Profile recording equipment malfunctions prevented *Nautilus* from obtaining under-ice draft data from this potentially very interesting portion of the Amundsen Basin.

Region V. The final distinctive ice region revealed by analysis of the under-ice topography recorded by *Nautilus* was noted to extend some 500 km across and along the Arctic Mid-Ocean

TABLE 2. *Nautilus* 1958 overall and regional statistics

Recorded at	Overall (50/180 kHz)	Region I (180 kHz)	Region II (180 kHz)	Region III (50 kHz)	Region IV (50 kHz)	Region V (50/180 kHz)
Length (km) ^a	2580	536	403	491	505	501
<i>Ice profile</i>						
Mean draft (m)	3.68	3.25	2.86	3.44	4.05	4.59
Corrected (m)	(3.36)	—	—	(2.87)	(3.39)	(4.31)
Std. dev. (±)	2.77	2.07	2.14	2.68	3.10	3.21
<i>Ice types^b</i>						
% young (0-29.9 cm)	2.60	2.02	4.22	4.57	1.98	1.02
% thin (30-69.9 cm)	4.35	3.55	5.85	5.12	4.40	1.98
% medium (70-119.9 cm)	6.69	5.07	10.19	7.41	7.32	3.90
% thick first-year (120-199.9 cm)	14.13	13.50	18.01	15.39	14.71	9.65
% second-year (200-299.9 cm)	21.29	29.03	23.27	20.33	17.81	16.58
% multi-year (300-399.9 cm)	18.33	23.54	17.68	16.68	14.90	19.22
% deformed (400-4599.9 cm)	32.62	23.29	20.78	30.51	38.88	46.34
<i>Level ice^c</i>						
% occurrence	55.2	61.9	64.2	51.8	51.5	48.3
Mean draft (m)	2.85	2.57	2.29	2.70	3.06	3.71
Std. dev. (±)	2.52	1.54	1.77	2.66	2.90	3.29
<i>Independent keels^d</i>						
Total	16055	3712	2415	3053	2939	3069
Mean draft (m)	5.68	5.14	4.99	5.05	6.34	6.70
Std. dev. (±)	3.04	2.57	2.60	2.59	3.31	3.51
% greater than 5.0 m draft	46.5	38.9	36.1	39.2	55.4	59.9
Mean draft (m)	8.17	7.62	7.70	7.60	8.59	8.79
% greater than 9.0 m draft	14.2	8.9	8.9	8.7	20.6	22.9
Mean draft (m)	11.62	11.35	11.28	11.24	11.63	11.99
Ridging intensity · km ⁻¹	1.03	0.70	0.59	0.69	1.33	1.69
Max keel draft (m)	>20.47	18.44	19.37	18.56	19.59	>20.47
<i>Polynyas/leads</i>						
% surfaceable areas (<200 cm thick)	27.8	24.1	38.3	32.5	28.4	17.9
Number of length greater than 400 m	131	28	51	21	24	3
Maximum length (m)	1690.0	992.0	1690.0	1559.9	870.4	606.7
% skylights (<100 cm thick)	10.6	8.0	16.2	13.8	10.3	6.6
Number of length greater than 400 m	34	6	15	9	4	0
Maximum length (m)	1558.2	792.6	1321.6	1558.2	539.1	378.6
% open water/new ice (<30 cm thick)	2.6	2.0	4.2	4.6	2.0	1.0
Number of length greater than 400 m	7	2	2	3	0	0
Maximum length (m)	1473.7	790.9	535.7	1473.7	343.1	240.0

^aIncludes all data gaps due to submarine recording equipment malfunction or ship's maneuvers.

^bArctic sea ice terminology is after Weeks, 1976, and Stringer *et al.*, 1984. The thicknesses are to be considered approximations only and not absolute limits.

^cBased on 1 in 40 gradient used by Wadhams (1981).

^dFor consistency and comparison purposes the author uses a definition originating with Williams *et al.* (1975), which was refined by Wadhams and Horne (1980).

Ridge from 87°05.0'N, 025°00.0'E via 85°25.0'N, 025°00.0'E to 83°25.0'N, 006°30.0'E, due north of a point midway between Spitsbergen and Greenland. As can be seen in Table 2, this region in 1958 had the most rugged under-ice topography recorded by *Nautilus*. Close examination of the statistical output and of the raw under-ice profile rolls that spanned this region revealed that within it were the deepest draft ice keels under-run by *Nautilus*, with 20.47 m the deepest recorded. Over 100 keels ran completely off the recording charts.

Figures 7 and 8 present a comparison of the five ice regions *Nautilus* encountered during her transpolar voyage. The principal indicators, listed in order of relative importance/evaluation weight, used to assess differences in areal ice conditions between regions and to make determinations as to the relative ice conditions encountered are: (1) uncorrected mean ice drafts and standard deviations; (2) total percentages of multi-year and deformed ice; and (3) percentages of open water/new ice. These figures confirm that *Nautilus* encountered the most moderate under-ice topography and the greatest number of open water and refrozen polynyas and leads within the Canada Basin.

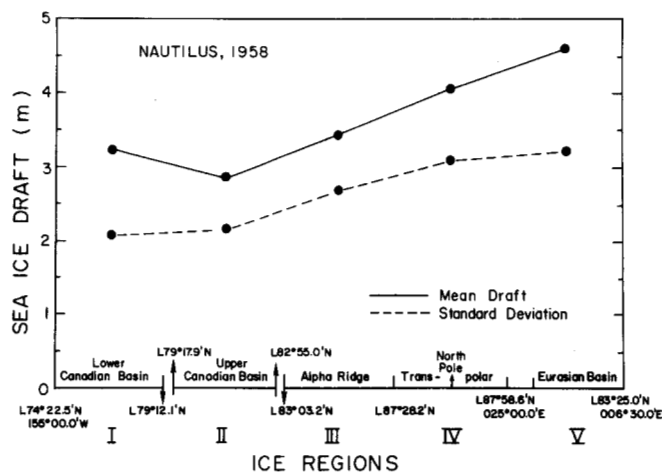


FIG. 7. Plot of mean ice draft (m) and standard deviation statistical results derived from under-ice thickness data recorded by *Nautilus* within five distinct ice regions encountered across the Arctic Basin.

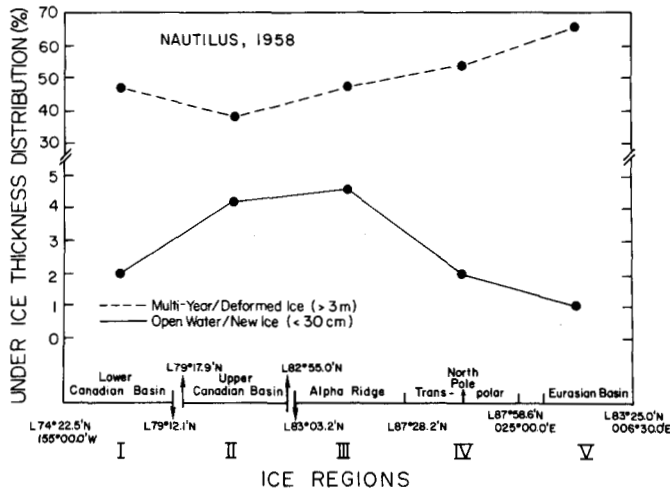


FIG. 8. Plot of mean multi-year and deformed ice and open water statistical results derived from under-ice thickness data recorded by *Nautilus* within five distinct ice regions encountered across the Arctic Basin.

These figures also indicate that the under-ice topography became progressively more rugged as *Nautilus* proceeded across the Arctic Basin and that she encountered the most severe under-ice topography along the Arctic Mid-Ocean Ridge within the Eurasian Basin.

COMPARISON OF NAUTILUS RESULTS WITH OTHER OBSERVATIONS

Comparison of Field Observations

Nansen (1897), based on *Fram* 1893-96 voyage measurements, reported that the average thickness of floes in the Trans-Polar Drift Stream ranged from 3.05 to 3.66 m. Ice thickness is taken to be the total thickness of sea ice as opposed to ice draft, which is that portion of the sea ice beneath the surface of the sea. The ratio of the above surface "sail" to the beneath the surface "keel" can range from 1:11.75, in the case of first-year ice, to 1:3.2 for deformed deep draft ice (Ackley *et al.*, 1976). Nansen found newly formed ice to reach a thickness of 2.74 m at the end of one season and 3.00 m after more than a year and a half; and that the greatest thickness ice reached "without being piled up" (i.e., mechanical/ridging action) was 4.22 m. Zubov (1943), from Soviet field measurements, reported that the thickness of old pack ice was not less than 3.0 m, the thickness of perennial ice was 2.31-3.30 m, and that the open water areas did not exceed 2% even in summer (this excludes refrozen leads/polynyas). He later (1959) stated that the maximum thickness of sea ice in the Arctic Basin varied between 3.0 and 5.0 m and that "flat" (i.e., level) ice thicknesses will be 1.90 m by the end of the first summer and 2.90 m by the end of the second summer. The *Nautilus* results reported herein generally agree with both Nansen's and Zubov's observations.

Wittmann and Schule (1966), in reporting U.S. submarine cruise results for 1960 and 1962, stated that: (1) the average arctic pack ice thickness was between 2.36 and 4.72 m and varied widely about an average of 3.94 m; (2) 13-18% of the Arctic is covered by pressure ice considerably thicker than the average; and (3) 12% of the Canadian Basin and 7% of the Eurasian Basin are open water during summer. *Nautilus's*

overall statistical results support Wittmann and Schule's pack ice thickness and pressure ice percentages but not the open water percentages reported.

Koerner (1970), from several hundred thickness measurements taken through ponded areas of multi-year floes during the 1968/69 British Trans-Arctic Expedition, reported a "modal value" between 2.0 and 3.0 m and an overall average of 4.17 m. Koerner later (1971, 1973) reported that: (1) the mode of the thickness measurements through level areas of old floes along the entire route is 2.27-2.75 m; (2) the season's maximum growth of ice from open water is 2.04 m; and (3) the mean overall pack ice thickness across the Arctic Basin is 3.7 m. A comparison of Koerner's results with the *Nautilus* Statistical Summary (Table 2) reveals that although Koerner's results are generally in accord, his estimates for overall level mean ice thicknesses are less than the level under-ice drafts (known to be less than overall ice thickness) measured by *Nautilus*.

Swithinbank's (1972) preliminary analysis of HMS *Dreadnought's* cruise to the North Pole in 1971 reported that: (1) the roughest ice bottom topography was found between 86° and 88°N (Eurasian Basin); (2) about 5% of the total track consisted of ice less than 30 cm thick; (3) a total of 13% was newly formed ice through first-year ice; (4) the mean draft of relatively undeformed (i.e., level) ice was 2.3 m; (5) there was no significant trend in the mean thickness of level ice from 80 to 90° latitude; and (6) mean overall and level ice drafts for the Eurasian Basin were 2.6 and 2.2 m respectively.

The statistical summaries for *Nautilus* Regions IV and V (Table 2), which cover approximately the same geographical area, appear compatible with all of Swithinbank's observations except for: (2) (percentage of ice less than 30 cm thick). *Nautilus* statistical results also confirm Koerner's (1973) and Swithinbank's (1972) suggestions that ridges (i.e., keels) account for a significant amount of the overall ice thickness in the Arctic.

Williams *et al.* (1975) reported a computer statistical analysis of the 1971 *Dreadnought* under-ice data. Their Table 3 (reproduced here as Table 3) compares Eurasian Basin mean ice drafts obtained by *Nautilus* in 1958 with those obtained by *Dreadnought* within 150 km geographically.

TABLE 3. Mean draft August 1958 compared with mean draft March 1971 (after Williams *et al.*, 1975)

Latitude (°N)	August 1958 (m) (<i>Nautilus</i> statistical analysis: McLaren, 1986)	March 1971 (m) (<i>Dreadnought</i>)	August 1958 (m) (<i>Nautilus</i> manual analysis: Lyon, 1961)
89-90	3.66	5.13	5.06
88-89	4.79	4.66	5.82
87-88	3.65	5.04	5.52
86-87	4.81	4.52	6.03
85-86	4.31	3.61	5.35
85-90	4.33	4.29	5.36

A comparison of the results of Williams *et al.* (1975) with this author's analysis of *Nautilus* 1958 data reveals that although the mean ice drafts attributed to Lyon (1961) are significantly higher, those from *Dreadnought* appear roughly comparable with *Nautilus* results. The Williams *et al.* (1975) mean level ice drafts (2.27-2.82 m) for the same geographic area can also be considered compatible. However, the large areas (up to 22%) of thin ice reported in the vicinity of 87°N are not confirmed, nor is

the mean draft and frequency of ice keels reported by Williams *et al.* (1975). Both are considerably greater than *Nautilus* recorded, possibly due to seasonal differences and attendant environmental effects.

Wadhams and Horne (1980) conducted an analysis of under-ice profiles recorded by the submarine *Gurnard* in the southern Beaufort Sea during April 1976. Analysis sections 8-13 of their report are geographically comparable with the first 88 km of *Nautilus*'s Region I. A comparison of the results obtained by both submarines using narrow beam acoustic profilers is of interest.

As can be seen in Table 4, concurrence of *Gurnard* 1976 data with *Nautilus* 1958 data is excellent; and differences in percentage of 0-100 cm draft ice and number of independent keels exceeding 9.0 m draft·km⁻¹ can be accounted for as expected seasonal variations.

TABLE 4. Beaufort Sea ice thickness distribution comparison

	<i>Gurnard</i> (April 1976) (Wadhams and Horne, 1980)	<i>Nautilus</i> (August 1958) (McLaren, 1986)
Overall mean ice		
ice draft (m)	3.55	3.54
% 0-200 cm draft ice	11.25	17.28
% 0-100 cm draft ice	1.97	9.18
% level ice	55.78	59.25
Overall mean level		
ice draft (m)	2.87	2.82
Independent keels >9.0 m draft		
Mean draft (m)	11.60	11.49
Number·km ⁻¹	1.52	0.70

Wadhams (1981) did a statistical analysis of HMS *Sovereign*'s Arctic Ocean cruise during October 1976. Central Arctic (Eurasian Basin) results, which are geographically comparable to *Nautilus* 1958 results, are as follows. As can be seen in Table 5, Wadhams's (1981) data are generally in accord with *Nautilus*'s 1958 measurements. Although differences in ice thickness distribution and lead/polynya percentages are those that would be expected seasonally, there is presently no explanation for the difference in the number of deep draft independent keels encountered.

TABLE 5. Eurasian Basin ice thickness distribution comparison

	<i>Sovereign</i> (October 1976) (Wadhams, 1981)	<i>Nautilus</i> (August 1958) (Regions IV and V)
Under-ice profile		
Mean draft (m)	5.37	4.33
Corrected	3.9-5.1	3.1-4.3
% 0-50 cm	1.56	3.64
% 50-200 cm	6.00	23.31
% 200-500 cm	50.00	50.21
% >500 cm	42.00	22.83
Level ice		
%	45-55	47-54
Mean draft (m)	3.0-3.1	2.6-3.8
Independent keels		
Number >9.0 m draft·km ⁻¹	2-3	1.0-1.7
Leads/polynyas		
% <100 cm thick	1-5	6.6-11.0
Number >500 m in length	2	1

Modeling Results

Sea ice thickness distribution is of particular interest to climate modelers because of its influence on the rate of heat input to the atmospheric and oceanic boundary layers (Thorndike *et al.*, 1975). Hibler (1980) presented a numerical framework for the simulation of a variable thickness sea ice cover over a seasonal cycle based largely on the ice thickness distribution model, expanded to include lateral melting effects and a fixed depth oceanic mixed layer, developed by Thorndike *et al.* (1975). By using it in conjunction with his previously developed dynamic model (Hibler, 1979) and a thermodynamic model similar to that of Semtner (1976), he was able to carry out a seasonal equilibrium simulation of the Arctic Basin using what he termed a "Variable Thickness Dynamic Thermodynamic Sea Ice Model."

Figures 9 and 10 reproduce Hibler's (1980) Figures 4 and 9, which depict average August ice thickness (m) contours as a result of the following variable-thickness sea ice cover five-year simulations: (1) mechanical and thermodynamic; (2) thermodynamics only; (3) high strength; and (4) high growth. *Nautilus*'s 1958 track is superimposed on Figures 9 and 10 for comparison purposes. Note that the actual regional mean ice drafts recorded by *Nautilus* along her track are significantly greater than the simulation ice thickness contours indicate for the same geographic areas.

CONCLUSION

This statistical analysis of the under-ice topography recorded by the USS *Nautilus* across the Arctic Basin during her historic voyage has yielded much to intrigue those doing research in arctic oceanography, glaciology and climatology.

The statistical results allow the following observations to be made: (1) with the exception of modeling, the statistical results from the 1958 *Nautilus* voyage are basically in agreement and support the findings of earlier sea ice researchers with no real variations in ice cover being revealed; their summer open water estimates, however, may be too high; (2) ice conditions appear to become progressively more severe when proceeding from the Canadian to the Eurasian side of the Arctic Basin; (3) the Canada Basin contained the most moderate under-ice topography and the greatest number of open water/refrozen leads and polynyas encountered by *Nautilus* during her transpolar voyage; (4) *Nautilus* encountered the most severe under-ice thickness distribution along the Arctic Mid-Ocean Ridge within the Eurasian Basin; and (5) the statistical results (Table 2) reveal that *Nautilus* passed beneath at least five distinct ice regions as she proceeded across the Arctic Basin.

In conclusion, this first detailed analysis of 2580 km of under-ice thickness distribution data recorded by *Nautilus* during her historic voyage across the Arctic Basin should provide sea ice and climate system modelers with a wealth of data suitable for modeling input and validation. It should also provide an invaluable basis for comparison with these yet unexamined under-ice topography recorded by over 50 American and British submarines during the almost 30 years that have followed *Nautilus*'s historic cruise.

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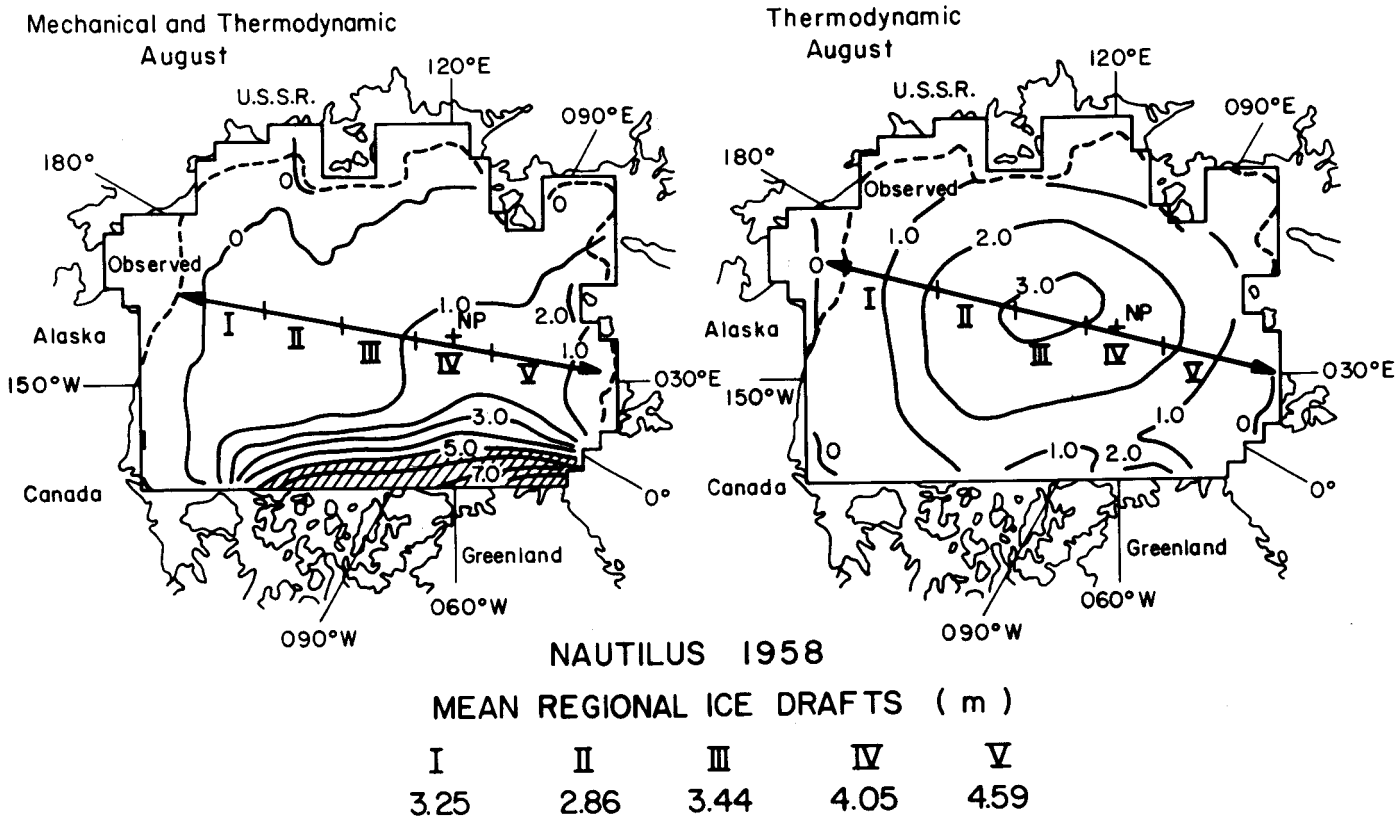


FIG. 9. Plot of route followed by *Nautilus* across the Arctic Basin superimposed on Hibler's (1980) plot of "Average August Thickness Contours (m) for the Fifth Year of Standard and Thermodynamics Only Simulations."

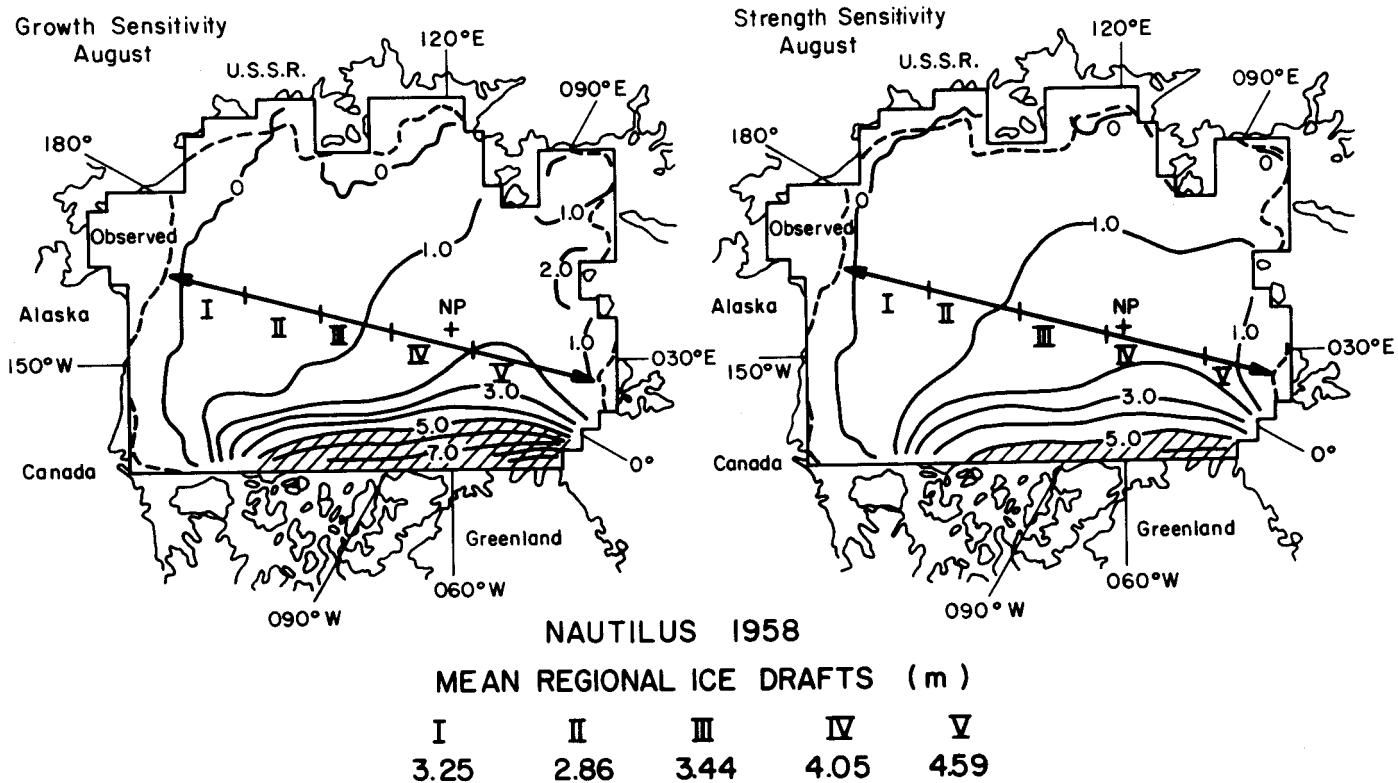


FIG. 10. Plot of route followed by *Nautilus* across the Arctic Basin superimposed on Hibler's (1980) plot of "Average August Thickness Contours (m) for High Strength and High Growth Simulations."

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REFERENCES

- ACKLEY, S.F., HIBLER, W.D., KUGZRUK, F.K., KOVACS, A., and WEEKS, W.F. 1976. Thickness and Roughness Variations of Arctic Multiyear Sea Ice. CRREL Report 76-18, USA CRREL, Hanover, New Hampshire.
- ANDERSON, W.R. 1959. Nautilus 90 North. Cleveland: The World Publishing Company. 251 p.
- HIBLER, W.D. 1979. A dynamic thermodynamic sea ice model. *Journal of Physical Oceanography* 9(4):815-846.
- _____. 1980. Modeling a variable thickness sea ice cover. *Monthly Weather Review* 108(12):1943-1973.
- _____, WEEKS, W.F., and MOCK, S.J. 1972. Statistical aspects of sea ice distributions. *Journal of Geographical Research* 77(30):5954-5970.
- KOERNER, R.M. 1970. Weather and ice observations of the British Trans-Arctic Expedition 1968-9. *Weather* 25(5):218-228.
- _____. 1971. Ice balance in the Arctic Ocean. *AIDJEX Bulletin* 6:11-26.
- _____. 1973. The mass balance of the sea ice of the Arctic Ocean. *Journal of Glaciology* 12(65):173-185.
- LYON, W. 1961. Ocean and sea-ice research in the Arctic Ocean via submarine. *Transactions of the New York Academy of Sciences Series II* 23(8):662-674.
- McLAREN, A.S. 1986. Analysis of the under-ice topography in the Arctic Basin as recorded by USS NAUTILUS in 1958 and USS QUEENFISH in 1970. Ph.D. dissertation, University of Colorado. 163 p.
- NANSEN, F. 1897. Some results of the Norwegian Arctic Expedition 1893-96. *Geographical Journal* IX(5):473-528.
- ROTHROCK, D.A., and THORNDIKE, A.S. 1980. Geometric properties of the underside of sea ice. *Journal of Geophysical Research* 85(C7):3955-3963.
- SEMTNER, A.J., Jr. 1976. A model for the thermodynamic growth of sea ice in numerical investigations of climate. *Journal of Physical Oceanography* 6:379-389.
- STRINGER, W.J., BARNETT, D.G., and GODIN, R.H. 1984. Handbook for sea ice analysis and forecasting, NAVENVPREDSCHFAC CR 84-03. Monterey, California: Naval Environmental Prediction Research Facility.
- SWITHINBANK, C.W.M. 1972. Arctic pack ice from below. In: Karlsson, T., ed. *Sea Ice, Proceedings of the International Sea Ice Conference*, Reykjavik, May 1971, National Research Council of Iceland. 246-254.
- THORNDIKE, A.S., ROTHROCK, G.A., MAYKUT, G.A., and COLONY, R. 1975. The thickness distribution of sea ice. *Journal of Geophysical Research* 80(33):4501-4513.
- WADHAMS, P. 1981. Sea-ice topography of the Arctic Ocean in the region 70 degrees W to 25 degrees E. *Philosophical Transactions of the Royal Society of London* 302(1464):45-85.
- _____. 1983. Arctic sea ice morphology and its measurement. *Journal of the Society for Underwater Technology* 9(2):1-12.
- _____, and HORNE, R.J. 1978. An analysis of ice profiles obtained by submarine sonar in the AIDJEX area of the Beaufort Sea. *Scott Polar Research Institute Technical Report 78-1*. Cambridge, England: Scott Polar Research Institute. 65 p.
- _____. 1980. An analysis of ice profiles obtained by submarine sonar in the Beaufort Sea. *Journal of Physical Oceanography* 25(93):401-424.
- WEEKS, W.F. 1976. Sea conditions in the Arctic. *AIDJEX Bulletin* 34:173-205.
- WILLIAMS, E., SWITHINBANK, C., and ROBIN, G. de Q. 1975. A submarine sonar study of Arctic pack ice. *Journal of Glaciology* 15(73):349-361.
- WITTMANN, W.I., and SCHULE, J.J. 1966. Comments on the mass budget of Arctic pack ice. In: Fletcher, J.O., ed. *Proceedings of the Symposium on the Arctic Heat Budget and Atmospheric Circulation, Memorandum RM-5233-NSF*, January 31 through February 4, 1966, Lake Arrowhead, California, Santa Monica, California, The Rand Corporation. 215-246.
- ZUBOV, N.N. 1943. *Arctic Ice*. Moscow: Izdatel'stvo Glavsevmorputi. Translated for the U.S. Air Force Cambridge Research Center by the USN Oceanographic Office and the American Meteorological Society. 360 p.
- _____. 1959. The maximum thickness of sea and continental ice. *Meteorologiya i Hidrologiya*:22-27. Translated by John Miller, American Meteorological Society, for the Geophysics Research Directorate, U.S. Air Force Cambridge Research Center.