FOIA Number: 2012-0769-F

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Correspondence with Panel

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Analysis & Technology, Inc.
Two Crystal Park
2121 Crystal Drive, Eighth Floor
Arlington, VA 22202
(703) 892-1042

6 April 1990

Dear Rick,

Here is the error budget requested by the Senator. Obviously in other environments and under other operating conditions the individual errors could change significantly, ... but the "potential" would be about the same.

I have had this reviewed by others who are experts in the field of ice profiling and have received general agreement.

I'll start on researching the international agreements for data sources next week.

Sincerely,

George

George B. Newton

GEORGE NEWTON

Analysis & Technology, Inc.
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Technology Park, Route 2
P.O. Box 220
North Stonington, CT 06359
(203) 599-3910

4 April 1990

Mr. Rick Adcock
393 R.B. Russell Senate Office Building
United States Senate
Washington, DC 20510-4204

Dear Mr. Adcock,

I have collected what I believe to be a reasonably complete description of the sources of error that may accumulate in the measurement of the ice profile on a submarine. They are described in some detail in enclosure(1). With some imagination I am sure others could be added. (Error budgets tend to be that sort of game.)

While the total maximum potential error may appear large, one should recognize that, as in any statistical evaluation, the individual errors seldom are at their maximum, nor are they of the same sign at the same time.

Please excuse me if I have written these in too simplistic a fashion. From my experience as a teacher, submarine concepts sometimes are difficult to absorb when written as a stand-alone explanation.

I have also included a copy of a brief explanation of the ability to estimate the amount of freeboard that should exist in flat, level sea ice, given an accurate ice profile dimension. It was prepared by Dr. Robert Bourke of the U.S. Naval Postgraduate School and a recognized expert in polar oceanography and sea ice.

If you have any questions on this please do not hesitate to call me. I will be in Woods Hole, Ma., 9-11 April where I will attend the quarterly meeting of the U.S. Arctic Research Commission. During that meeting, I have been asked to provide the Commissioners a brief overview on the the objectives Senator Gore's Sea Ice Panel.

Sincerely,

Geoge B. Newton
Department Manager
Advanced Systems and
Arctic Technology

GBN:ltj:90:17-003
P6002.02.002

Enclosures: (2)

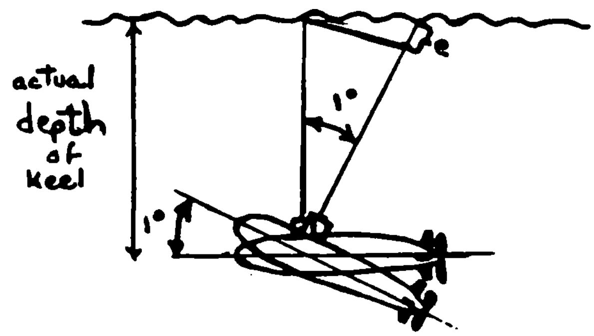
Copy to:
List of Sea Ice Specialists

SOURCES OF ERROR
IN ICE PROFILE MEASUREMENTS

1. Effect of SSN trim angle an ice profile accuracy.

a. Surface Sounder is not compensated for any deviation of submarine trim angle 0 degrees (the horizontal).

b. Given that the SSN has a 1°trim angle (from the horizontal) the conceptual measurement of the underice profile would be subject to an error (e) as shown:



If the SSN is at keel depth of 250° the error introduced to the profiler is small, - on the order of 0.5 inches. For trim angles less than 1°, a more likely occurrance, the error is even smaller.

2. Effect of a change in sound velocity in sea water.

a. Surface Sounder has a manually adjustable selection for the sound velocity of sea water:

4712 feet per second (fps)
4800 fps
4900 fps
5000 fps

b. If the sound velocity set in the profiling system is 4800 fps and the actual average sound velocity between the SSN transducer and the underside of the ice is 4900 fps, the following describes the error magnitude.

Assume the SSN is at 250 feet in open water. If the sound velocity is 4800 fps (same as that set in the profiler system), then the time for a sound impulse to be sent to the ice and returned is determined using the 2 way transmission time and the formula:

$$\text{distance} = \text{speed} \times \text{time}$$

or

$$500 = 4800 \times \text{time}$$

or

$$t = \frac{500}{4800}$$

$$t = .10416 \text{ seconds.}$$

This, when compared to the SSN keel depth of 250', results in a display of 0' on the ice profiler (open water).

Now if the actual water column sound velocity is 4900 fps (average), but 4800 is set in the machine, an error is introduced. The sound impulse travels to and returns from the ice as follows:

$$500 = 4900 \times \text{time}$$

and $$t = .10204 \text{ seconds}$$

The difference in time between the echo returns is:

$$t = .10416 - .10204 = .00212 \text{ seconds}$$

Returning to the original formula, and the equation the system believes it is solving:

$$\Delta d = 4800 \times \Delta t$$

$$\Delta d = .00212\text{s} \times 4800$$

$$\Delta d = 10.176 \text{ feet}$$

Recall the 10.176 feet is total distance traveled and thus the profiler displays one half of that, or 5.1 feet of ice overhead, as opposed to 0.0 feet of ice or open water.
This error is removed every time the SSN is in open water at a given depth. At that time, the system correction can be determined for that depth and the correction factor noted on the recorder.

c. Worse yet, as the SSN goes deeper and records the ice profile, the error caused by the 100 fps error in average sound velocity proportionally becomes larger. For example, solving the foregoing problem if the SSN is at keel depth of 400 feet instead of 250 feet, the error increases by a factor of 1.6 times and 8.16 feet of ice would be displayed where, in fact, there was no ice overhead. Looking at this error source from a different perspective, if the SSN is at deep depths, even a small difference in the set and actual sound velocities will result in a significant (and erroneous) ice profile being displayed.

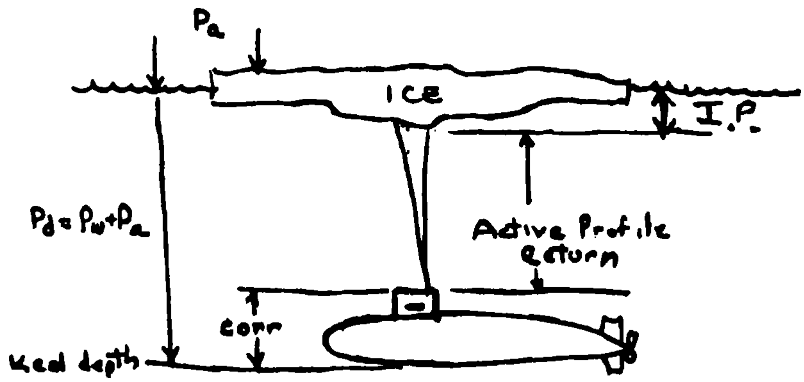
3. **Other possible sources of ice profiling errors:**

a. The submarine depth detector system employs a classic bourdon tube sensor. These are reasonably accurate and reliable. An accepted system error is ±0.5 feet.

b. The synchro transmission system used to distribute (transmit) SSN keel depth to the BQ5-15 ice profiling sub-system has been observed to be as much as ±2.0 feet.

4. **Effect of atmospheric pressure on ice profiling system.**

a. The submarine ice profiling sub-system develops its readout from the combination of two inputs. The profiler gets one input from the ship's depth detector and corrects that depth (which is keel depth) to reflect the position of profiler projector on the top of the sail. The second input comes from the return of the high frequency profilier pulse which travels from the projector to the top of the water column and is reflected from the air-water or ice-water interface, which ever it sees.



Conceptually the determination of the ice profile (I.P.) dimension is as follows:

$$\text{I.P.} = (\text{Pd} - \text{Keel Correction}) \pm (\text{Active Profiler Return}) \qquad (1)$$

b. The original keel depth input signal is a value that is a measure of the sea pressure at the depth of the submarine's keel. That pressure reflects the sum of the water pressure (Pw) and atmospheric pressure (Pa):

$$\text{Pd} = \text{Pw} \pm \text{Pa} \qquad (2)$$

Therefore, if Pa changes from its reference setting of 29.92 inches of mercury (14.7 psi), then the Pd input changes, and an equivalent error is created in the first term of the ice profile equation (1).

c. The magnitude of that error is shown as follows:

If the current atmospheric pressure (Pa_2) decreases by one inch of mercury from the pressure (Pa_1) at which the system was "zeroed" in open water (at which time the atmospheric pressure was, for example, 29.92" Hg), then the ratio of the two pressures is:

$$\frac{Pa_2}{Pa_1} = \frac{28.92}{29.92} = .9666 \qquad (3)$$

or converting the pressure difterential to english units we have:

$$Pa_1 \times .966 = Pa_2$$

$$14.7 \times .966 = 14.209 \text{ psi} \qquad (4)$$

and the difference in pressure becomes:

$$Pa_1 - Pa_2 = Pa$$

$$14.7 - 14.209 = .491 \text{ psi} \qquad (5)$$

Now at a depth of 100 feet, the sea pressure is 44.6 psi at nominal atmospheric pressure of 29.92" Hg. Therefore at 28.92" Hg the ship's pressure detector at 100' would see a change of:

$$\frac{.491}{44.6} = .011 \text{ or } 1.1\% \text{ change}$$

and thus

.011 X 100' = 1.1 ft error for a 1" Hg change.

d. Example:

If the SSN is at 100' Keel depth and atmosphereic pressure is 29.92" Hg, and there is actually 1.9' of ice, formula (1) becomes:

$$I.P. = (100 - 51.1) - 47$$

$$I.P. = 1.9'$$

However, if the atmospheric pressure is actually 28.92" Hg, without rezeroing the system, the depth gauge reads 100' but the SSN is really at 101.1', and formula (1) yields:

$$I.P. = (101.1 - 51.1) - 47$$

or

$$I.P. = 50 - 47 = 3'$$

and I.P. = 3' is indicated when there is 1.9' actual ice overhead.

5. Effect of position of the ice profiler projector on SSN 637 Class platforms:

The SSN ice profiling sub-system must correct the depth detector input from keel depth to the actual location of the projector on the top of the SSN sail. The current sub-system is part of the BQS-15 underice sonar designed for the SSN 688 Class. The correction built into the system is the actual keel-to-sail difference of that class, 51.1 feet. The SSN 637 Class uses the same sub-system (called the OD-161 Modification). However, the actual keel-to-sail dimension is 51.46 feet. Thus an error of +0.36 feet (4.3 inches) is introduced into all ice profile values. (The error was neglected in the earlier discussion of errors caused by atmospheric pressure.)

6. Summary of Potential errors in ice profile measurements (Total Error Budget):

		Feet
a.	Trim angle error (1° @ 250')	±0.042
b.	Sound Velocity error (100 fps @ 250')	±5.1
c.	Keel depth sensor error	±0.5
d.	Synchro transmission error	±2.0
e.	Atmospheric pressure change (1" Hg)	±1.1
f.	Ice profiler projector position in SSN 637 Class	0.36
TOTAL MAXIMUM POTENTIAL ERROR:		**±9.102 feet**

Best Estimate of Above-Ice Portion From Under-Ice Submarine Profile Data

By Robert H. Bourke

Introduction

Determining the total thickness of sea ice has always been a difficult task—difficult to measure and difficult to estimate. The most accurate measurements are those determined by drilling a hole, a laborious and time-consuming effort not suitable for wide-area surveys. It is also possible to arrive at an ice thickness by measuring the draft of the below-sea-level portion of the ice through an upward-looking submarine sonar and add to it the freeboard, the above-sea-level portion, determined from airborne laser profiliometry. This technique has not proved very successful, however, due to the difficulty of navigational control. Each of the latter methods—echo sounder and profilometer—can provide an accurate assessment of the draft and freeboard, respectively, but not of the total ice thickness. Estimating one based on measurements of the other is unreliable in determining ice thickness statistics.

Of the two, an accurate determination of the ice draft is far more important in establishing the total ice thickness, as the draft comprises 70% to 95% of the ice thickness. Submarine under-ice profiles of the ice draft are considered accurate within 0.05 to 0.06 m (Wadhams, 1983), and many thousands of kilometers of submarine under-ice track lines exist over almost all areas of the Arctic Ocean (Garrett, 1985).

To date, no technique exists to estimate the high-frequency component of the freeboard, but several techniques have been suggested to estimate its low-frequency component. Of these, the simplest and most often-used technique is to assume that the ice is homogeneous with a constant density. Based on the principal of isostatic equilibrium, the freeboard can then be estimated from a measurement of the ice draft. It is known, however, that there are large horizontal and vertical variations in ice salinity and brine content and, hence, in its density distribution (Cox and Weeks, 1974). To overcome this problem, Ackley et al. (1976) suggested a method employing a variable ice density scheme to estimate ice thickness. This technique is the primary method used in the analyses of ice thickness in this study.

Methodology

Ackley et al. (1976) measured the ice thickness of three multiyear floes, ranging from 80 to 200 m long, by drilling closely spaced holes along transects that crossed them. Simultaneously, laser profilometry of the freeboard along these transects was obtained. The density of the ice at each profile point was estimated from the measured values of freeboard, ice thickness, and snow depth and a linear regression was fitted to the data. An estimate of the ice thickness could then be derived from a measured effective freeboard (snow depth converted into an equivalant ice thickness assuming a mean snow density) and ice density determined from the linear regression. Ackley et al. (1976) present a field nomogram (Figure 2-1) that graphically preforms the transformation. This figure permits an estimation of ice thickness from measurements of effective freeboard.

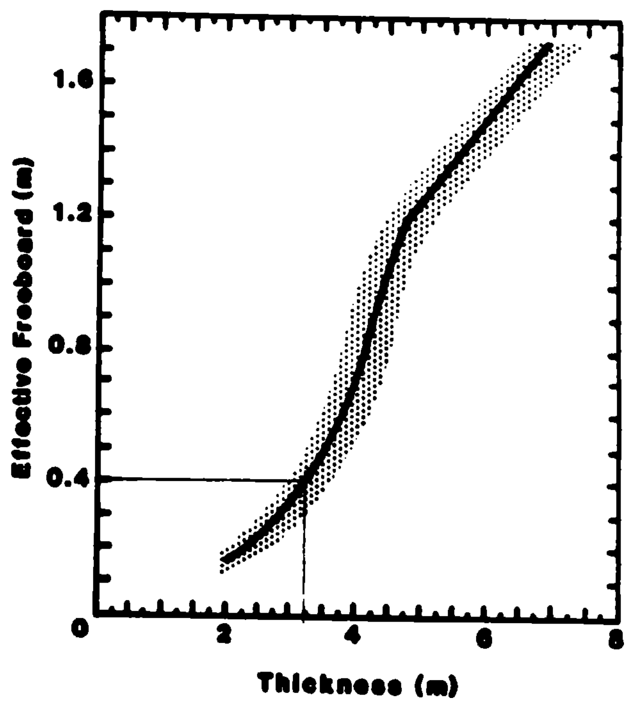


Figure 2-1. Ice Thickness Plotted as a Function of Effective Freeboard Using the Variable Density Prediction Scheme [from Ackley et al., 1976]

In contrast to the data of Ackley et al., ice draft, not freeboard, was the measured variable for this study. The data in Figure 2-1 were replotted to express this condition based on the relation

$$d = t - f' ,$$

where d is the ice draft, t is its thickness, and f' is the effective freeboard. A plot of ice thickness as a function of ice draft is shown in Figure 2-2.

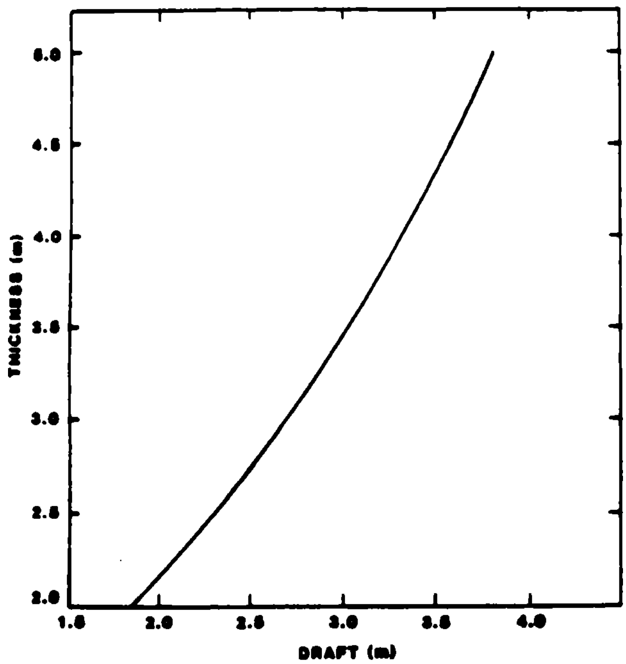


Figure 2-2. Ice Thickness Plotted as a Function of Ice Draft (based upon a transformation of Figure 2-1)

Analysis of the curve in Figure 2-2 indicates that the draft/freeboard ratio (more commonly known as the keel/sail height ratio) monotonically decreases with increasing draft, thereby suggesting that Figure 2-2 can be used only within prescribed upper- and lower-bound ice draft limits. Ice thicknesses exceeding 5 m (i.e., ice drafts in excess of 3.8 m) are assumed to be associated with pressure ridges. Measurements of 15 multiyear, nongrounded pressure ridges by Wright et al. (1978) indicate a fairly constant keel/sail height ratio for multiyear pressure ridges of 3.2:1. This is approximately the value calculated using the nomogram for t = 5 m, d = 3.8 m, and f' = 1.2 m (i.e., d/f' = 3.17). Hence, the freeboard for all ice drafts exceeding 3.8 m was calculated assuming a constant keel/sail height ratio of 3.2:1, whereas the nomogram was used for drafts less than 3.8 m.

Ice having a thickness less than 2 m (i.e., ice drafts less than 1.8 m as determined from the nomogram) was assumed to be first-year ice with a mean ice density of 940 kg/m^3. This is the density of gas-free sea ice at −2°C and a salinity of approximately 8 parts per thousand (Cox and Weeks, 1974). Isostatic equilibrium based on this density results in a keel/sail height ratio of 11.75:1, approximately the same value when using the nomogram for d = 1.85 m, t = 2 m, f' = 0.15 m, and d/f' = 12.33. Thus, the nomogram is useful for drafts in the range 1.85 to 3.8 m. Drafts less than 1.85 m are assumed to be related to the freeboard by assuming a constant ice density of 940 kg/m^3.

The submarine under-ice profile analysis also provides data on the quantity of thin ice present. Ice in this category (i.e., ice having drafts between 0.2 and 0.6 m) was assumed to have a salinity of 10 parts per thousand or slightly greater and a density of 950 kg/m^3 (Cox and Weeks, 1974). The freeboard of thin ice was calculated based on this value.

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland
20771

NASA

Reply to Attn of: 671

FEB 23 1990

Honorable Albert Gore, Jr.
United States Senate
393 Russell Senate Office Building
Washington, DC 20510-4202

Dear Senator Gore:

Thank you for your letter of January 16, 1990, regarding the role of polar regions in global warming and for the copy of the article by Michael Zimmerman concerning Navy information on Arctic ice thickness.

Knowing whether or not the Arctic sea ice cover is thinning is important because it may serve as an early indicator of global climate warming. The melting of sea ice, unlike the melting of the landed ice sheets of Greenland and Antarctica, will not result in a rise of sea level. Nevertheless, this issue is important and I agree that it should be addressed as soon as possible. The Navy apparently does have a very valuable data set that could be used to address the ice-thinning problem. Submarine sonar is the only source of ice thickness data currently available for studying this problem on an Arctic-wide basis. Current satellite data do an excellent job in delineating polar sea ice extent and ice cover density, but cannot be used to measure ice thickness directly. The combination of ice extent data from satellites with ice thickness data from submarines over a 10-year period may provide an indication of whether or not the Arctic ice mass has been decreasing during the 1980's, one of the warmest decades on record.

I will be glad to provide any assistance I can either to your office or to the Navy Department with regard to this matter.

Sincerely,

Donald J. Cavalieri

Donald J. Cavalieri
Oceans and Ice Branch
Laboratory for Oceans

United States Senate

MEMORANDUM

Rick --

Callahan's Executive Officer, Cmdr Ron Fauquet, will be attending the mtg, as Callahan will be out of town. Call him back @ same time -

— Jim

ALBERT GORE, JR.
TENNESSEE

393 RUSSELL SENATE OFFICE BUILDING
PHONE: 202-224-4944

United States Senate

WASHINGTON, DC 20510-4202

January 16, 1990

addressee

Dear _________:

I am writing to you and to a small number of your colleagues (see attached list), because of your expertise in polar ice research. My purpose is to solicit your advice and help in a venture which might speed up concensus on predictions regarding the polar-region impacts of global warming.

Perhaps you also happened upon a recent article concerning Navy information on the thickness of the Arctic polar ice-cap (attached). After reading it, I asked the Navy to brief me on the information they have collected. The Navy confirmed that it has been accumulating data on water depth below the polar ice cap. The Navy believes that the information at its disposal might be combined with open-source information from satellites, in a way that might shed light on trends in the thickness of the polar ice cap -- which in turn could help document temperature trends in the Arctic.

The Navy is prepared to attempt to work out a regime which would release scientifically useful information, providing this can be done in a way that does not compromise the security of its operations. The Navy agreed to do this on the basis of my suggestion, as follows:

- A select group of scientists would identify a grid of coordinates covering the polar ice cap, where time-sequence information on ice thickness would be useful.

- The Navy would then decide unilaterally, how much of the information at its disposal could be released.

You have been identified as a possible member of the scientific team that could work with the Navy on this matter. I feel that it offers a rare opportunity to analyze recent global environmental trends, using a new and potentially powerful database. If you would like to discuss this further, please feel free to call either Leon Fuerth or Rick Adcock of my staff, at (202) 224-4944. I look forward to your response.

Sincerely,

Al Gore
U.S. Senator

enclosures

ICE PROFILING SPECIALISTS

CAPT Chuck Armitage
Director, Arctic Submarine Laboratory
Naval Ocean Systems Command
San Diego, CA 92152-5000
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U.S. Naval Observatory
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Washington, D.C. 20392-1800
(202) 653-1604

CAPT Thomas E. Callaham
Commanding Officer, Naval Polar Oceanography Center
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4301 Suitland Road *Message w/Sec*
Washington, D.C.20395-5180 *= will send Com. Don Fauquet*
(301) 763-5524

* Dr. G. Leonard Johnson
Director, Geoacoustics and Arctic Sciences Division
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(703) 696-4118

* Mr. George Newton
Analysis & Technology, Inc.
Two Crystal Park
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Arlington, VA 22202
(703) 892-1042

SEA ICE SPECIALISTS RECEIVING JANUARY 16, 1990 LETTER

1. Dr. Claire L. Parkinson *message*
   Oceans and Ice Branch
   NASA-Goddard Space Flight Center
   Greenbelt, MD 20771
   (301) 286-6507

2. Dr. Donald Cavalieri *yes*
   Oceans and Ice Branch
   NASA-Goddard Space Flight Center
   Greenbelt, MD 20771
   (301) 286-2444

3. Dr. Josefino Comiso *message*
   Oceans and Ice Branch
   NASA-Goddard Space Flight Center
   Greenbelt, MD 20771
   (301) 286-9135

4. Mr. Steve Ackley
   Sea Ice Specialist
   Cold Region Research and Engineering Laboratory
   U.S. Army Corps of Engineers
   72 Lyme Road
   Hanover, NH 03755
   (603) 646-4258

5. Dr. Norbert Untersteiner
   Director, Polar Science Center
   Applied Physics Laboratory
   University of Washington
   Seattle, WA 98105
   (206) 543-1367

6. Dr. Seelye Martin
   School of Oceanography WB-10
   University of Washington
   Seattle, WA 98195
   (206) 543-6438

7. Dr. Kenneth Hunkins
   Lamont-Doherty Geological Observatory
   Columbia University
   Palisades, NY 10964
   (914) 359-2900

###

ALBERT GORE, JR.
TENNESSEE

393 RUSSELL SENATE OFFICE BUILDING
PHONE: 202-224-4944

United States Senate

WASHINGTON, DC 20510-4202

January 16, 1990

Dr. Josefino Comiso
Oceans and Ice Branch
NASA-Goddard Space Flight Center
Greenbelt, MD 20771

Dear Dr. Comiso:

I am writing to you and to a small number of your colleagues (see attached list), because of your expertise in polar ice research. My purpose is to solicit your advice and help in a venture which might speed up concensus on predictions regarding the polar-region impacts of global warming.

Perhaps you also happened upon a recent article concerning Navy information on the thickness of the Arctic polar ice-cap (attached). After reading it, I asked the Navy to brief me on the information they have collected. The Navy confirmed that it has been accumulating data on water depth below the polar ice cap. The Navy believes that the information at its disposal might be combined with open-source information from satellites, in a way that might shed light on trends in the thickness of the polar ice cap -- which in turn could help document temperature trends in the Arctic.

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1. A select group of scientists would identify a grid of coordinates covering the polar ice cap, where time-sequence information on ice thickness would be useful.

2. The Navy would then decide unilaterally, how much of the information at its disposal could be released.

You have been identified as a possible member of the scientific team that could work with the Navy on this matter. I feel that it offers a rare opportunity to analyze recent global environmental trends, using a new and potentially powerful database. If you would like to discuss this further, please feel free to call either Leon Fuerth or Rick Adcock of my staff, at (202) 224-4944. I look forward to your response.

Sincerely,

Albert Gore Jr.
U.S. Senator

enclosures

Claire —

Brenda has confirmed that its OK for them to work w/ Seaton

its confirmed, & now getting approval through Goddard System.

They're ready.

add: Dr. Willie Weeks
Alaska SAR Facility
Geophysical Institute
Univ. of Alaska
Fairbanks, AK 99775-0800
(907) 474-7280

has tried to get sea ice data in the past

Norbert has off + on tried to get Navy data for 32 yrs -- long-timer of the group -- excited, but warns that data may not be as good as we want...

NASA Facsimile Transmission

Transmitting station	Voice phone contact	Total pages inc. lead	Date
(301) 286-2717 888-2717 FTS	(301) 286-8670 888-8670 FTS	4	January 26, 1990

From

Claire L. Parkinson

NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

Office code
671

Office phone no.
286-6507

To

Rick Adcock
(Senator Gore's office)

Rick--The following are the suggestions Don and Joey and I came up with yesterday and today, with some inputs by phone from Steve Ackley and Norbert Untersteiner. I hope this helps, at least as a start.

In order to investigate the issue of possible long-term trends in Arctic ice thickness, it would be most useful if the Navy data could be gridded onto the grid of the DMSP Special Sensor Microwave Imager (the SSMI grid) and given to us in digital form. Monthly averaged data should be fully sufficient, but we would like the data for the full period of the data record. Specifically, the grid, time period, time resolution, and variables that we desire are:

o Grid. We would like the data gridded onto the SSMI grid (25-kilometer resolution), a description and map of which are given on the following two pages, taken from the *NASA Ocean Data System User Handbook, volume II* (NASA Jet Propulsion Laboratory, Document JPL D-61, February 1987). Use of the SSMI grid will make it convenient to compare the Navy ice-thickness data with particular ancillary data sets such as the SSMI passive-microwave data. If it is impossible or impractical for the Navy to use the full SSMI grid, the most important subregion would be the central Arctic.

o Time Period. We would like the data for the full length of the Navy data set. A long time series is essential for determining climatic trends.

o Time Resolution. Monthly averaged data should be sufficient.

o Variables. For each month, we would like the values of the following variables for each grid element of the SSMI grid:

Average ice thickness.
Standard deviation of the ice thickness.
Number of observations included in the average, with a breakdown according to the class of sensor.
Biweekly data sampling frequency.
Operating frequency and beam width of each sensor.
Number of leads used for referencing.

Ideally, we would like each month's data to be separated according to reliability, so that for each month we receive matrices of the above variables for each of several classes of sensor reliability. Alternatively, we would need a measurement of the sensor accuracy of each class of sensor used for the observations.

CC.1.4.1.4.3 Map Projection And Conversion

The SSM/I polar grids (see Figures CC-1 and CC-2) assume a polar stereographic map projection which has its projection plane located at +- 70 degrees latitude, perpendicular to the earth's polar axis. The reasons for this selection are outlined in JPL TM 3349-85-101, 3 May 1985, by C. S. Morris.

The SSM/I geodetic latitude and longitude are based on an ellipsoid with a Earth equatorial radius of 3443.992 nautical miles or 6378.273 kilometers and an eccentricity of (e) of 0.081816153 or e**2 = 0.006693883 (Hughes Aircraft Company, Special Sensor Microwave Imager (SSM/I), Computer Program Specification (Specification for FNOC), Volume II, Sensor Data Processing, Computer Program Component (SMISDP), December, 1980).

The formulae for converting between the geodetic latitude and longitude and the SSM/I polar grid X,Y coordinates can be found in Map Projections Used by the U.S. Geological Survey (Snyder, J. P., Geological Survey Bulletin 1532, U.S. Government Printing Office, 1982) and JPL TM 3349-85-101 (3 May 1985) by C. S. Morris.

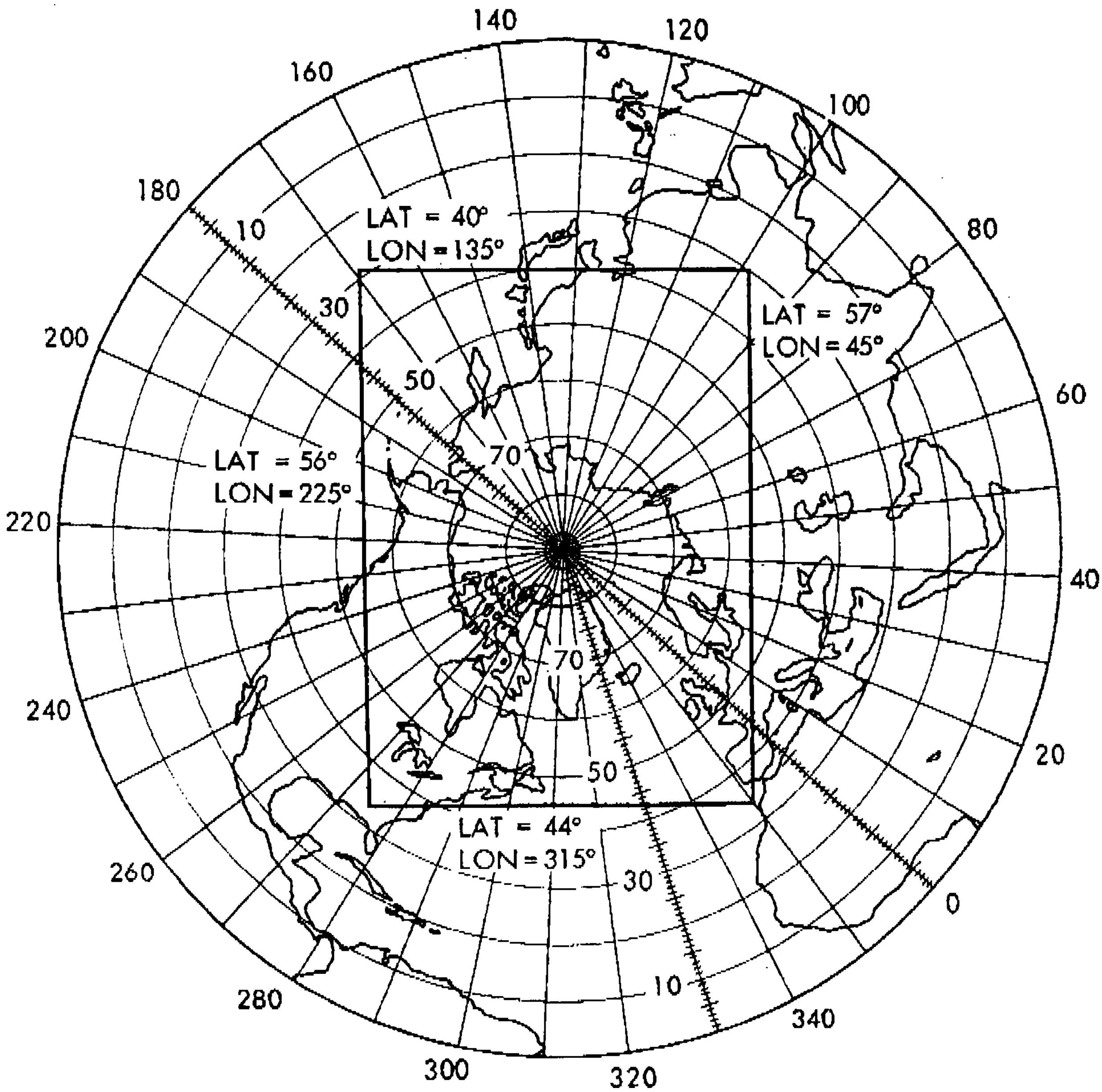
CC.1.4.1.5 SSM/I Ice Concentration Archive

The SSM/I sea ice concentrations are calculated for a three-day period on a 50 km grid using an algorithm described below. The algorithm uses as input the gridded brightness temperatures. Currently, only three of the seven brightness temperature channels are required to determine the ice concentrations. The calculation of the three-day average ice concentrations is performed by computing the ice concentrations for four 25 km grid cells for each day in the given three-day period. The 12 values (four grid cells x three days) are then averaged.

The ice concentrations are given in percent and are restricted to the range 0.0 to 100.0 percent. If the computed ice concentration is between -20 and 0 percent, the value is set to 0 percent. If the concentration is between 100 and 120 precent, the value is set to 100 percent. This adjustment, if necessary, is done after the initial calculation of total, 1st-year, and multi-year ice concentrations for a given 25 km grid cell. If the computed ice concentration is less than -20 percent or greater than 120 percent for either the total, 1st-year or multi-year concentrations, the calculation for all three is considered void and that 25 km grid cell (on that day) will not be used to compute the 50 km average.

Data in a given 25 km grid cell (for a given day) will not be used in the 50 km ice concentration calculation if one of the necessary brightness temperatures is missing. In addition, the ice concentrations are not calculated over land. A 50 km grid land mask is used to determine whether or not a specific 50 km grid cell is designated open water or land. If there is any land within the grid

FIGURE CC-1


140
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NASA Facsimile Transmission

Transmitting station	Voice phone contact	Total pages inc. lead	Date
(301) 286-2717 888-2717 FTS	(301) 286-8670 888-8670 FTS	4	January 26, 1990

From
Claire L. Parkinson
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

Office code
671

Office phone no.
286-6507

To
Rick Adcock
(Senator Gore's office)

Rick--The following are the suggestions Don and Joey and I came up with yesterday and today, with some inputs by phone from Steve Ackley and Norbert Untersteiner. I hope this helps, at least as a start.

In order to investigate the issue of possible long-term trends in Arctic ice thickness, it would be most useful if the Navy data could be gridded onto the grid of the DMSP Special Sensor Microwave Imager (the SSMI grid) and given to us in digital form. Monthly averaged data should be fully sufficient, but we would like the data for the full period of the data record. Specifically, the grid, time period, time resolution, and variables that we desire are:

o Grid. We would like the data gridded onto the SSMI grid (25-kilometer resolution), a description and map of which are given on the following two pages, taken from the *NASA Ocean Data System User Handbook, volume II* (NASA Jet Propulsion Laboratory, Document JPL D-61, February 1987). Use of the SSMI grid will make it convenient to compare the Navy ice-thickness data with particular ancillary data sets such as the SSMI passive-microwave data. If it is impossible or impractical for the Navy to use the full SSMI grid, the most important subregion would be the central Arctic.

o Time Period. We would like the data for the full length of the Navy data set. A long time series is essential for determining climatic trends.

o Time Resolution. Monthly averaged data should be sufficient.

o Variables. For each month, we would like the values of the following variables for each grid element of the SSMI grid:

Average ice thickness.
Standard deviation of the ice thickness.
Number of observations included in the average, with a breakdown according to the class of sensor.
Biweekly data sampling frequency.
Operating frequency and beam width of each sensor.
Number of leads used for referencing.

Ideally, we would like each month's data to be separated according to reliability, so that for each month we receive matrices of the above variables for each of several classes of sensor reliability. Alternatively, we would need a measurement of the sensor accuracy of each class of sensor used for the observations.

PROCESSING ALGORITHMS

CC.1.4.1.4.3 Map Projection And Conversion

The SSM/I polar grids (see Figures CC-1 and CC-2) assume a polar stereographic map projection which has its projection plane located at +- 70 degrees latitude, perpendicular to the earth's polar axis. The reasons for this selection are outlined in JPL TM 3349-85-101, 3 May 1985, by C. S. Morris.

The SSM/I geodetic latitude and longitude are based on an ellipsoid with a Earth equatorial radius of 3443.992 nautical miles or 6378.273 kilometers and an eccentricity of (e) of 0.081816153 or e**2 = 0.006693883 (Hughes Aircraft Company, Special Sensor Microwave Imager (SSM/I), Computer Program Specification (Specification for FNOC), Volume II, Sensor Data Processing, Computer Program Component (SMISDP), December, 1980).

The formulae for converting between the geodetic latitude and longitude and the SSM/I polar grid X,Y coordinates can be found in Map Projections Used by the U.S. Geological Survey (Snyder, J. P., Geological Survey Bulletin 1532, U.S. Government Printing Office, 1982) and JPL TM 3349-85-101 (3 May 1985) by C. S. Morris.

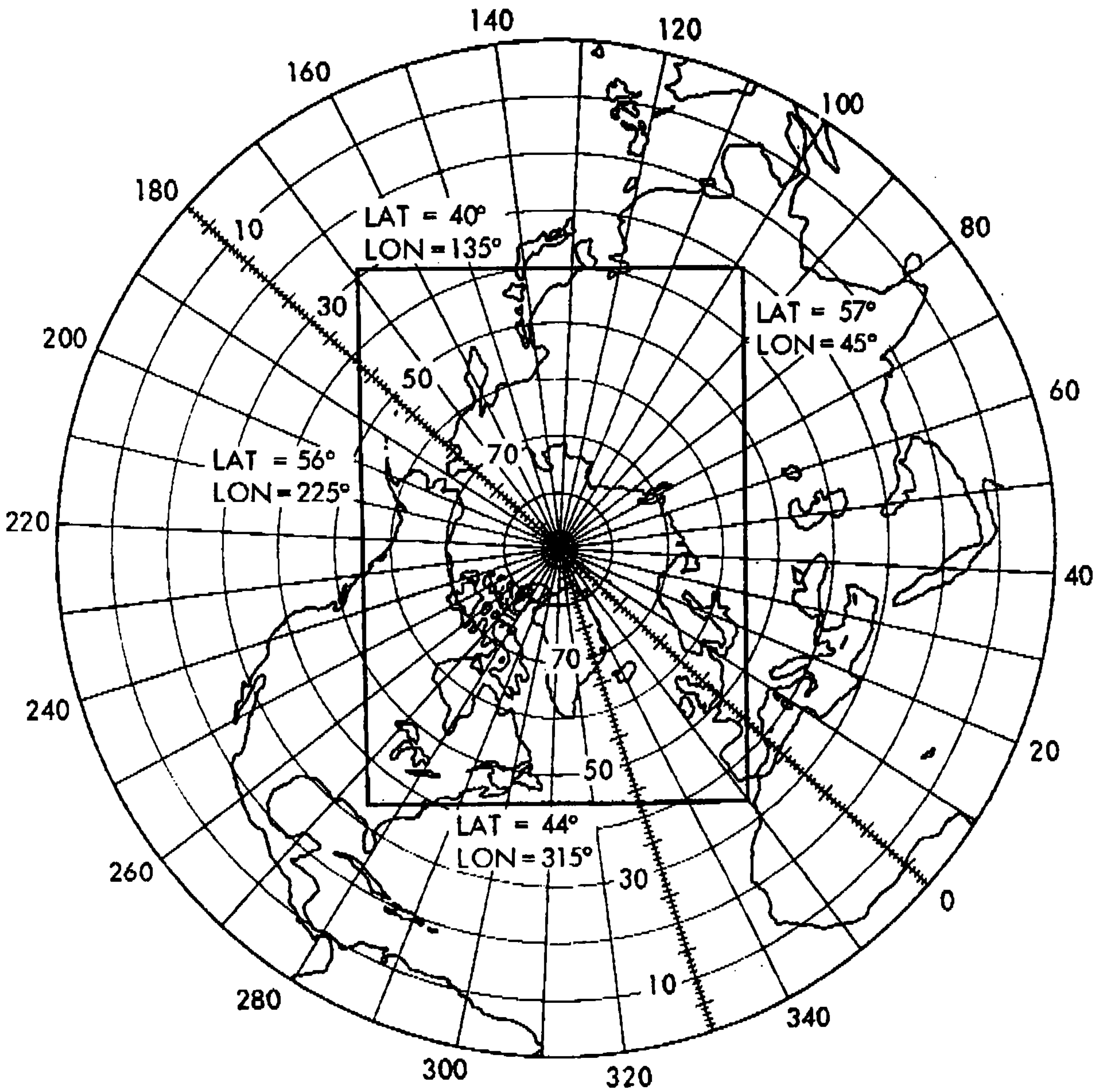
CC.1.4.1.5 SSM/I Ice Concentration Archive

The SSM/I sea ice concentrations are calculated for a three-day period on a 50 km grid using an algorithm described below. The algorithm uses as input the gridded brightness temperatures. Currently, only three of the seven brightness temperature channels are required to determine the ice concentrations. The calculation of the three-day average ice concentrations is performed by computing the ice concentrations for four 25 km grid cells for each day in the given three-day period. The 12 values (four grid cells x three days) are then averaged.

The ice concentrations are given in percent and are restricted to the range 0.0 to 100.0 percent. If the computed ice concentration is between -20 and 0 percent, the value is set to 0 percent. If the concentration is between 100 and 120 precent, the value is set to 100 percent. This adjustment, if necessary, is done after the initial calculation of total, 1st-year, and multi-year ice concentrations for a given 25 km grid cell. If the computed ice concentration is less than -20 percent or greater than 120 percent for either the total, 1st-year or multi-year concentrations, the calculation for all three is considered void and that 25 km grid cell (on that day) will not be used to compute the 50 km average.

Data in a given 25 km grid cell (for a given day) will not be used in the 50 km ice concentration calculation if one of the necessary brightness temperatures is missing. In addition, the ice concentrations are not calculated over land. A 50 km grid land mask is used to determine whether or not a specific 50 km grid cell is designated open water or land. If there is any land within the grid

FIGURE CC-1



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LON = 315°
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DEPARTMENT OF THE NAVY
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON, DC 20350-2000

IN REPLY REFER TO

1 March 1990

Honorable Albert Gore, Jr.
United States Senate
393 Russell Senate Office Building
Washington, D.C. 20310-4202

Dear Senator Gore,

I was provided with a list of your proposed panel of sea ice specialists to investigate the effects of global warming on polar ice thickness. This distinguished panel will benefit from interaction with Navy polar oceanographic and sea ice specialists who can provide the Navy's perspective regarding the security, availability, accuracy and reduction of under ice profile data. I propose that the individuals on the attached list (or their direct representative) be invited to participate in this effort.

Ice profiling data is available from over 55 submarine missions in the Arctic. Most of the information is unprocessed data, available on paper rolls, magnetic tapes or diskettes. Several of the paper rolls and magnetic tapes have been reduced and digitized, and there are plans to reduce and digitize the data on the diskettes. However, the Navy has no funding to reduce the majority of the historical data which exists on paper rolls and magnetic tapes.

A review of submarine tracks in the Arctic indicates that ice profiling data is available which has been collected in the same geographical areas over a period of years which may be suitable for trend analysis. These areas include the Greenland Sea, Chukchi Sea, Beaufort Sea and the Arctic Ocean surrounding the North Pole.

The submarine force is pleased to assist in this important global issue. RADM R. F. Pittenger, Oceanographer of the Navy, is ready to provide further assistance as the Navy's point of contact for Arctic oceanographic and scientific matters.

Sincerely,

D. L. COOPER
Vice Admiral, U.S. Navy
Assistant Chief of
Naval Operations
(Undersea Warfare)

ICE PROFILING SPECIALISTS

CAPT Chuck Armitage
Director, Arctic Submarine Laboratory
Naval Ocean Systems Command
San Diego, CA 92152-5000
(619) 553-7441

Mr. Richard Hayes
CNO OP-963C
Office of Oceanographer of the Navy
U.S. Naval Observatory
34th Street and Massachusetts Ave., N.W.
Washington, D.C. 20392-1800
(202) 653-1604

CAPT Thomas E. Callaham
Commanding Officer, Naval Polar Oceanography Center
Federal Building No. 4
4301 Suitland Road
Washington, D.C.20395-5180
(301) 763-5524

Dr. G. Leonard Johnson
Director, Geoacoustics and Arctic Sciences Division
Office of the Chief of Naval Research
Ballston Centre Tower #1
800 N. Quincy Street
Arlington, VA 22217
(703) 696-4118

Mr. George Newton
Analysis & Technology, Inc.
Two Crystal Park
2121 Crystal Drive, Eighth Floor
Arlington, VA 22202
(703) 892-1042

DEPARTMENT OF THE NAVY
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON, DC 20350-2000

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Honorable Albert Gore, Jr.
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393 Russell Senate Office Building
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Dear Senator Gore,

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The submarine force is pleased to assist in this important global issue. RADM R. F. Pittenger, Oceanographer of the Navy, is ready to provide further assistance as the Navy's point of contact for Arctic oceanographic and scientific matters.

Sincerely,

D. L. Cooper

D. L. COOPER
Vice Admiral, U.S. Navy
Assistant Chief of
Naval Operations
(Undersea Warfare)

ICE PROFILING SPECIALISTS

CAPT Chuck Armitage
Director, Arctic Submarine Laboratory
Naval Ocean Systems Command
San Diego, CA 92152-5000
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Two Crystal Park
2121 Crystal Drive, Eighth Floor
Arlington, VA 22202
(703) 892-1042

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland
20771

NASA

Reply to Attn of: 671

FEB 23 1990

Honorable Albert Gore, Jr.
United States Senate
393 Russell Senate Office Building
Washington, DC 20510-4202

Dear Senator Gore:

Thank you for your letter of January 16, 1990. I would be pleased to be on the team examining the sea-ice thickness data of the Navy. Such data can be an extremely important complement to the data more readily obtainable from space satellites, namely the data on ice compactness and extent; and I applaud you in your initiative in encouraging the Navy to make these data available. I feel I should caution you, however, that the thickness data will not be able to reveal as much information as might be expected from reading the article on "Global warming: National security?" that was enclosed with your letter. In particular, the article claimed that: "it is surely true that if we know the rate at which ice is melting we can calculate the rate at which the atmosphere is warming." This unfortunately is not the case. Sea ice thickness is a complicated function of many variables, including ocean temperature, winds, currents, and salinity as well as air temperature. Consequently, knowledge of the rate of ice melt could not be used by itself to determine air temperature changes unequivocally. However, ice thickness is still an important climate variable, and thus the study you suggest could be of great value in adding to the growing evidence of climate change. This will be especially true if there is a long time series of data and good spatial coverage. I look forward to working with you and your staff and to examining the ice thickness data.

Sincerely,

Claire L Parkinson

Claire L. Parkinson
Oceans and Ice Branch
Laboratory for Oceans

United States Senate

COMMITTEE ON FOREIGN RELATIONS

WASHINGTON, DC 20510-6225

February 13, 1990

The Honorable Albert Gore, Jr.
The United States Senate
Washington, D.C. 20510

Dear Senator Gore:

It is my understanding that you are assembling a task force of experts to research the effects of global warming at the North Pole. In this regard, I enclose the curriculum vitae of Captain Alfred Scott McLaren, U.S. Navy (retired).

Captain McLaren is well known to me, and I believe that his qualifications would make him an invaluable asset to the global warming task force. The depth of his knowledge and experience in the field clearly would serve him in good stead on the mission to the North Pole.

As one who shares your deep interest in protecting the global environment, I am pleased to recommend Captain McLaren's membership on the task force. I attach copies of several pertinent journal articles written by Captain McLaren; I hope that you will review the enclosed materials and give his candidacy your serious consideration.

With every good wish.

Ever sincerely,

Claiborne Pell

Enclosures

ALFRED SCOTT MCLAREN

Alfred McLaren is a Senior Research Associate at the Cooperative Institute for Research in Environmental Sciences (CIRES) and an Associate Professor in the Department of Geography at the University of Colorado, Boulder. He is also one of five Co-Principal Investigators from the University of Colorado and Dartmouth College on a large Office of Naval Research administered University Research Initiative five year grant for Arctic Ocean Atmosphere-Ice System Studies. He and his Colorado colleague's recent identification of recurring late summer reversals of ice motion within the Beaufort Gyre of the Arctic Ocean, subsequently called the "Arctic finding of the decade", resulted in their being recommended for an Office of Naval Research Scientific Achievement Award. A significant portion of Dr. McLaren's present research is devoted to global climate change. His writings include more than 40 magazine and professional journal articles. He is a strong proponent of using submarines for scientific and commercial purposes in the polar regions.

Dr. McLaren received his Ph.D. in the Physical Geography of the Polar Regions from the University of Colorado. He has additionally earned an M.Phil. in Polar Studies from Cambridge University, England and an M.S. in International Affairs from George Washington University. He is a graduate of the U.S. Naval Academy.

A career naval officer for 26 years and a submariner for 24, Dr. McLaren has participated in three Arctic expeditions on nuclear submarines. One was on the USS SEADRAGON during the first submerged survey of the Northwest Passage enroute the North Pole. Two others were onboard USS QUEENFISH. These include a winter Baffin Bay cruise and a summer North Pole expedition which included the first survey, under ice, of the entire Siberian Continental Shelf. He commanded QUEENFISH during this expedition and for a total of four years. Other tours of duty included the nuclear attack submarines SKIPJACK and GREENLING, the U.S. Naval War College as a student and instructor, various senior submarine force staff positions and command of a major Department of Defense scientific laboratory of over 3,000 scientists and engineers, the Naval Underwater Systems Center. His awards include the nation's highest peacetime award, the Distinguished Service Medal, and two Legions of Merit. He retired as a Captain in 1981.

Dr. McLaren's professional life has taken him to the Arctic and subarctic regions on numerious occasions. He is a Fellow of the Explorers Club and the Chairman of its Environmental Committee. He is also a Fellow of the Royal Geographical Society and the Arctic Institute of North America and a member of the Comite' Arctique International of Monaco, the Arctic Club of Cambridge, the Societe Arctique Francaise de Paris, the American Geophysical Union and the Oceanographic Society.

VITAE

CAPTAIN ALFRED SCOTT MCLAREN U.S. NAVY (RETIRED)

The Cooperative Institute for Research
in Environmental Sciences (CIRES)
Campus Box 449, University of Colorado
Boulder, Colorado 80309
United States of America

Telephone: (303) 492-1272

Home Mailing Address:
1085 14th Street
Suite 1505
Boulder, Colorado 80302
United States of America

Telephone: (303) 444-5030

PRESENT POSITIONS

Associate Professor Attendant Rank, Department of Geography, University of Colorado

Senior Research Associate, CIRES, University of Colorado

A Principal Investigator on the Office of Naval Research University Research Initiative Grant for the Arctic

EDUCATION

Ph.D.	1986	Physical Geography of the Polar Regions, University of Colorado
M.Phil.	1982	Polar Studies, Cambridge University (Peterhouse), England
M.S.	1968	International Affairs, George Washington University
B.S.	1955	Electrical Engineering, U.S. Naval Academy

Graduate of:
- U.S. Navy Major Shore Commanders School - 1978
- Admiral Rickover's Prospective Nuclear Submarine Commanding Officers School - 1969
- U.S. Naval War College - 1969
- U.S. Naval Nuclear Power School - 1960
- U.S. Naval Submarine School - 1957

Additional graduate credits in: Statistics, Climatology, Computer Science, Environmental Psychology, Philosophy, Chinese Government and Politics, and Etruscan Art and Archaeology.

LANGUAGES

Spanish and some Italian (written and spoken)

QUALIFICATIONS (CERTIFICATION) ATTAINED

Surface Warfare Specialist
SCUBA
Submarine Warfare Specialist
Chief Operator - S3G Land Based Nuclear Power Plant
Engineer Officer - Nuclear Submarines
Submarine Command - Conventional and Nuclear Powered
Major Shore Command
FAA Private Pilot License (Instrument Rated)

HONORS/AWARDS/ELECTED MEMBERSHIPS

1989 Elected Chairman of the Environment Committee, The Explorers Club

1988 Nominated for Office of Naval Research Scientific Achievement Award (with R. Barry and M. Serreze)

1988 Granted title of "Senior Research Associate" by the University of Colorado for "demonstrated superior service and performance as an outstanding researcher in my field"

1988 Elected Chairman for Chapter Relations, the Explorers Club

1986 Chairman, Rocky Mountain Chapter, The Explorers Club

1985 Elected a Member of the Comite Arctique International

1985 Elected a Member of the United Oxford & Cambridge University Club

1983 Societe de Geographie Paris Silver Medal for Polar Exploration

1983 La Medaille de la Ville De Paris (Echelon Argent)

1983 Elected a Fellow of the Arctic Institute of North America

1983 Elected a Member of the Societe Arctique Francaise de Paris

1982 Elected a Fellow of the Royal Geographical Society

1982 Elected a Member of the Arctic Club of Cambridge

1973 Navy Commendation Medal

1973 Selected for the rank of Captain, USN, two years in advance of contemporaries

1972 Distinguished Service Medal (Nation's highest peacetime award)

1972 Meritorious Service Medal

1972 Golden Anchor Award for highest ship reenlistment rate in the Pacific Fleet

1971 Elected a Fellow of the Explorers Club

1971 Legion of Merit (Gold Star in lieu of second award)

1970 Legion of Merit

1960,1968,1970,1973 Navy Unit Commendation ribbon (with bronze stars for second, third and fourth awards)

PROFESSIONAL POSITIONS

1984-86 Consultant on commercial submarine matters to the President of Micoperi S.p.A., Milan, Italy

1981-83 Consultant on Arctic transportation matters to the President of ARCO International

1980-81 Staff, U.S. Naval War College

1978-80 Commanding Officer, U.S. Naval Underwater Systems Center (NUSC); a major Department of Defense Research and Development Laboratory, employing 3200 scientists and engineers with an annual budget of approximately one-half billion dollars.

1976-78 Chief of Staff for Operations and Plans, Submarine Forces, U.S. Pacific Fleet (included responsibility for all deep submergence programs)

1973-76 Chief Staff Officer, Submarine Development Group Two, New London, Connecticut

1969-73 Commanding Officer of the nuclear attack submarine USS QUEENFISH (SSN-65l)

1968-69 Instructor in War Gaming, U.S. Naval War College

1968 (June-October) Command Watch Officer, nuclear attack submarine USS GREENLING (SSN-6l4)

1965-67 New Construction/Commissioning Executive Officer and Navigator, USS QUEENFISH (SSN-651)

1963-65 Engineer Officer, nuclear attack submarine USS SKIPJACK (SSN-585)

1962-63 Diving Officer and Navigator, USS SKIPJACK (SSN-585)

1960-62 Diving Officer, Weapons Officer, Electrical and Reactor Control Officer, Main Propulsion and Damage Control Assistant; nuclear attack submarine USS SEADRAGON (SSN-584)

1957-59 Weapons Officer and Diving Officer, diesel submarine USS GREENFISH (SS-35l)

1955-57 Gunnery Officer and Anti-Submarine Warfare Officer, destroyer USS GREGORY (DD-805)

ARCTIC RELATED EXPERIENCES AND ACCOMPLISHMENTS

1985 Travel in Iceland and Greenland

1981-82 Study/research (10 months) at the Scott Polar Research Institute, Cambridge University.

1981,1985 Visited Canadian Arctic Islands on and off shore petroleum exploration sites/wells as guest of Panarctic Oils Ltd.

1978-80 As Commanding Officer of the Naval Underwater Systems Center, personally initiated several Arctic-related programs and supervised the Center's participation in already existing ones (i.e., MIZEX and ICEXs).

1973-80 Actively participated in the planning for all U.S. Navy submarine expeditions to the Arctic Ocean and contiguous marginal sea ice zones.

1970 Commanding Officer of the USS QUEENFISH (SSN-65l) during a summer of l970 Arctic Expedition in which an extensive oceanographic survey was conducted of previously uncharted areas of the Arctic Basin and contiguous continental shelf areas. This voyage also included surfacing at the North Pole and surveying the entire Siberian Continental Shelf for the first time in history.

1967 Actively participated in a U.S. Navy "Birds Eye" flight from Argentia, Newfoundland to Thule, Greenland and return.

1965-67 Executive Officer and Navigator during construction, fitout, sea trials and shakedown cruises of the USS QUEENFISH (SSN-651), the first of a new class of 37 nuclear attack submarines, all of which have the capability to operate submerged within the polar regions year-round. During my tour of duty we traveled north of the Arctic Circle in Baffin Bay (February 1967) to thoroughly test this capability.

1960 Served as Diving Officer and Photographic Officer on board the USS SEADRAGON (SSN-584) during the first extensive submerged examination of deep draft icebergs in Baffin Bay and the first submerged transit/survey of the Northwest Passage enroute Pearl Harbor, Hawaii via the North Pole. I also participated in a "Survival on the Ice" exercise. Vilhjalmur Stefansson assisted us in the preparations for this voyage. Commodore O.C.S. Robertson of the Royal Canadian Navy--who commanded the icebreaker LABRADOR during an earlier passage--accompanied us.

MAJOR RESEARCH GRANTS/CONTRACTS

Numerous multi-million dollar grants personally obtained during my command of the U.S. Naval Underwater Systems Center, Newport, RI; Atlantic Richfield Oil Company grant for Arctic research at Cambridge University (1981-82); Office of Naval Research grant for Arctic research at Cambridge University (with Wadhams, Scott Polar Research Institute) (1981-82); Office of Naval Research grants for analysis of submarine recorded under-ice thickness distributions (with Weaver) (1983-86); Sandia National Laboratories grants for analysis of submarine recorded under-ice thickness distributions (with Weaver and Professor R. Bourke of Naval Postgraduate School)(1985-87); Army Cold Regions Engineering Laboratory (CRREL), grant for analysis of submarine recorded under-ice thickness distributions (with Weaver)(1987); Arctic Ocean ice-climate system studies (with Barry and Schnell)(ONR/URI, 1986-1990).

COURSES TAUGHT

Geography of the Polar Regions (graduate Level), Department of Geography, University of Colorado, Spring Semester 1988.

Physical Geography (undergraduate level) Labs-1983, 1984 and 1985, Department of Geography, University of Colorado.

Political Geography (undergraduate and graduate levels) Teaching Assistant, 1985, Department of Geography, University of Colorado.

PUBLICATIONS

Theses:

1968 Military Control of the Marginal Sea Ice Zone, Its Importance to our National Security. George Washington University, 120 pp.

1982 The Arctic Submarine, An Alternative to Icebreaker Tankers and Pipelines. Scott Polar Research Institute, Cambridge University, 122 pp.

1986 Analysis of the Under-ice Topography of the Arctic Basin as Recorded by USS NAUTILUS in 1958 and USS QUEENFISH in 1970. University of Colorado, 163 pp. (University Microfilms International Publication No. 86-18979).

Research Papers:

1971 Mining the Soviet Northern Sea Route (Classified). For the Naval Ordnance Laboratory, White Oak, Maryland, Annual Mine Warfare Conference.

1980 A Brief History and Results of Submarine Exploration of the Arctic Basin and Contiguous Marginal Sea Ice Zones. For the NATO Advanced Study Institute on Underwater Acoustics and Signal Processing, Copenhagen, Denmark.

1981 Under the ice in submarines. U.S. Naval Institute Proceedings, Vol. I 7/7/941: 105-109.

1982 Exploration under the Arctic ice. Explorers Journal, Vol. 60, No. I: 34-39.

1982 An Analysis of Ice Profiles from Baffin Bay and the Northwest Passage. Technical Report for the U.S. Office of Naval Research, Arctic Programs (with P. Wadhams and R. Weintraub).

1983 The development of cargo submarines for polar use. Polar Record, Vol. 21, No. 133: 369-381.

1983 The Arctic Submarine: Its Evolution and Scientific and Commercial Potential. For the 8th International Colloquy of the Centre d'Etudes Arctiques, Centre National de la Recherche Scientifique, Paris VIIeme, France.

1984 Transporting Arctic petroleum: a role for commercial submarines. Polar Record, Vol. 22, No. 136: 7-23.

1984 Arctic submarine beginnings. The Submarine Review, January 1984: 45-51.

1984 The sea ice topography of M'Clure Strait in winter and summer of 1960 from submarine profiles. Arctic, Vol. 37, No. 2, June 1984: 110-120 (with P. Wadhams and R. Weintraub).

1984 Laurie Island in the South Orkneys: site of Antarctica's first scientific station and territorial dispute. Il Polo, Anno 40, N.3, Settembre 1984: 65-70.

1984 The evolution of the Arctic submarine. The Journal of Navigation, Vol. 37, No. 3, September 1984: 380-397.

1984 The Arctic Submarine - Its Scientific and Commercial Potential, for the Arctic Offshore Technology Conference and Exposition, Calgary, Alberta, Canada.

1985 The ice thickness distribution in Davis Strait in February from submarine sonar profiles. Journal of Geophysical Research, Vol. 90, No. C1, January 20, 1985: 1069-1077. (with P. Wadhams and R. Weintraub)

1985 Rotte future transpolari e dell'Arctico superiore. Il Polo, Anno XLI, I/bis, Aprile 1985: 30-41.

1985 Micoperi submarines: closed circuit diesel powered for commercial, scientific and military purposes. Subnotes, Vol. 5, No. 4, October 1985: 16-17.

1985 The evolution and potential of the Arctic submarine. Proceedings of the 8th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC 85), Narssarssuag, Greenland: 848-857.

1985 The evolution and potential of the Arctic submarine. Ocean Engineering and the Environment (OCEANS 85), Conference Record, San Diego, California: 448-453.

1986 The under-ice topography of the Arctic Basin as recorded in 1958 and 1970: a comparison. For the Ice Penetration Technology Workshop, 16-19 June 1986, Monterey, California.

1986 Digitization and statistical analysis of submarine under-ice profiles (with R. Weaver and R. Bourke). For the Ice Penetration Technology Workshop, 16-19 June 1986, Monterey, California.

1987 Seasonal variations of sea ice motion in the Canada Basin and their implications (with M. C. Serreze and R. Barry), Geophysical Research Letters, Vol.14, No.11: 1123-1126.

1987 The Arctic Submarine: its evolution and scientific and commercial potential. Pôle Nord, 1983. Histoire de sa compuete er problemes contemporains de navigation maritime et aerienne: 329-341.

1988 Seasonal variations of atmospheric circulation and sea ice motion in the Arctic. Second Conference on Polar Meteorology and Oceanography, Madison, WI, 20-23.

1988 Analysis of the under-ice topography in the Arctic Basin as recorded by the USS NAUTILUS, August 1958. Arctic 41:117-126.

1988 Spectral analysis of Canada Basin under-ice draft distribution as recorded by the USS QUEENFISH, August 1970 (with J. Key). Geophysical Research Letters , Vol.15, no.10: 1117-1120.

1988 Digitization and statistical analysis of submarine under-ice profiles. Technical Report SAND 86-7090, for Sandia National Laboratories (with R. L. Weaver, R. H. Bourke and R. L. Woodfin).

1988 The under-ice thickness distribution of the Arctic Basin as recorded by USS NAUTILUS in 1958 and USS QUEENFISH in 1970: a comparison. POAC '87 Proceedings, Vol. II, W. Sackinger, ed.

1989 Periodicities and keel spacings in the under-ice draft distribution of the Canada Basin (with J. Key). Cold Regions Science and Technology, 16:1-10.

1989 The under-ice thickness distribution of the Arctic Basin as recorded by USS NAUTILUS in 1958 and USS QUEENFISH in 1970. Journal of Geophysical Research, Vol.94, No. C4, April 15, 1989:4971-4983.

1989 Statistical analysis of lead data in the eastern Arctic based upon NOAA AVHRR satellite imagery. Technical Report for the Office of Naval Research. (with R. L. Weaver and A. Cowan)

1989 Summertime reversals of the Beaufort Gyre and its effects on ice concentration in the Canada Basin (with M.C.Serreze and R.G.Barry). Journal of Geophysical Research, Vol.94, No.C8, August 15, 1989:10955-10970.

1989 Editorial on: The future of the Arctic Ocean: realities and problems. Inter-Nord, No. 18:7-8.

1989 Seasonal variations of sea ice motion in the Transpolar Drift Stream (with M.C. Serreze and R.G. Barry), Geophysical Research Letters, 16(8):811-814.

1989 The commercial potential of the Arctic submarine. Arctic Technology and Economy Colloquy International Proceedings, Paris, 15-17 February 1989.

1989 Arctic sea-ice statistics from recent submarine topsounder measurements. Technical Report SAND 86-7094, for Sandia National Laboratories (with R. L. Weaver, E. V. Thomas, R. H. Bourke and R. L. Woodfin).

1989 Statistical descriptions of the under-ice draft distribution in the western Arctic Basin, Summer 1970 and Fall 1978 (with J. Key). Journal of Geophysical Research (submitted).

1989 Les possibilite commerciales des sous - marins en Arctique. Navigation, Vol.37, Numero 147, Juillet 1989:378-391.

1989 Statistical descriptions of keel-related features in the under-ice draft distribution. (with J. Key) IGARSS '89 Twelfth Canadian Symposium on Remote Sensing Proceedings, Vol.4:2346-2349.

SPEECHES AND LECTURES

1971 - Present:
Have lectured on the history of submarine exploration of the Polar regions, submarine scientific work in the Arctic basin, the development of the Arctic submarine, the use of Arctic capable submarines for commercial purposes, sea ice, the under-ice topography of the Arctic Basin, ecology, paleoecology and political geography of the polar regions, and the Law of the Sea as it applies to the polar regions. Lectures presented to over 40 universities and colleges, innumerable scientific groups, agencies, institutes and laboratories, and academic, scientific and military audiences in the United States, Canada, Great Britain, France, West Germany, Norway, Sweden, Denmark, Italy, Switzerland, Greenland, Iceland, and Japan.

Invited presentations of note include:

1972 Explorers Club Annual Dinner - Waldorf Astoria - New York.

1980 NATO Advanced Institute on Underwater Acoustics and Signal Processing, Copenhagen, Denmark.

1981 Scott Polar Research Institute, Cambridge University, England.

1983 The 8th International colloquy of the Centre d'Etudes Arctiques, Center de la Recherche Scientifique, Paris (also President of the 6th Session).

1984 6th International Symposium on Circumpolar Health, Anchorage, Alaska.

1984 ICEDIVE '84, Stockholm, Sweden.

1984 Presidents of the Comite Arctique International and Vevey Engineering and the U.S. Ambassador to Switzerland, Laussane, Switzerland.

1984 Arctic Offshore Technology Conference and Exposition, Calgary, Canada.

1984 British Broadcasting Corporation (BBC) World and Marine News (two broadcasts), London, England.

1985 U.S. Naval Postgraduate School, Monterey, California (March and May).

1985 Institute of Arctic and Alpine Research, University of Colorado.

1985 Centre d'Etudes Arctiques, CNRS-EHESS, Paris.

1985 Alpine Club of Iceland, Reykjavik, Iceland.

1985 The 8th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC 85), Narssarssuaq, Greenland.

1985 Danish Ministry for Greenland, Copenhagen, Denmark.

1985 OCEANS '85, San Diego, California.

1986 U.S. Naval Postgraduate School, Monterey, California.

1986 Ice Penetration Workshop, Naval Postgraduate School, Monterey, California.

1986 American Geophysical Union, Fall meeting, San Francisco, California

1986 Scott Polar Research Institute, Cambridge University, England

1987 U.S. Naval Postgraduate School, Monterey, California

1987 Ice Penetration Workshop, Naval Surface Weapons Center, White Oak, Maryland

1987 Lawrence Livermore Laboratories, Livermore, California

1987 Naval Air Development Center, Warminster, Pennsylvania

1987 55th Military Operations Readiness Society, Air Ministry, Maxwell Air Force Base, Montgomery, Alabama

1987 Thayer School of Engineering and Institute for Canada-U.S. Studies, Dartmouth College

1987 Mitre Institute, Distinguished Lecturer Series, McLean, Virginia

1987 Office of Naval Research, Washington, D.C.

1987 Arctic Submarine Lab, NOSC, San Diego, California

1987 Scott Polar Research Institute, Cambridge University

1987 POAC 87, Fairbanks, Alaska

1987 American Geophysical Union, Fall meeting, San Francisco, California

1988 2nd Conference on Polar Meteorology and Oceanography of the American Meteorological Society

1988 U.S. Naval Academy, Annapolis, Maryland

1988 Colorado/Wyoming Academy of Sciences (keynote speaker), Pueblo, Colorado

1988 Naval Air Development Center, Warminster, Pennsylvania

1988 Naval Underwater Systems Center, New London, Connecticut

1988 Twelfth Northern Libraries Colloquy, University of Colorado, Boulder, Colorado

1988 Scott Polar Research Institute, Cambridge University

1988 Submarine League, Submarine Base, New London, Connecticut

1988 Naval Underwater Systems Center, Newport, Rhode Island

1989 U.S. Naval Postgraduate School, Monterey, California

1989 Arctic Technology and Economics: Present Situation and Problems, Future Issues Colloquy International, Paris

1989 Naval Underwater Systems Center, New London, Connecticut

1989 Commander Submarine Development Squadron 12, Submarine Base, New London, Connecticut

1989 U.S. Army Cold Regions Engineering Laboratory, Hanover, New Hampshire

1989 Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire

1989 Office of Naval Research

1989 Oceanographer of the Navy

PROFESSIONAL SOCIETIES

American Geophysical Union
International Glaciological Society
Rotary Club, Boulder, Colorado (Chairman of Fellowship and Vice Chairman of World Community Service and Program Committees
Association of American Geographers
American Polar Society
U.S. Naval Institute
Toastmasters International
Sierra Club
National Geographic Society
Cambridge Society
Aircraft Owners and Pilots Association
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PERSONAL

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The Under-Ice Thickness Distribution of the Arctic Basin as Recorded in 1958 and 1970

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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 profiles were recorded. In August 1970 USS *Queenfish* (SSN-651) retraced *Nautilus*' route, yielding the only duplicate transect of under-ice topography across the Arctic Basin. Comparisons of the statistical analysis of the under-ice draft measurements obtained through use of wide-beam and narrow-beam and narrow-beam only acoustic profilers by *Nautilus* and *Queenfish*, respectively, along the coincidental route are presented. Geographic areas found to have distinct under-ice characteristics and ice composition are identified. The under-ice statistics of both cruises are considered in relation to representative field observations and modeling results of other researchers. Principal findings are (1) *Nautilus* recorded generally more severe ice conditions within the Canada Basin than did *Queenfish* 12 years later; overall mean drafts were 3.08 and 2.39 m, respectively, (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 may contain the most moderate under-ice topography and the greatest number of open water and refrozen polynyas and leads within the central Arctic Basin, (4) the Makarov and Amundsen basins and the Arctic mid-ocean ridge may contain some of the most severe under-ice topography within the Arctic Basin, and (5) the present study indicates an overall Arctic Basin mean of 3–4% open water/new ice (less than 30 cm) in summer.

INTRODUCTION

Considerable interest has developed in recent years in the physical oceanography of the Arctic Basin and the influence of its vast sea ice cover, particularly ice thickness distribution, on the climate of the northern hemisphere. During the summers of 1958 and 1970 the nuclear submarines *Nautilus* and *Queenfish*, respectively, following identical routes across 2174 km of the Arctic Basin, continuously recorded the under-ice topography from latitude 74°23.0′N, longitude 155°00.0′W in the southwest corner of the Canada abyssal plain via the north pole to latitude 86°01.0′N, longitude 25°00.0′E on the Arctic mid-ocean ridge (Figure 1). *Nautilus* followed this route from 0218 UT, August 2 until 1542 UT, August 4, 1958. *Queenfish* retraced *Nautilus*' track from 1433 UT, August 2 until 1402 UT, August 6, 1970.

The *Nautilus* and *Queenfish* voyages are the only two, in almost 3 decades of submarine Arctic Ocean exploration and scientific data collection, which followed identical routes across the entire Arctic basin via the north pole. The scientific data which they collected are thus the only ones which can be directly compared to reveal temporal changes in overall Arctic Basin under-ice topography.

The Arctic ice pack is an exceedingly complex mixture of open water and many different ice types and thicknesses. The principal ice pack characteristics which control the amounts of heat, moisture, and momentum exchange between the Arctic Ocean and the atmosphere above are its geographical extent and its thickness distribution. Two processes act to alter the thickness of floating ice and hence cause changes in thickness distribution: thermodynamic effects which are responsible for mass changes at the lower and upper surfaces and mechanical processes which result from the nonuniform motion of the ice, causing the formation of open leads/polynyas and pressure ridges/deep draft keels. The principal difference between the two processes is that over the course of a year the thermodynamic forces strive for single equilibrium thickness by net accretion to the thin ice and net ablation from the thick ice, while the mechanical processes create both thick pressure ice and open water [*Thorndike et al.* 1975].

Thickness distribution is basically the frequency of different ice thicknesses arising from the spatial coverage of open water, thin ice, and thick ice. A particular combination generally determines its degree of roughness (i.e., the thicker and more varied, the rougher). The thickness distribution can vary widely both spatially and temporally due to such things as wind, currents, upwellings, and tidal actions.

Physical and empirical models of sea ice which are used as part of larger climatological models encompassing both the ocean and atmosphere need to use reliable data on the ice thickness distribution in the Arctic Ocean. The importance of the *Nautilus* and *Queenfish* records of which this paper provides a portion [*McLaren* 1986] is that they provide these data in the form of ice draft distribution, which is directly related to ice thickness distribution through the mean density of the sea ice. The under-ice topography statistics presented here should therefore provide sea ice and climate system modelers with results suitable for modeling input and validation.

METHODOLOGY

The Data

Nautilus 1958 and *Queenfish* 1970 continuous analog under-ice draft 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 recorded by *Nautilus* was measured by a Navy Electronics Laboratory variable frequency (20 to 200 kHz) upward beamed sonar. *Queenfish* used the 205 kHz upward beamed acoustic profiler of her AN/BQS-8 under-ice sonar system to record the under-ice topography.

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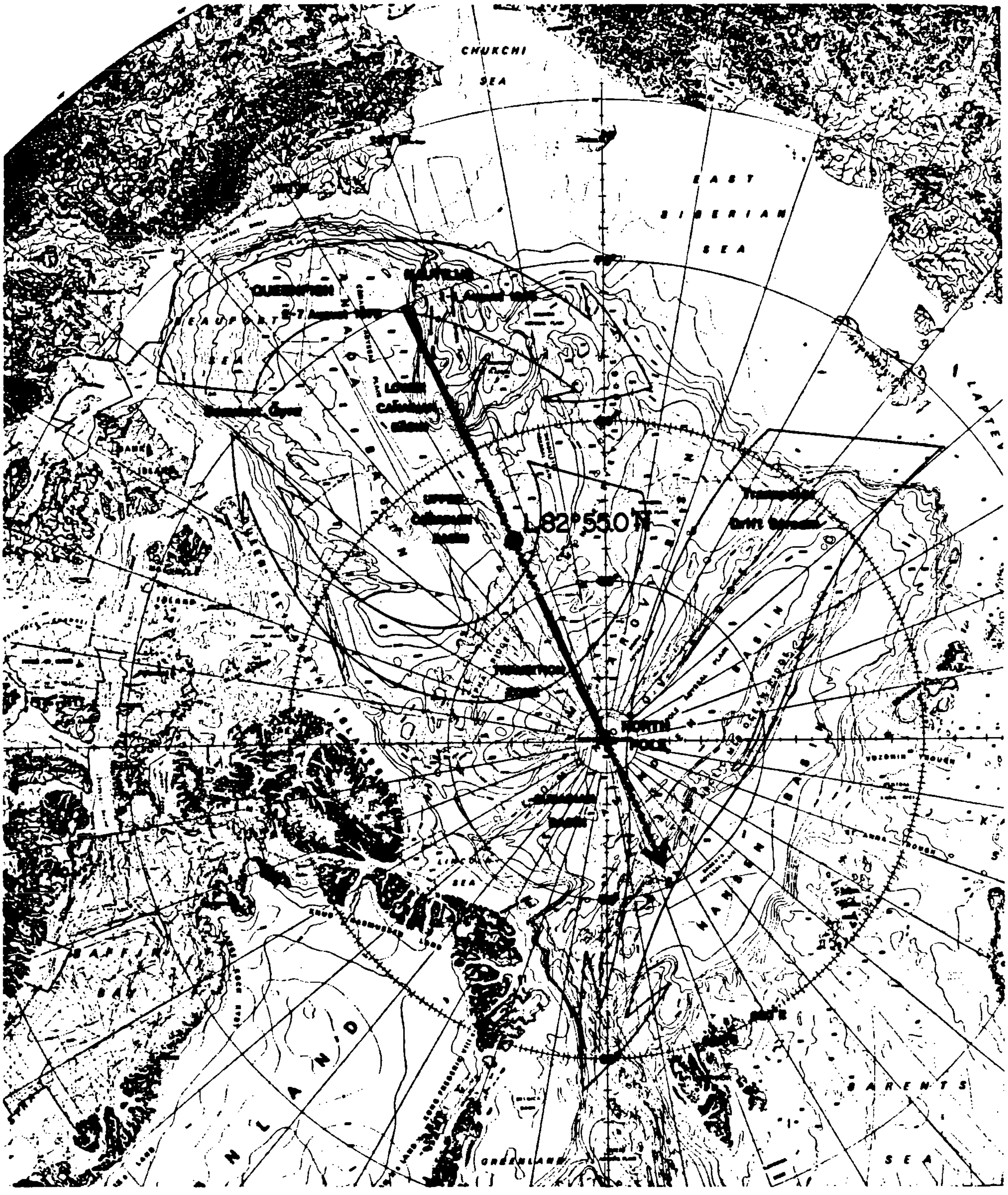

Fig. 1. Map (adapted from Canadian Hydrographic Service [1983]) showing coincidental route traveled by *Nautilus* and *Queenfish* across the Arctic Basin during August 1958 and 1970, respectively, and the four geographical areas into which the data recorded by each submarine was divided for more detailed regional comparative analysis.

Both acoustic measuring devices could be termed "upward beamed" fathometers. The received return echoes from these sonars were fed in both cases 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 speed 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 on a recording chart (Figure 2).

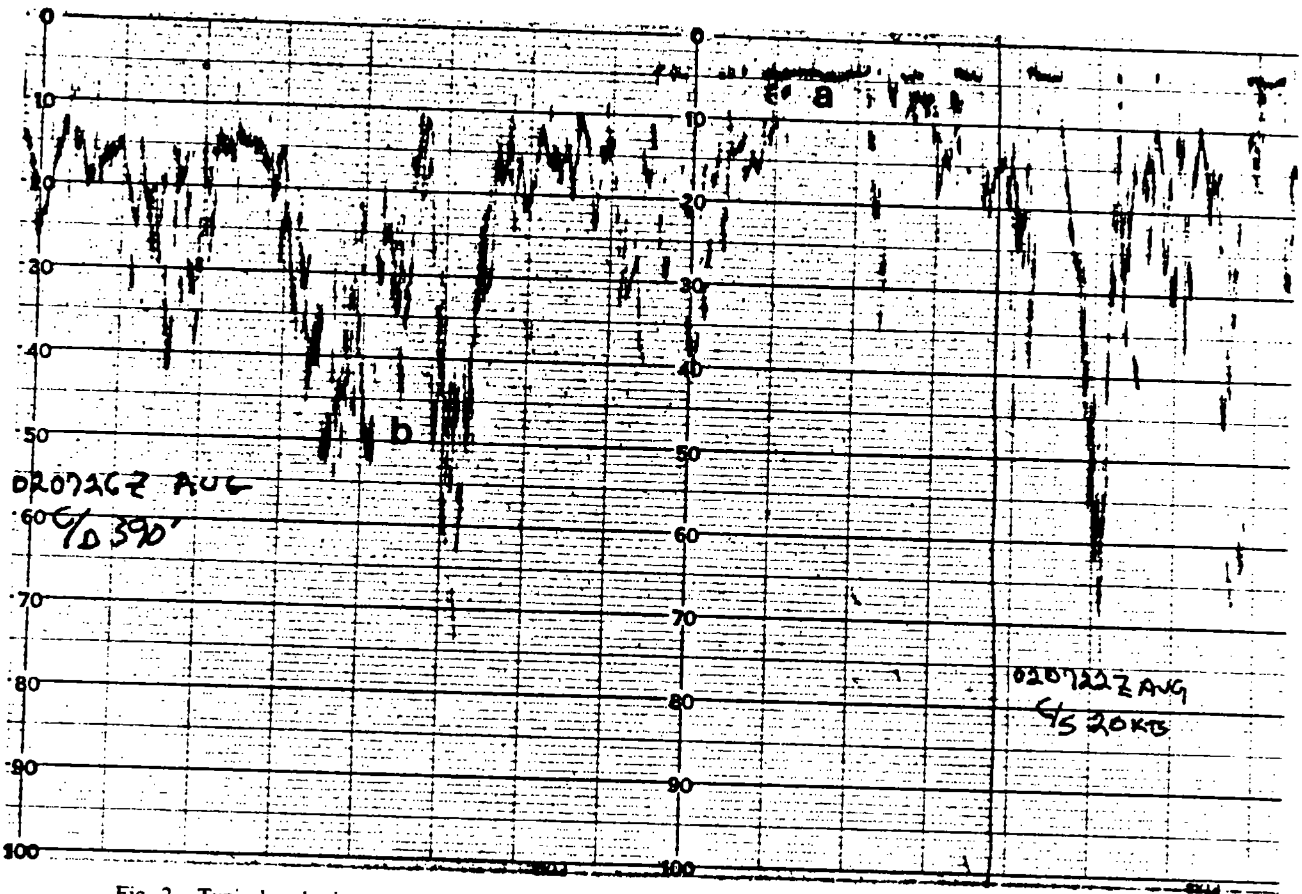

Fig. 2. Typical under-ice topography acoustic recording, of approximately 3 km in length (vertical scale 0–100 ft/0 to 30.5 m) obtained by *Queenfish* during her 1970 transit beneath the polar ice pack. (*a*) Open lead/polynya of 200 m in length. (*b*) Heavy deep draft keel [after McLaren, 1986].

Nautilus used frequencies of either 50 or 180 kHz almost exclusively. The beam width for the 180-kHz signal, used 47% of the time, was 3°; 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%). Both frequencies and beam widths were experimental, with the higher frequency and narrower beam width proving, during the analysis, to yield the more accurate ice draft data. 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 which had been recorded at 50 kHz. This correction was applied in order to make mean ice drafts more comparable to the narrow-beam data recorded by *Queenfish*, since *Nautilus*' wide-beam 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. However, the absolute drafts of most independent deep draft keels (i.e., greater than 5.0 m) were, as *Wadhams* [1981] determined, accurately measured. *Queenfish* used a frequency of 205 kHz with a narrow 2° beam width exclusively throughout her voyage. No beam width corrections were applied to the statistics derived from her under-ice topography data, since she was considered the standard for comparison. Finally, it was noted that the *Nautilus* 180 kHz and *Queenfish* 205 kHz narrow-beam acoustic under-ice profiling systems provided essentially identical samplings of the under-ice topography.

Processing of the Data

The under-ice thickness data recorded on each set of analog recordings were manually digitized by the author using a curve follower and a digitizer tablet which produced one data point every 0.002 in (0.05 mm) of the recording chart. Over 5 million data points were obtained for subsequent statistical analysis. The basic reference for under-ice draft measurements should be the actual sea level. Since no independent measurement of sea level was available, to maintain accuracy, sea level had to be determined through frequent reference (i.e., 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, *Nautilus* and *Queenfish* under-ice thickness distribution data were initially put through an interpolation process to ensure that individual data points were equally spaced at 1.5 m intervals thus assuring a more balanced representation of under-ice thickness. This process also did much to make the basic raw data from the two cruises more directly comparable in preparation for subsequent statistical analysis.

It is important to note that all results are subject to (1) the accuracy of the submarine's under-ice acoustic profiler (±15 cm at best), (2) the accuracy with which the under-ice topography is digitized and actual sea level is estimated, and (3) the precision of the interpolation routine (estimated to be ±1.0 cm).

The digitized data were edited and analyzed statistically using a data processing and statistics software package, writ-

TABLE 1. Comparative Statistics at 85°00.0'N, 155°00.0'W

	Nautilus 1958	*Queenfish* 1970 (Narrow Beam)	*Queenfish* 1970 (Simulated Wide Beam)
Length, km	6.0	6.0	6.0
		Ice Profile	
Mean draft, m	3.57	3.08	3.42
Standard deviation	±2.23	±2.22	±2.44
		Ice Types	
Young (0-29.99 cm), %	0.07	1.00	0.36
Thin (30-69.99 cm), %	0.52	10.28	9.97
Medium (70-119.99 cm), %	2.57	0.60	0.55
Thick first year (120-199.99 cm), %	24.66	10.71	6.67
Second year (200-299.99 cm), %	23.61	43.59	41.11
Multiyear (300-399.99 cm), %	16.79	12.50	14.27
Deformed (400-4599.99 cm), %	31.78	21.32	27.08
		Level Ice	
Occurrence, %	52.7	46.7	55.8
Mean draft, m	2.63	1.92	2.42
Standard deviation	±1.58	±1.03	±1.56
		Independent Keels	
Total	59	102	85
Mean draft, m	5.17	4.77	5.01
Standard deviation	±2.42	±2.70	±2.78
Greater than 5.0 m draft, %	39.0	35.3	38.8
Mean draft, m	7.78	7.57	7.61
Greater than 9.0, %	10.2	7.8	8.2
Mean draft, m	10.18	11.84	12.22
Ridging intensity	1.0	1.3	1.2
Maximum keel draft, m	13.14	16.92	16.92
		Polynyas/Leads	
Surfaceable areas (<200 cm thick), %	27.8	22.6	17.5
Number with length greater than 400 m	0	0	0
Maximum length, m	309.0	262.5	255.2
Skylights (<100 cm thick), %	2.1	11.7	10.7
Number with length greater than 400 m	0	0	0
Maximum length, m	94.5	248.0	240.7
Open water/new ice (<30 cm thick), %	0.1	1.0	0.4
Number with length greater than 400 m	0	0	0
Maximum length, m	4.5	16.0	8.7

ten 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 tracks and smaller evaluation segments of these tracks were determined as simple frequencies. Ice draft data were screened and sorted to generate mean statistics and standard deviations (as 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.

Comparison of Coincidental Route Statistical Results

A comparison of the overall statistics of the two submarines' voyages is presented in two parts. The first part is a comparison of the under-ice thickness distribution recorded by both submarines from the very beginning of the coin-

TABLE 2. Comparative Statistics at 90°00.0′N

	Nautilus 1958	*Queenfish* 1970 (Narrow Beam)	*Queenfish* 1970 (Simulated Wide Beam)
Length, km	5.0	5.0	5.0
		Ice Profile	
Mean draft, m	5.32	4.01	4.40
Standard deviation	±2.86	±2.56	±2.77
		Ice Types	
Young (0-29.99 cm), %	0.35	0.49	0.29
Thin (30-69.99 cm), %	2.14	3.76	3.27
Medium (70-119.99 cm), %	1.13	0.55	0.52
Thick first year (120-199.99 cm), %	2.99	2.05	1.19
Second year (200-299.99 cm), %	11.91	42.39	34.23
Multiyear (300-399.99 cm), %	16.16	19.97	23.78
Deformed (400-4599.99 cm), %	65.33	30.79	36.72
		Level Ice	
Occurrence, %	42.8	42.6	51.9
Mean draft, m	4.41	2.70	3.28
Standard deviation	±2.65	±1.07	±1.90
		Independent Keels	
Total	46	100	66
Mean draft, m	7.93	4.99	5.92
Standard deviation	±3.14	±3.24	±3.52
Greater than 5.0 m draft, %	82.6	31.0	45.5
Mean draft, m	8.75	8.93	8.86
Greater than 9.0 m draft, %	34.8	13.0	18.2
Mean draft, m	11.34	12.11	12.22
Ridging intensity/km	3.2	2.6	2.4
Maximum keel draft, m	16.79	17.79	17.79
		Polynyas/Leads	
Surfaceable areas (<200 cm thick), %	6.6	6.9	5.3
Number with length greater than 400, m	0	0	0
Maximum length, m	144.00	107.30	100.05
Skylights (<100 cm thick), %	3.0	4.6	3.9
Number with length greater than 400 m	0	0	0
Maximum length, m	82.50	97.15	89.90
Open water/new ice (<30 cm thick), %	0.4	0.5	0.3
Number with length greater than 400 m	0	0	0
Maximum length, m	7.50	21.75	14.50

cidental track (latitude 74°23.0′N, longitude 155°00.0′W) across 941 km of the Canada Basin to latitude 82°55.0′N, longitude 155°00.0′W. Both submarines recorded the under-ice topography during this portion of their voyage using high-frequency, narrow-beam under-ice acoustic profiles (i.e., *Nautilus*, 180 kHz; *Queenfish*, 205 kHz). As a result, no data correction was considered necessary, as the statistics were essentially directly comparable. The second part compares the remaining coincidental route under-ice topography recorded by both submarines from latitude 82°55.0′N, longitude 155°00.0′W across the north pole to latitude 86°01.0′N, longitude 25°00.0′E. This comparison must, of necessity, be only a rough one, since *Nautilus* recorded the under-ice topography at a wide beam 50 kHz. However, two approximately 5-km statistical comparison examples which begin at latitudes 85°00.0′ and 90°00.0′N, respectively, along the longitudes previously

TABLE 3. Canada Basin Statistics Comparison, *Nautilus* 1958 (180 kHz) with *Queenfish* 1970 (205 kHz)

	Nautilus 1958	*Queenfish* 1970
Length, km[a]	941.0	941.0
	Ice Profile	
Mean draft, m	3.08	2.39
Standard deviation	±2.13	±1.66
	Ice types[b]	
Young (0-29.99 cm), %	3.33	3.96
Thin (30-69.99 cm), %	4.54	3.75
Medium (70-119.99 cm), %	7.22	6.91
Thick first year (120-199.99 cm), %	15.35	36.45
Second year (200-299.99 cm), %	26.33	26.38
Multiyear (300-399.99 cm), %	20.90	10.64
Deformed (400-4599.99 cm), %	22.32	11.92
	Level Ice[c]	
Occurrence, %	62.6	58.3
Mean draft, m	2.45	1.74
Standard deviation	±1.70	±0.93
	Independent keels[d]	
Total	6900	8600
Mean draft, m	5.04	4.25
Standard deviation	±2.57	±2.07
Greater than 5.0 m draft, %	37.3	24.0
Mean draft, m	7.63	7.23
Greater than 9.0 m draft, %	8.7	4.1
Mean draft, m	11.34	11.01
Ridging intensity/km	0.73	0.41
Maximum keel draft, m	> 19.59	36.53
	Polynyas/Leads	
Surfaceable areas (<200 cm thick), %	30.4	51.1
Number with length greater than 400 m	70	104
Maximum length, m	1500.0	1450.0
Skylights (<100 cm thick), %	11.9	10.6
Number with length greater than 400 m	21	5
Maximum length, m	1383.0	701.8
Open water/new ice (<30 cm thick), %	3.4	4.0
Number with length greater than 400 m	5	0
Maximum length, m	1308.0	397.3

[a]Includes all data gaps due to submarine recording equipment malfunction or ship's maneuvers.
[b]Arctic sea ice terminology [after *Weeks*, 1976; *Stringer et al.*, 1984]. The thicknesses are to be considered approximations only and not absolute limits.
[c]Based on a 1 in 40 gradient used by *Wadhams* [1981].
[d]For consistency and comparison purposes the author uses a definition originating with *Williams et al.* [1975], which was refined by *Wadhams and Horne* [1980].

cited, are provided (Tables 1 and 2) in order to show the degree to which the under-ice thickness distribution statistical output would be affected by degrading/convolving the higher-quality *Queenfish* data by simulating the passage of the wide-beam *Nautilus* acoustic profiler across it. It is interesting to note that this causes the overall draft to increase approximately 10%, the percentages of the ice types less than 3.0 m in draft to decrease, and the percentages of the ice types greater than 3.0 m in draft to increase. Although this implies that this process could then be applied to the *Queenfish* data overall, the author feels strongly that the narrow-beam *Queenfish* statistical data in its entirety is of such high quality that it should be fully presented in this report rather than only a degraded/convolved version. It would thus be of considerably greater value to future researchers, particularly when more submarine-recorded under-ice thickness distribution data of

TABLE 4. Transpolar and Eurasian Statistics Rough Comparison, *Nautilus* 1958 (50 kHz) with *Queenfish* 1970 (205 kHz)

	Nautilus 1958	*Queenfish* 1970
Length, km[a]	1235	1235
Ice Profile		
Mean draft, m	4.06	3.57
Corrected	(3.39)	
Standard deviation	±3.09	±2.46
Ice types[b]		
Young (0-29.99 cm), %	2.20	3.34
Thin (30-69.99 cm), %	4.34	4.07
Medium (70-119.99 cm), %	6.73	1.43
Thick first year (120-199.99 cm), %	14.08	6.80
Second year (200-299.99 cm), %	17.91	39.68
Multiyear (300-399.99 cm), %	15.61	17.72
Deformed (400-4599.99 cm), %	39.13	26.95
Level Ice[c]		
Occurrence, %	49.9	45.0
Mean draft, m	3.15	2.28
Standard deviation	±3.03	±1.14
Independent keels[d]		
Total	8063	19924
Mean draft, m	6.10	4.62
Standard deviation	±3.25	±2.80
Greater than 5.0 m draft, %	52.5	28.9
Mean draft, m	8.44	8.17
Greater than 9.0 m draft, %	18.0	8.5
Mean draft, m	11.70	11.77
Ridging intensity	1.42	1.63
Maximum keel draft, m	>20.47	31.27
Polynyas/Leads		
Surfaceable areas (<200 cm thick), %	27.4	15.7
Number with length greater than 400 m	27	24
Maximum length, m	891.0	1450.0
Skylights (<100 cm thick), %	10.3	8.1
Number with length greater than 400 m	6	18
Maximum length, m	808.5	1450.0
Open water/new ice (<30 cm thick), %	2.2	3.3
Number with length greater than 400 m	1	6
Maximum length, m	462.0	1450.0

[a]Includes all data gaps due to submarine recording equipment malfunction or ship's maneuvers.
[b]Arctic sea ice terminology [after *Weeks*, 1976; *Stringer et al.*, 1984]. The thicknesses are to be considered approximations only and not absolute limits.
[d]For consistency and comparison purposes the author uses a definition originating with *Williams et al.* [1975], which was refined by *Wadhams* [1980].

equal or higher quality, with which it can be compared spatially and temporally, becomes available for analysis. Finally, the statistical data are then divided into geographical areas to facilitate general regional comparisons. Comparisons in each area are then drawn between the under-ice topography encountered by *Nautilus* in 1958 and by *Queenfish* in 1970.

Overall Comparison

The overall under-ice statistics for the *Nautilus* and *Queenfish* coincidental route are presented in Tables 3 and 4. Standard deviations have not been compared for all under-ice statistics parameters in view of the sample sizes. The differences between the means for overall ice drafts, level ice drafts, and independent keel drafts, however, are significant at better than the 0.1 level. It should be noted that each of the transects presented in Table 3 essentially bisects the Beaufort gyre, and each of the transects presented in Table 4 essentially bisects the Transpolar drift stream.

Table 3 shows that the under-ice topography along the first 941 km of the coincidental route, the Canada Basin, was more

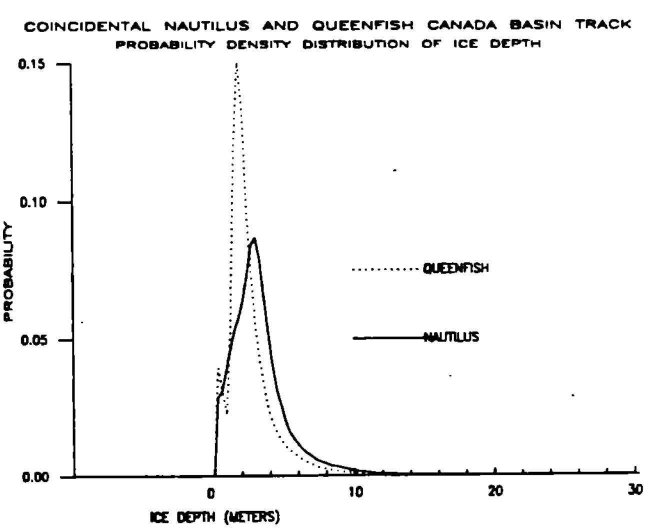

Fig. 3. Comparison of overall probability under-ice thickness densities recorded by *Nautilus* and *Queenfish* along the coincidental route traveled by each submarine across the Canada Basin [after

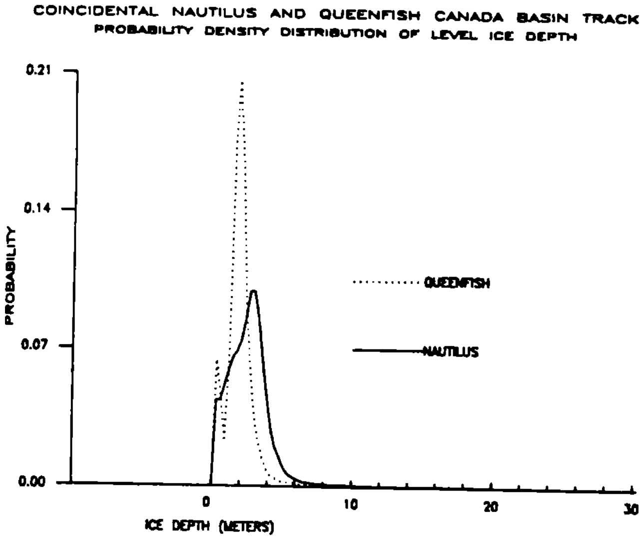

Fig. 4. Comparison of overall probability densities of level ice recorded by *Nautilus* and *Queenfish* along the coincidental route traveled by each submarine across the Canada Basin [after *McLaren*, 1986].

year in 1958. The rough comparison presented in Table 4, however, does not indicate this to be true for the transpolar and Eurasian Basin regions. That *Queenfish* encountered generally milder conditions in the Canada Basin in particular was further indicated by (1) lower overall mean ice drafts, (2) considerably less multiyear and deformed ice, (3) more open water and surfaceable areas, and (4) more large (greater than 400 m in length) open and refrozen leads and polynyas of up to 2.0 m in thickness. Figures 3–7, which present superimposed probability density plots and histograms of the data recorded by both submarines across the Canada Basin, also illustrate these findings.

Geographical Area Comparison

The data have been partitioned into four geographical areas (see Figure 1 and Table 5) for purposes of more detailed regional comparative analysis and to gain further insights into the relative severity of conditions encountered during each cruise.

Figures 8 and 9 present comparison by year (i.e., *Nautilus*, 1958; *Queenfish*, 1970) and geographical area. The principal indicators, listed in order of relative importance/evaluation weight, used to assess differences in areal ice conditions between voyages and to make determinations as to the relative ice conditions encountered are (1) mean ice drafts and standard deviations, (2) total percentages of multiyear and deformed ice, and (3) percentages of open water/new ice. These figures reveal that the Canada Basin appears to contain the most moderate under-ice topography and the greatest number of open water and refrozen polynyas and leads within the

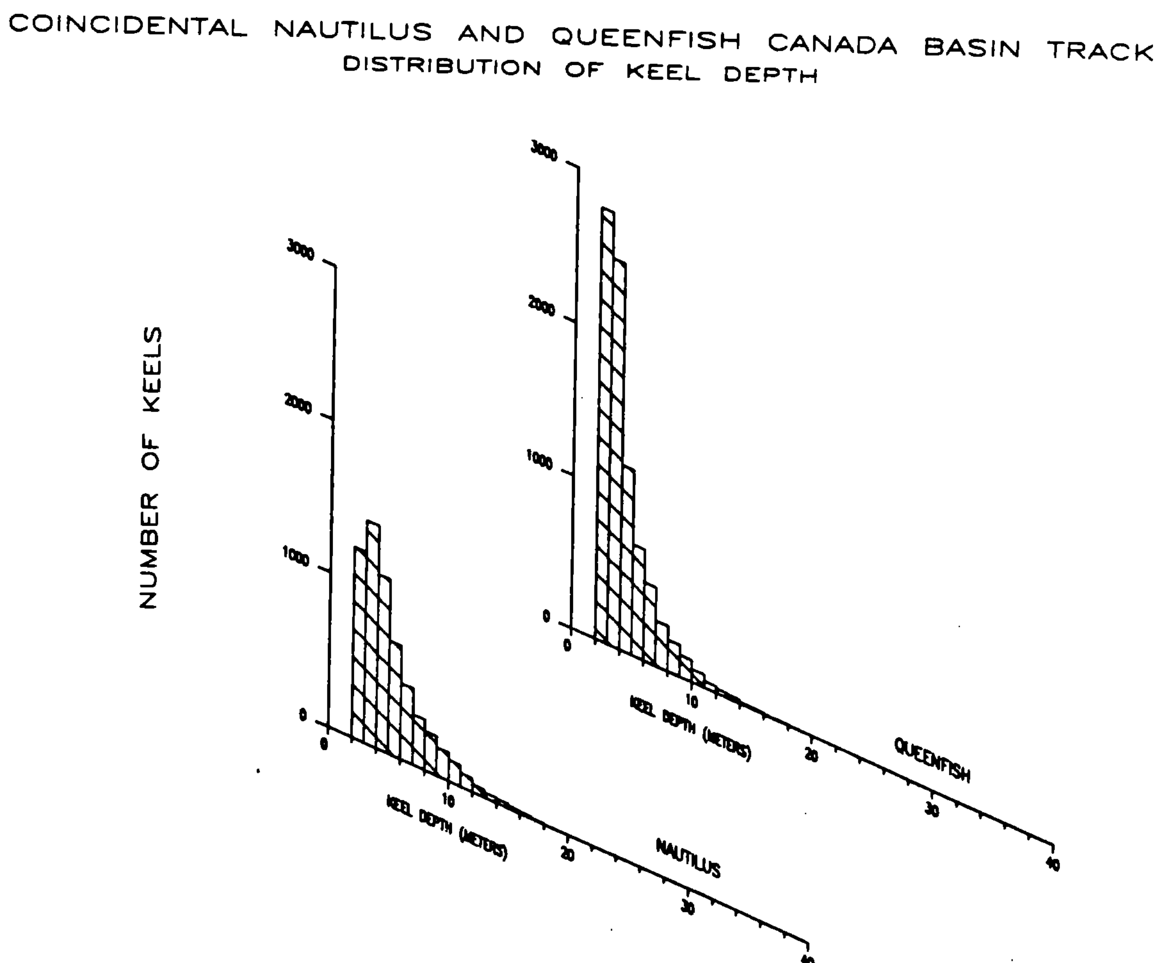

Fig. 5. Comparison of the number and size of independent keels recorded by *Nautilus* and *Queenfish* along the coincidental route traveled by each submarine across the Canada Basin [after *McLaren*, 1986].

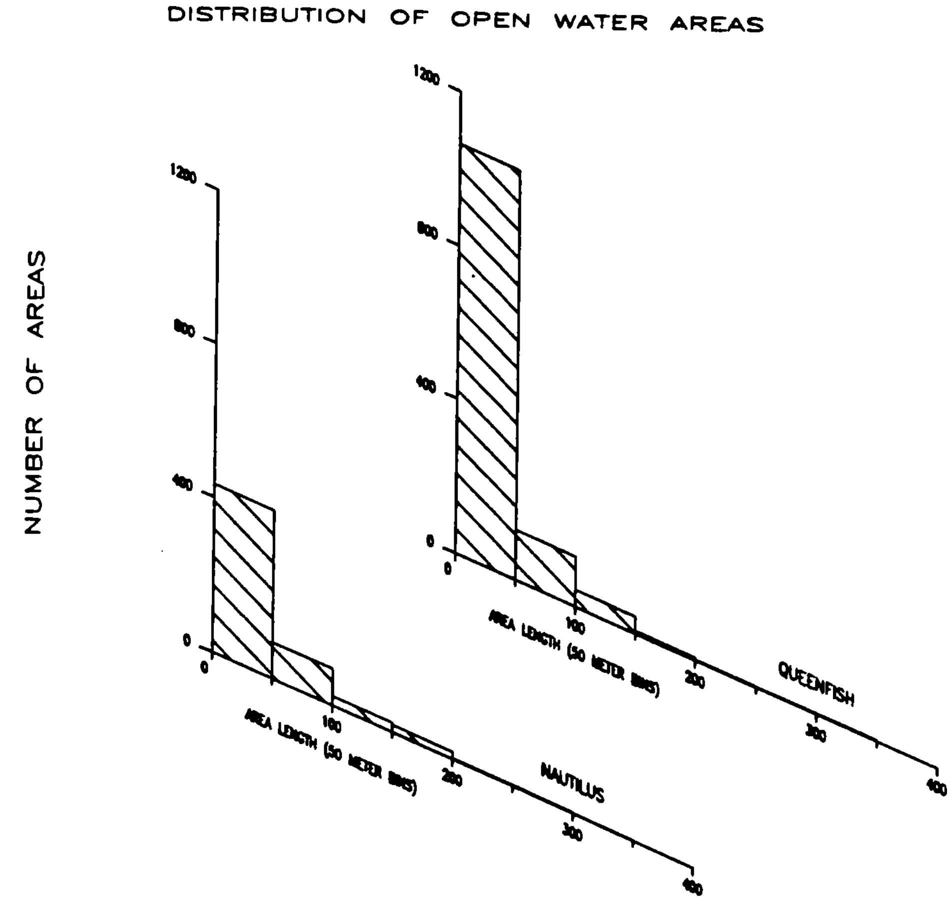

Fig. 6. Comparison of the number and size of open water/new ice areas recorded by *Nautilus* and *Queenfish* along the coincidental route traveled by each submarine across the Canada Basin [after *McLaren*, 1986].

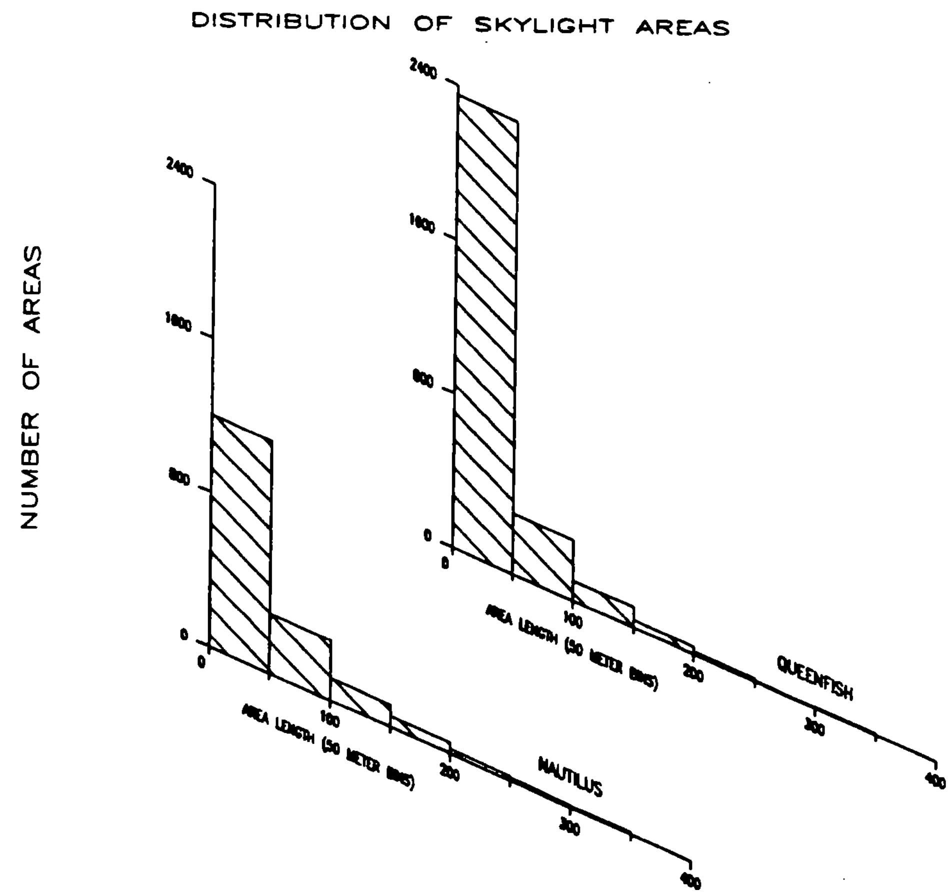

Fig. 7. Comparison of the number and size of refrozen polynya/lead areas of thicknesses up to and including 1.0 m ("Skylights") recorded by *Nautilus* and *Queenfish* along the coincidental route traveled by each submarine across the Canada Basin [after *McLaren*, 1986].

TABLE 5. Partition of Data Into Geographical Areas

Geographical Area	Encompasses	Latitudes	Longitude
Lower Canadian Basin	Lower Canada Basin	75°–80°N	155°00.0′W
Upper Canadian Basin	Upper Canada Basin	80°–85°N	155°00.0′W
Transition Zone	Alpha Ridge, Makarov Basin, Lomonosov Ridge	85°–90°N	155°00.0′W
Eurasian Basin	Amundsen Basin, Arctic Mid-Ocean Ridge	90°–86°N	025°00.0′E

Arctic Basin. It can be seen that *Queenfish* encountered considerably more moderate ice of greater geographical extent within this area in 1970 than did *Nautilus* 12 years earlier. These figures also indicate that the Makarov and Amundsen basins may contain the most severe under-ice topography within the central Arctic Basin. It should be noted that both submarines encountered more rugged under-ice conditions within these basins and in the vicinity of the Arctic mid-ocean ridge than anywhere else within the Arctic Basin.

Comparison of *Nautilus* and *Queenfish* Results With Other Observations

Comparison of Field 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 was covered by pressure ridge ice considerably thicker than the average, and (3) 12% of the Canada Basin and 7% of the Eurasian Basin was open water during summer. The results of analysis of the *Nautilus* and *Queenfish* data generally support items 1 and 2 above but not 3.

Wadhams [1981] did a statistical analysis of H. M. *Sovereign*'s Arctic Ocean cruise during October 1976. Table 6 presents the central Arctic (Eurasian Basin) results, which are geographically equivalent to *Nautilus* 1958 and *Queenfish* 1970. Value ranges are those noted during evaluation of statistical data segments used by both *Wadhams* [1981] and *McLaren* [1986] within the Eurasian Basin. As can be seen from this rough comparison, *Wadhams*' [1981] wide-beam data are generally in accord with *Nautilus*' 1958 and *Queenfish*'s 1970 measurements. Differences in ice thickness distribution and lead/polynya percentages are those that would be expected due to time of year.

Comparison with Modeling Results

The late 1960s saw the development of sea ice models of varying types and complexity. 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 ocean boundary layers [*Thorndike et al.* 1975].

Hibler [1980], for example, 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 10 and 11 replicate *Hibler*'s [1980, Figures 4 and 9], which depict average August ice thickness (in meters) contours as a result of the following variable thickness sea ice cover

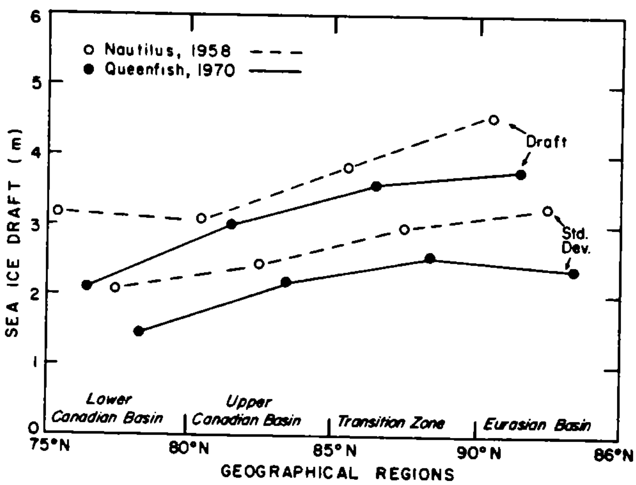

Fig. 8. Comparative plots of mean ice draft and standard deviation statistical results derived from under-ice thickness data recorded within four geographical areas by *Nautilus* and *Queenfish* along the coincidental route traveled by each submarine across the Arctic basin [after *McLaren*, 1986].

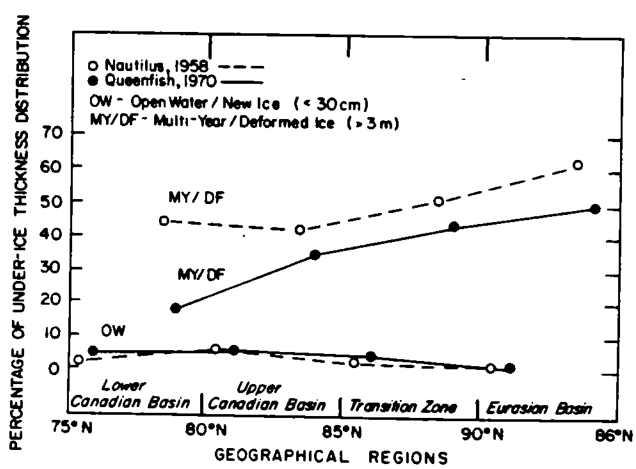

Fig. 9. Comparative plots of mean multiyear and deformed ice and open water statistical results derived from under-ice thickness data recorded within four geographical areas by *Nautilus* and *Queenfish* along the coincidental route traveled by each submarine across the Arctic Basin [after *McLaren*, 1986].

TABLE 6. Comparison of *Sovereign* 1976 [*Wadhams*, 1981], *Nautilus* 1958, and *Queenfish* 1970 [*McLaren*, 1986]: Under-Ice Profile Results

	Sovereign October 1976	*Nautilus* August 1958	*Queenfish* August 1970
	Under-Ice Profile		
Mean draft, m	5.37	4.33	3.69
Corrected	3.9–5.1	3.1–4.3	3.1–4.3
0-50 cm, %	1.56	3.64	4.10
50-200 cm, %	6.00	23.31	5.17
200-500 cm, %	50.00	51.21	72.04
>500 cm, %	42.00	22.83	18.69
	Level ice		
Occurrence, %	45–55	47–54*	32–56
Mean draft, m	3.0–3.1	2.6–3.8*	2.1–2.9
	Independent keels		
Number >9.0 m draft/km	2–3	1.0–1.7	0.6–2.6
	Leads/Polynyas		
<100 cm thick, %	1–5	6.6–11.0	1.8–14.7
Number >500 m in length	2	1	2

*Unadjusted.

5-year simulations: (1) mechanical and thermodynamic, (2) thermodynamics only, (3) high strength, and (4) high growth. *Nautilus*' 1958 and *Queenfish*'s 1970 tracks are superimposed on Figures 10 and 11 for comparison purposes. Note that the actual overall mean ice drafts recorded by *Nautilus and Queenfish*, respectively, along these tracks (Tables 3 and 4) are significantly greater than the simulation ice thickness contours indicate for the same geographic areas.

Comparison with Satellite Observations

Brief mention should also be made of recent satellite observations of Arctic Basin sea ice thickness and extent from the Nimbus 5 electronically scanning microwave radiometer (ESMR) and Nimbus 7 satellites. *Gloersen et al.* [1978] and *Campbell et al.* [1980] both reported the presence of two very large (over 100 km in diameter) open water areas or polynyas between 80° and 85°N in the Eurasian Basin during August and September 1974. The observations were derived from interpretation of Nimbus 5 ESMR 1.55-cm wavelength relatively low brightness temperature (less than 185°K) observations of the area. *Crane et al.* [1982] questioned this interpretation and stated that since it was not possible to determine the relative contributions of melt ponds, open leads, and open water to the total signature of the features observed, these areas could also be interpreted to be extensive meltwater puddling. Although coincidental satellite data are not available

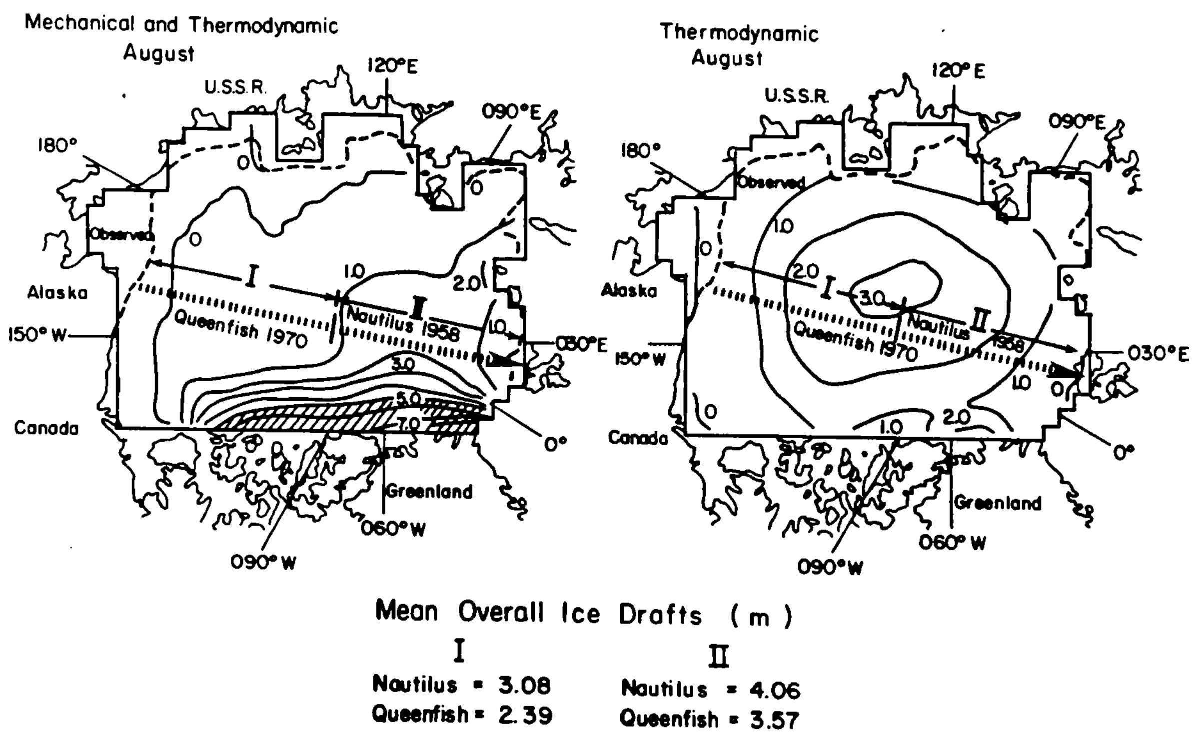

Fig. 10. Plot of coincidental route followed by *Nautilus* and *Queenfish* across the Arctic Basin superimposed on *Hibler*'s [1980] plot of "Average August thickness contours (m) for the fifth year of standard and thermodynamics only simulations."

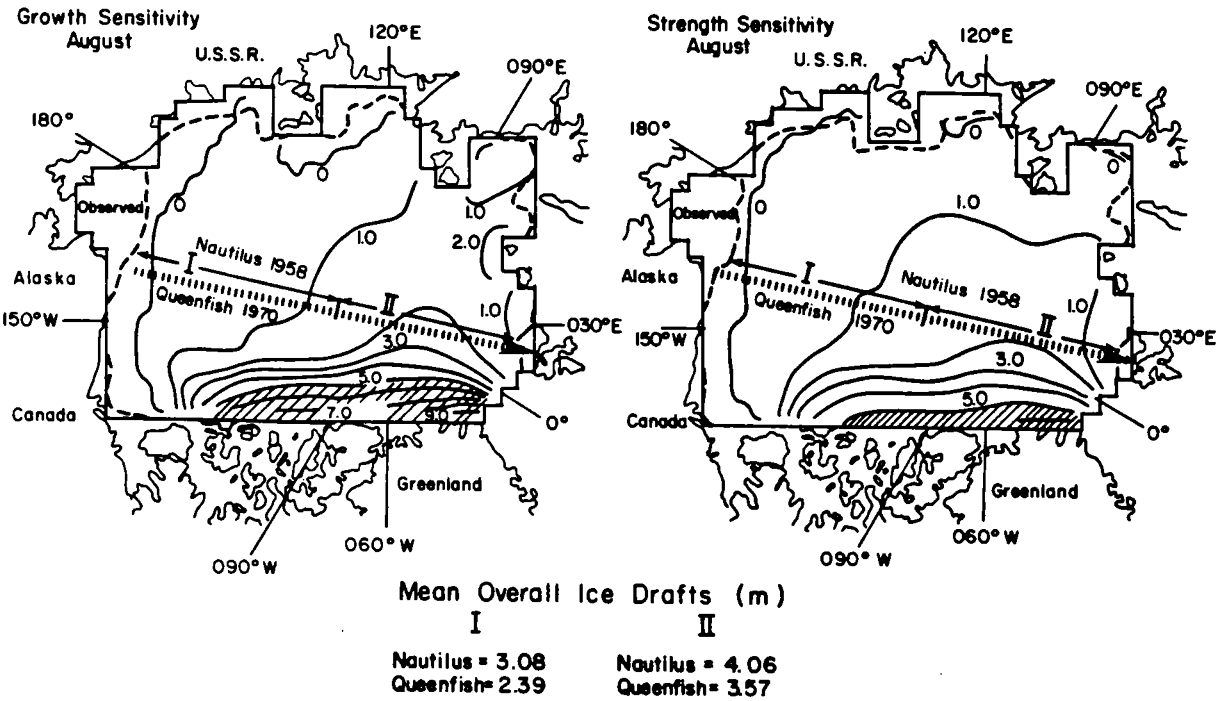

Fig. 11. Plot of coincidental route followed by *Nautilus* and *Queenfish* across the Arctic basin superimposed on *Hibler's* [1980] plot of "Average August thickness contours (m) for high strength and high growth simulations."

along *Nautilus*' 1958 and *Queenfish*'s 1970 tracks across the Arctic Basin, it is interesting to note that the continuous and more accurate *Nautilus* and *Queenfish* recordings of the Arctic basin under-ice topography within these latitude bands [*McLaren*, 1986] and further north, as reported in this paper, revealed no open water or refrozen polynya areas greater than approximately 2.5 km in length. Finally, *Cavalieri and Zwally* [1985] reported that interpretation of Nimbus 7 scanning multichannel microwave radiometer observations of the Canadian and Eurasian Basins revealed open water percentages as high as 12%. *Nautilus* and *Queenfish* smaller-scale evaluation segment (i.e., 20–50 km) statistical results revealed the same percentages [*McLaren*, 1986].

Conclusion

This statistical analysis of the *Nautilus* and *Queenfish* records represents the first detailed data on the under-ice topography across the Arctic Basin. They are the only such data that can be directly compared to reveal temporal changes in Arctic basin under-ice topography. A comparison of the data from the coincidental routes allows the following observations to be made: (1) with the exception of modeling, the statistical results from the 1958 *Nautilus* and 1970 *Queenfish* voyages are basically in agreement with and support the findings of most sea ice researchers; this most recent analysis indicates, however, that the summer open water estimates of many studies may be too high, (2) *Nautilus* recorded generally more severe ice conditions within the Canada Basin during August of 1958 than did *Queenfish* 12 years later, (3) ice conditions appear to become progressively more severe when proceeding from the Canadian to the Eurasian side of the Arctic Basin, (4) the Canada Basin may contain the most moderate under-ice topography and the greatest number of open water and refrozen polynyas and leads within the central Arctic Basin, and (5) the Makarov and Amundsen basins and Arctic mid-ocean ridge may contain some of the most severe under-ice topography within the central Arctic Basin.

In a more speculative sense the results reported herein suggest that (1) the more severe under-ice thickness distribution noted within the Makarov and Amundsen basins may be a permanent feature and directly related to the passage of the Transpolar drift stream, which transports and tends to further cause ice convergence through these areas, and (2) the moderate under-ice thickness distributions noted within the Canada Basin, as evidenced by the higher percentages of first-year ice and open/refrozen leads and polynyas, may be a permanent feature and directly related to newly discovered dynamic characteristics of the Beaufort gyre [*McLaren et al.*, 1987]. They could therefore be an important climate affecting parameter since, as *Maykut* [1982] noted, the absorption of shortwave radiation by summer leads results in annual net radiation totals for the Arctic Basin more than double those over ice.

In conclusion, this first detailed analysis of over 5300 km of under-ice data across the Arctic basin as well as the findings summarized in this article 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 recent satellite passive microwave data and future synthetic aperture radar data and the as yet unexamined under-ice topography recorded by American and British submarines during the almost 3 decades which have followed *Nautilus*' historic cruise.

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

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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 eurasien 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 eurasien, sous-marin arctique

Traduit pour le journal par Nésida Loyer.

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

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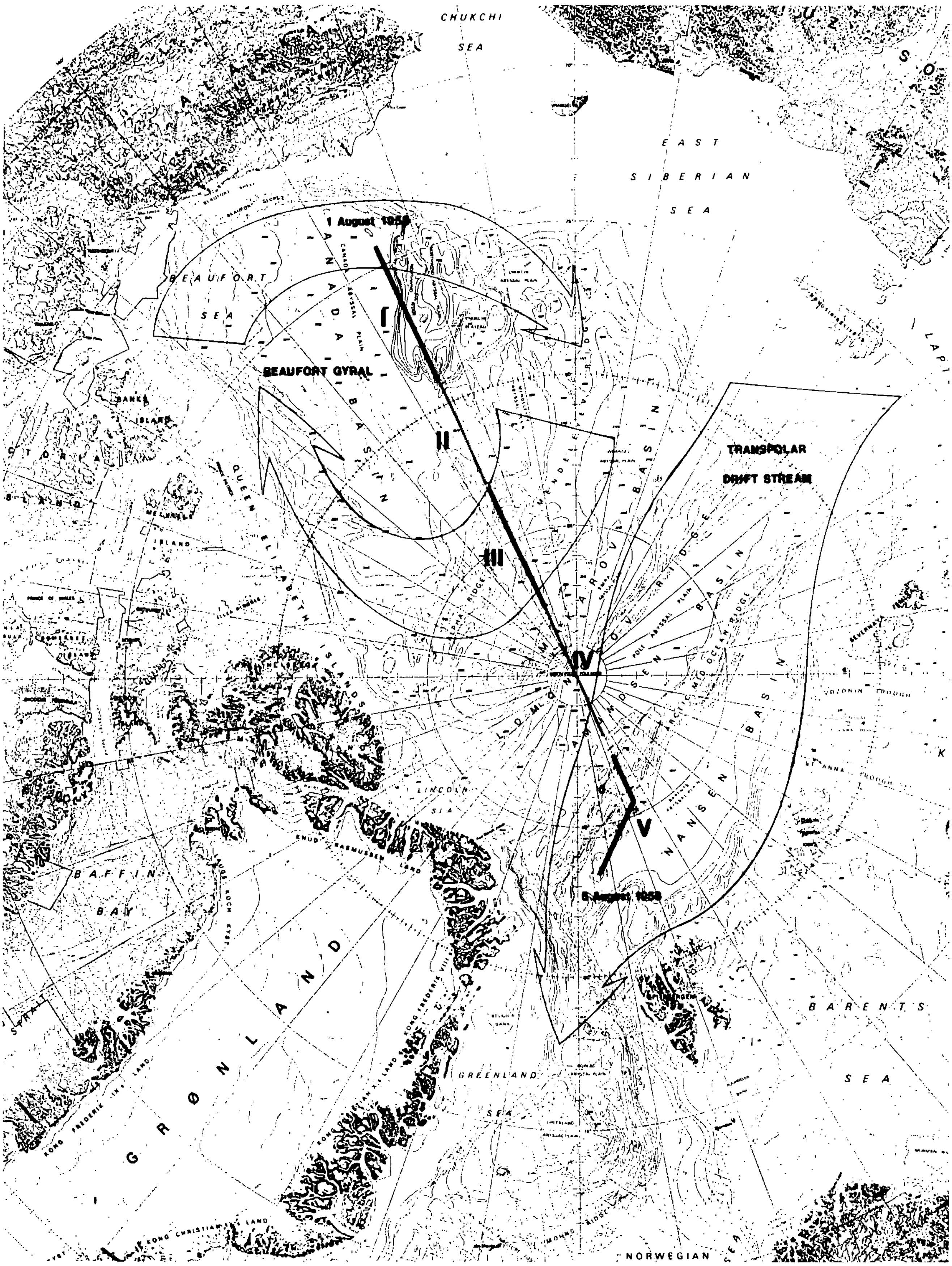

FIG. 1. Map (adapted from Canadian Hydrographic Service) showing USS *Nautilus*'s route across the Arctic Basin and the five distinct ice regions encountered during early August 1958.

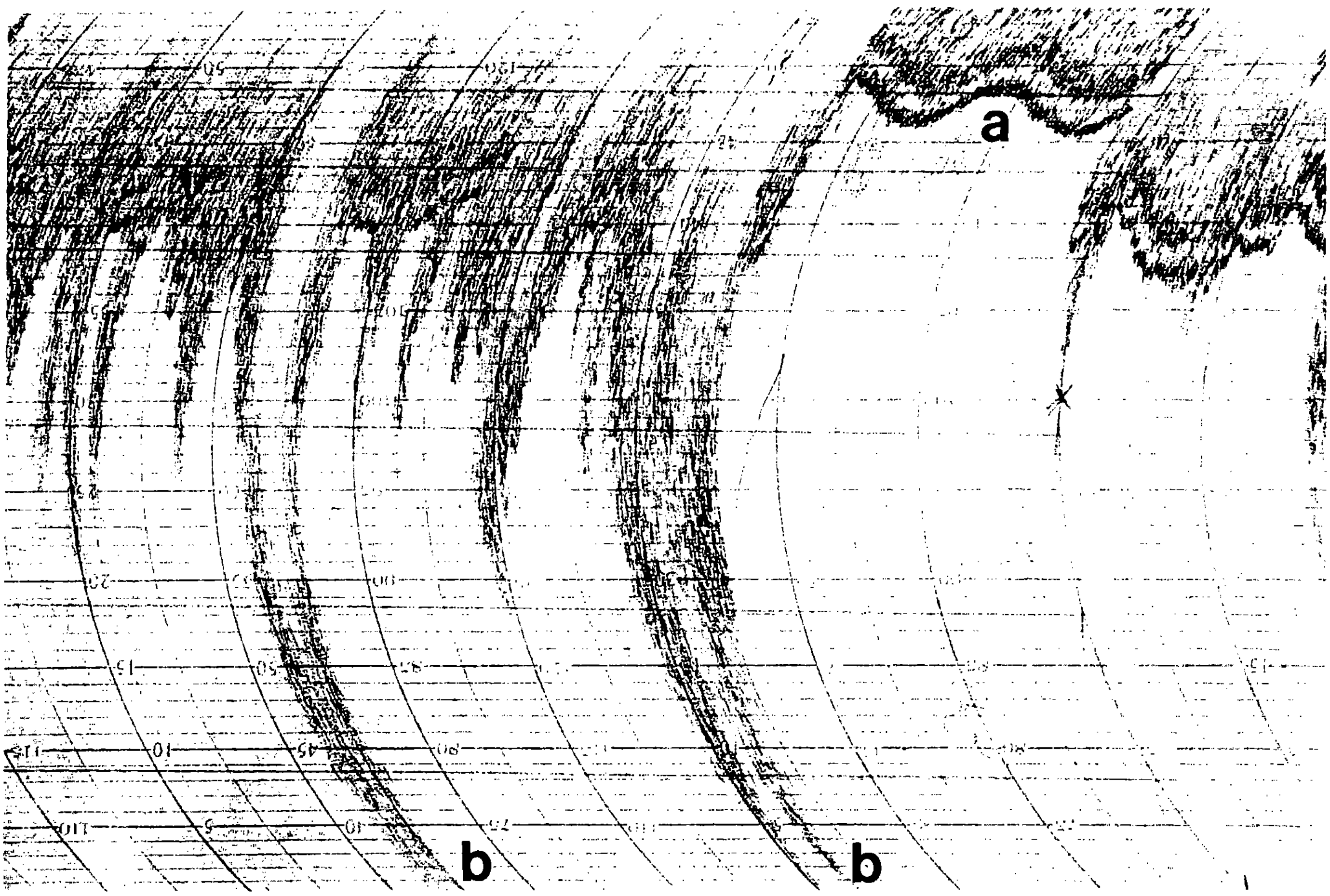

FIG. 2. Typical under-ice topography acoustic recording of approximately 3 km in length (vertical scale 0-55 ft/0-16.8 m) obtained by *Nautilus* during her 1958 transit beneath the polar ice pack. (a) Open lead/polynya of approximately 680 m in length. (b) Heavy deep draft keels (source: U.S. Navy).

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

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

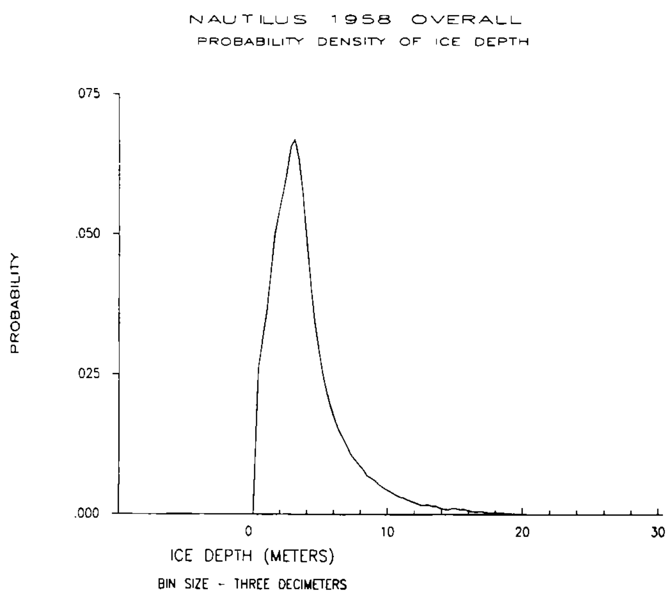

FIG. 3. Overall under-ice thickness probability density recorded by *Nautilus* across the Arctic Basin (after: McLaren, 1986).

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

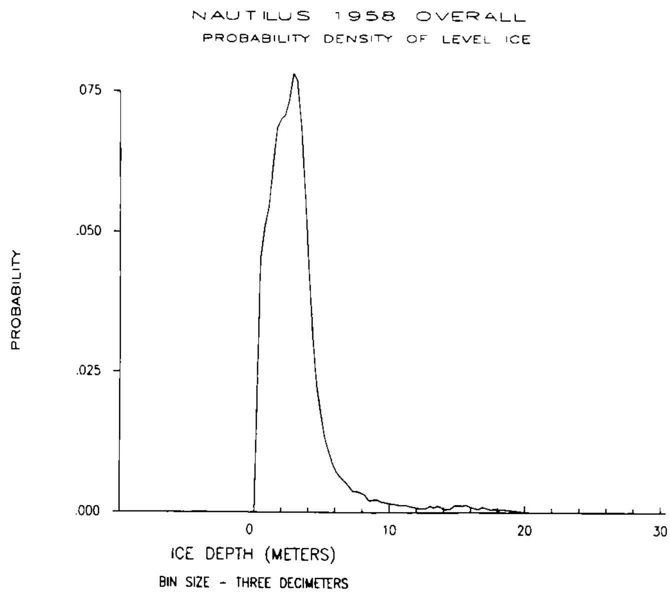

FIG. 4. Overall probability density of level ice recorded by *Nautilus* across the Arctic Basin (after: McLaren, 1986).

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

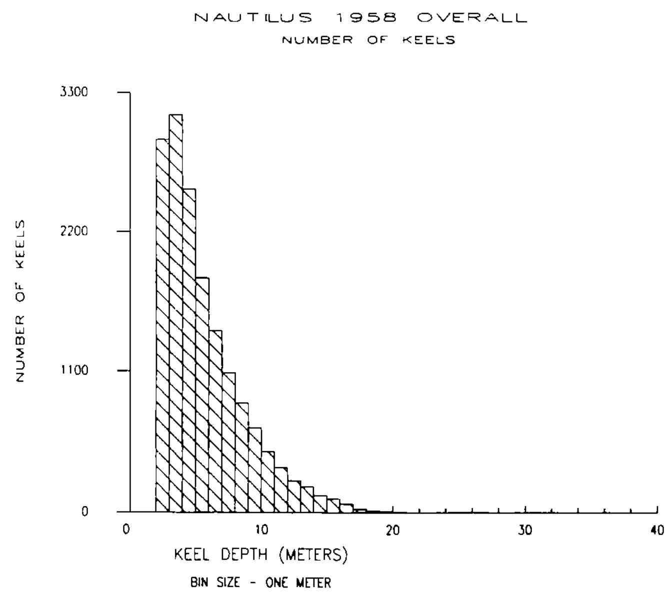

FIG. 5. The number and size of independent keels recorded by *Nautilus* across the Arctic Basin (after: McLaren, 1986).

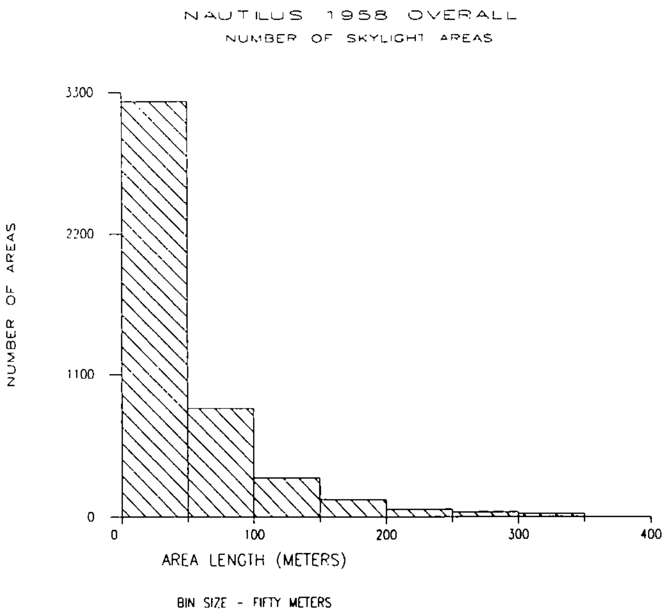

FIG 6. The number and size of refrozen polynya/lead areas of thicknesses up to 1.0 m (skylights) recorded by *Nautilus* across the Arctic Basin (after: McLaren, 1986).

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 (50/180kHz)	Region I (180kHz)	Region II (180kHz)	Region III (50 kHz)	Region IV (50 kHz)	Region V (50/180kHz)
Length (km)[a]	2580	536	403	491	505	501
Ice profile						
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
Ice types[b]						
% 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
Level ice[c]						
% 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
Independent keels[d]						
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
Polynyas/leads						
% 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

[a]Includes all data gaps due to submarine recording equipment malfunction or ship's maneuvers.
[b]Arctic sea ice terminology is after Weeks, 1976, and Stringer *et al.*, 1984. The thicknesses are to be considered approximations only and not absolute limits.
[c]Based on 1 in 40 gradient used by Wadhams (1981).
[d]For 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 underrun 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.

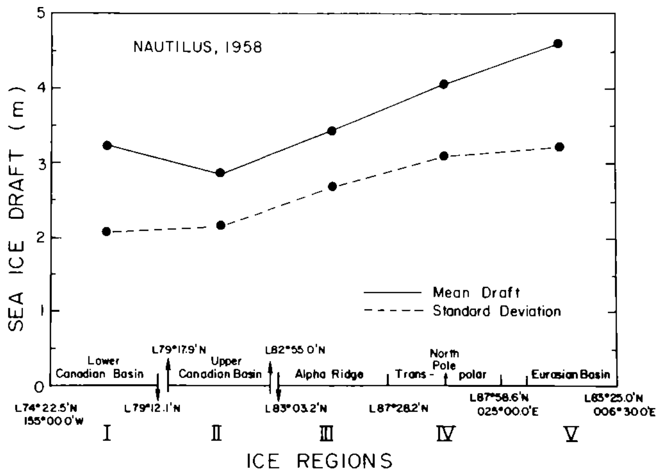

FIG. 7. Plot of mean ice draft (m) and standard deviation statistical results derived from under-ice thickness data recorded by *Nautilus* within five distinct ice regions encountered across the Arctic Basin.

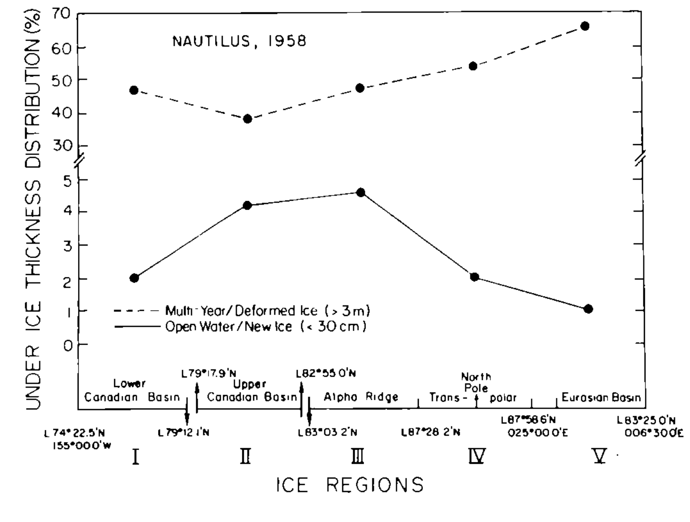

FIG. 8. Plot of mean multi-year and deformed ice and open water statistical results derived from under-ice thickness data recorded by *Nautilus* within five distinct ice regions encountered across the Arctic Basin.

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) (*Nautilus* statistical analysis: McLaren, 1986)	March 1971 (m) (*Dreadnought*)	August 1958 (m) (*Nautilus* 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

	Gurnard (April 1976) (Wadhams and Horne, 1980)	*Nautilus* (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, Wadham'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

	Sovereign (October 1976) (Wadhams, 1981)	*Nautilus* (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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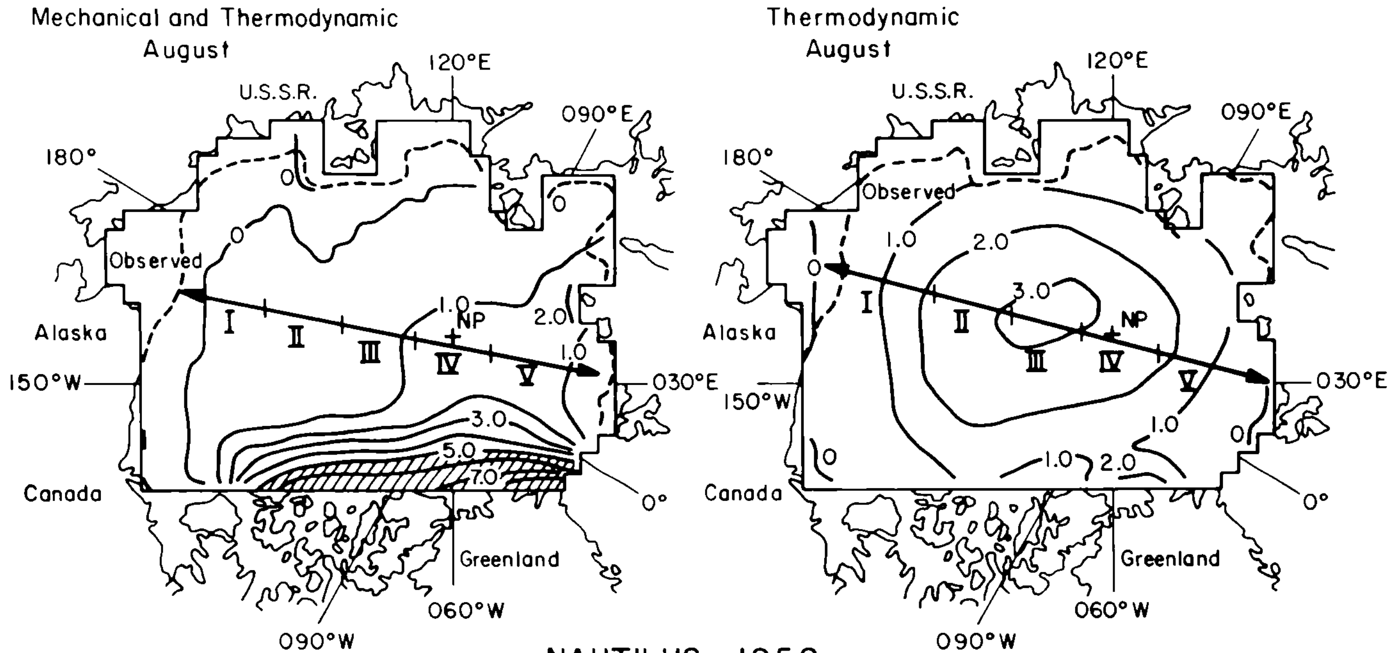
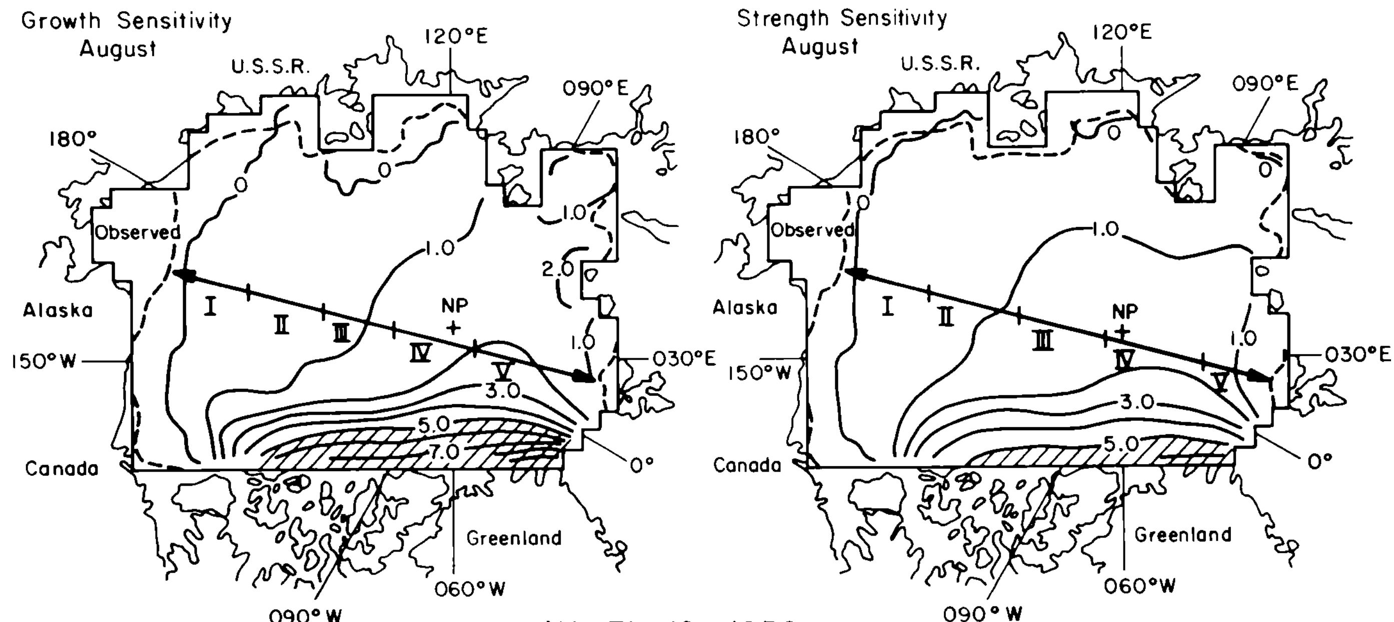


NAUTILUS 1958

MEAN REGIONAL ICE DRAFTS (m)

I	II	III	IV	V
3.25	2.86	3.44	4.05	4.59

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."



NAUTILUS 1958

MEAN REGIONAL ICE DRAFTS (m)

I	II	III	IV	V
3.25	2.86	3.44	4.05	4.59

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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SEASONAL VARIATIONS OF SEA ICE MOTION IN THE CANADA BASIN AND THEIR IMPLICATIONS

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Abstract. Ice velocities and sea level pressure data from Arctic drifting buoys for 1979-85 are used to examine the seasonal variation of sea ice drift in the Canada Basin. A recurring reversal of the mean anticyclonic gyre is demonstrated in late summer, in response to changes in atmospheric forcing. The identification of this reversal of ice motion is significant for numerical modeling of Arctic atmosphere-ocean-ice interactions.

Introduction

The drift of sea ice in the Arctic Basin has been extensively investigated since Nansen's famous voyage in the "Fram", 1894-96. The main features of the mean pattern of ice circulation [Fel'zenbaum, 1958; Gordienko, 1958] are a large-scale drift away from the Siberian coastline and across the Pole in the Transpolar Drift Stream, with ice exiting the basin through the Fram Strait between Greenland and Svalbard. In the Canada Basin, the motion of the surface waters and ice is characterized by the clockwise Beaufort Gyre that corresponds roughly to the mean surface anticyclone in the atmosphere [Campbell, 1965; Newton, 1973; Carmack, 1986]. Mean velocities of ice drift in the gyre are about 5-6 km d^{-1}. The AIDJEX program in the southern Beaufort Sea investigated ice behavior on a 100 km space scale and one day time scale [Pritchard, 1980]. Subsequently, basin scale data on ice motion have been provided by a network of Arctic drifting buoys [Thorndike and Colony, 1980]. Recent analysis of submarine sonar measurements of ice draft collected by the USS NAUTILUS in August 1958 and the coincident August 1970 transect of the USS QUEENFISH across the Canada Basin along 155° W indicates that the ice in the central part of the Beaufort Gyre may be thinner and more open than elsewhere [McLaren, 1986] contrary to the earlier interpretation of the NAUTILUS data by Lyon [1961]. McLaren's analysis provided the impetus for a study of ice motion in the Canada Basin.

The long-term mean ocean gyre accounts for up to half of the mean ice motion in the Canada Basin, away from coastal areas, but about 70 percent of the variance of the daily ice velocity is contributed by the geostrophic winds [Thorndike and Colony, 1982]. Felzenbaum [1958, cited in Campbell, 1965] notes that surface currents in the Arctic Basin vary little over intervals of 10-30 days; but the ice approaches steady-state motion within a few hours after a change of wind stress. The size of the sea ice gyre is determined primarily by gyre velocity and internal ice friction: the area of lower velocities expands as gyral velocities decrease [Campbell, 1965]. The locus of this Beaufort Gyre, centered about 80° N, 155° W [Thorndike, 1986], is influenced by both the air stress field and the internal ice friction. In summer, when the ice is more open, internal friction is at a minimum [Hibler, 1980]. Floe motion in summer 1975 during AIDJEX showed a strong linear correlation with local synoptic winds. There was also high coherence in the cross-spectra of winds at two stations 100 km apart and in the cross-spectra of their drift [Colony and Thorndike, 1980].

Previous studies of ice motion in the Arctic have focused on short-term fluctuations and their causes, or on the long-term mean motion but have not identified any major seasonal changes [Colony and Thorndike, 1984; Thorndike, 1986]. The variance spectra of ice drift data show peaks for periods of 4-10 days [Coachman and Aagaard, 1974; Thorndike, 1986], indicative of the effects of synoptic weather systems, superimposed on longer period effects. Hibler [1980] notes occasional reversals in ice drift direction lasting about a week. Available monthly buoy trajectories for the Beaufort Sea from 1959 through 1981, summarized by Thomas [1983], showed strong southeastward drift in summer 1975, but he considered that season to be "an anomalous one . . ., possibly representing an extreme event." Results from Hibler's [1979, Figure 19] dynamic/thermo-dynamic sea ice model, forced by 8-day averaged geostrophic winds for May 1962-May 1963, show an area of low ice compactness about 80° N, 180° W, suggesting ice divergence. Submarine observations in that region in late July 1962 indicated ice concentrations below 70 percent [Dunbar and Wittmann, 1963]. Hibler states "whether or not this is a regular annual feature of the ice concentration is not known."

Data and Methods

Since 1979, a network of Arctic drifting buoys has been operated through the University of Washington's Polar Science Center [Thorndike and Colony, 1980; and subsequent reports through Colony and Muñoz, 1986]. Data collected by these buoys are routinely incorporated into the National Meteorological Center pressure analyses. The pressure data may be subject to biases of about 1 mb. The locational accuracy is generally within a 300 m radius. Between 7 and 16 buoys were operative most of the time between 1979 and 1985. The pressure analyses published by Thorndike and Colony also incor-

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SEASONAL VARIATIONS OF SEA ICE MOTION IN THE TRANSPOLAR DRIFT STREAM

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Abstract. Drifting buoy data for 1979-85 and meteorological fields for 1960-85 are used to assess sea ice motion in the Transpolar Drift Stream. Although the long-term mean ice drift in this stream is toward the Fram Strait, three years (1979-81) with adequate drifting buoy data coverage show reversed ice motion over 30-day periods in summer. This phenomenon is a response to seasonally changing wind forcing.

Introduction

Away from coastal influences, short-term variations in sea ice motion within the arctic icepack are largely wind-driven [Nansen, 1902; Zubov, 1943; Thorndike and Colony, 1982]. Recent analysis [McLaren et al., 1987; Serreze et al., 1989] of drifting buoy data and improved arctic surface pressure fields [Thorndike and Colony, 1980] for 1979-85 has revealed a frequent tendency for the ice motion in the normally clockwise Beaufort Gyre (Figure 1) to reverse in late summer to early autumn, in response to persistent atmospheric cyclonic activity. In summer, with conditions of low ice compactness, cyclonic ice motion gives rise to ice divergence [Hibler, 1974], which may exceed 0.5% per day for 30 days, with model-estimated reductions in ice concentration of 15-20% [Serreze et al., 1989]. These buoy-estimated concentration changes are supported by interpretations of passive microwave data, confirmed using visible-band imagery [Barry and Maslanik, 1989].

In view of these findings in the Canada Basin, ice motion in the thicker, heavier ice of the adjacent Transpolar Drift Stream (TPDS) has been examined. We demonstrate that seasonal changes in the sea ice circulation are not limited to the Canada Basin, but are also manifested in the TPDS (Figure 1), and can be directly related to atmospheric pressure features.

Data

As part of the United States' contribution to the First GARP Global Experiment (FGGE), University of Washington's Polar Science Center (PSC) has maintained a network of drifting buoys in the Arctic Ocean, with the aims of defining the large-scale sea ice circulation and improving the quality of pressure analyses [Thorndike and Colony, 1980]. Data are currently available for 1979-85. Satellite-determined buoy positions are accurate to within about 200 m. Daily ice velocities at the buoy locations are obtained from smoothed and interpolated Lagrangian time series of position measurements [Thorndike et al., 1983]. These data are subsequently used to obtain daily gridded fields of estimated ice velocity and velocity gradients using optimal interpolation [Gandin, 1965].

The PSC also uses optimal interpolation on a blend of buoy pressure measurements, high-latitude station data and National Meteorological Center (NMC) analyses to obtain daily gridded fields of pressure and pressure derivatives (2° lat by 10° long from 70-90°N). An additional PSC data set comprises the daily 1200 UTC buoy velocities and geostrophic winds optimally interpolated to the changing buoy positions. We use the latter data along with the 1200 UTC gridded pressure fields.

Atmospheric Circulation

Serreze and Barry [1988] recently re-examined the variability of the atmospheric circulation over the Arctic Ocean for 1979-85, using the improved FGGE pressure analyses. Surface pressure analyses prior to the early 1950s were often biased towards anticyclonic conditions as a result of the inadequate observational network [Jones, 1987]. The daily position and central pressure of cyclones and anticyclones, lasting two days or longer and attaining a central pressure of <1012 mb (for cyclones) and ≥1012 mb (for anticyclones), were totaled in equal-area boxes of 196,000 km² and converted into percent frequencies, allowing analysis of the seasonal distribution of pressure features. We use the same data set here, but

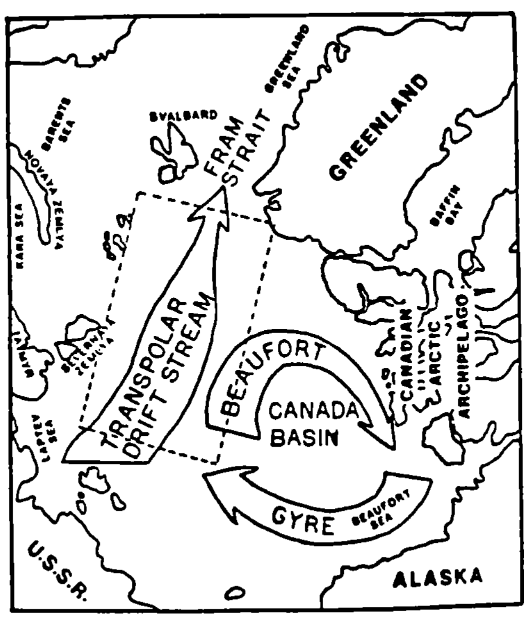

Fig. 1. Location map of the Arctic showing study area (dashed lines) in the Transpolar Drift Stream.

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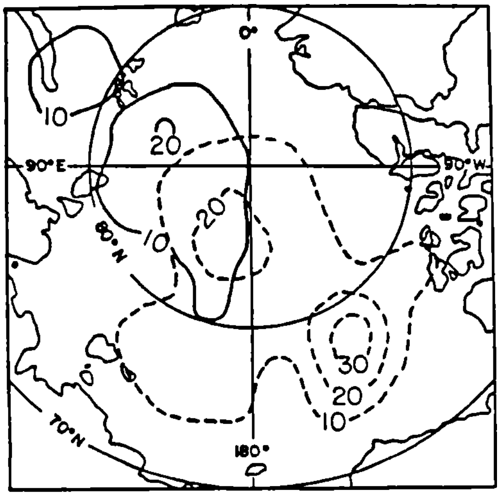

Fig. 2. Distribution of winter (Jan.-Mar.) cyclones (solid) and anticyclones (dashed) within the Arctic Basin, 1979-85, in squares of 196,000 km², expressed as system days.

express the cyclone and anticyclone distributions in terms of system days (Figures 2 and 3).

Winter (Jan.-Mar.) anticyclones are most common in the Canada Basin, with a subsidiary peak centered at approximately 85°N lat and 160°E long. Winter cyclones are common only in the eastern Arctic (Figure 2). Keegan [1958] obtained similar results for Dec.-Feb., 1952-1957. This contrasts sharply with summer (Jul.-Sept.) when the regions of cyclone and anticyclone maxima essentially reverse (Figure 3). Cyclonic activity predominates in the Canada Basin from 80-90°N, as noted by Dzerdzeevskii, [1945] and Reed and Kunkel [1960], the latter study using Jul.-Sept. data for 1952-56. For 1979-85, cyclonic activity generally peaks in Aug. [Serreze and Barry, 1988], but with an interannual variability of about one month. Summer anticyclones are common near the northern tip of Novaya Zemlya, the Laptev Sea, and the Beaufort Sea, about latitude 78°N. Figure 3 also implies frequent alternation of high and low centers in the Beaufort Sea. This alternation occurs on a day-to-day basis as well as between years with contrasting persistent regimes. The transitional seasons, spring (Apr.-Jun.) and autumn (Oct.-Dec.) have cyclone and anticyclone patterns similar to winter, although peak cyclonic activity in spring is shifted to the south, near Svalbard.

These seasonal patterns are generally represented in mean pressure fields. Because of the irregular variability of the circulation, such patterns may be obscured when means are calculated only for calendar months. During Jul.-Sept., 1979-85, means for 30-day periods corresponding to peak cyclonic activity over the Canada Basin characteristically show low pressure over the Canada Basin with a ridge, or in some years, a closed high over Novaya Zemlya that extends eastward towards Taymyr. This pattern was best developed for Jun. 28-Jul. 27, 1979, Jul. 28-Aug. 26, 1981 and Jun. 26-Jul. 25, 1984. For Aug. 13-Sept. 11, 1980, low pressure dominated nearly the entire Arctic Basin with a weak attendant ridge, while for Aug. 26-Sept. 24, 1983, the ridge was positioned further east over the Laptev Sea. This "paired" pattern was weakly developed in 1982 and 1985.

Relationships with Sea Ice Motion

Wind fields reflect these seasonal changes in atmospheric pressure patterns and their interannual differences. For the study region (Figure 1), the maps of cyclone and anticyclone frequency imply that winds are predominantly from the Pole in winter (Figure 2) while in summer (Figure 3), directions are more variable, but winds from the west or south can occur with greater frequency. The ice motion can be expected to reflect these changes.

To examine the importance of the wind-driven drift in the TPDS, we employ a statistical model [Thorndike and Colony, 1982] of the form $U = A\,G + \langle c \rangle + E$, where U, the ice velocity, G, the geostrophic wind, $\langle c \rangle$, a constant (in summer roughly interpreted as the surface geostrophic ocean current, see also Moritz and Colony [1988]), and E, the unexplained residual, are vectors. The complex multiplier $A = |A| (\cos\theta - i\sin\theta)$ consists of a scaling factor $|A|$ and a turning angle θ, measured clockwise positive from G to U. Using least squares regression, $|A|$, θ, $\langle c \rangle$, and the squared correlations between U and G were obtained for all Lagrangian time series during the summers (Jul.-Sept.) 1979-85 in which the mean buoy position was located inside the study region (Figure 1) and there were >30 observations.

The squared correlations indicate that the local geostrophic wind typically accounts for 60% to 80% of the variance of the daily ice velocity, agreeing with Thorndike and Colony's [1982] findings. Average buoy values for $|A| = 0.011$ and $\theta = 17$ denote that the ice generally moves at about 1% of the geostrophic wind and 17° to its right. These values are nearly identical to summertime averages for the Canada Basin [Thorndike and Colony, 1982; Serreze et al., 1989], suggesting similar summer sea ice environments in the two regions.

Ice velocity vectors for 1979-81, estimated from drift trajectories during the 30-day periods of peak atmospheric cyclonic activity identified above, are plotted with the corresponding mean pressure fields in Figures 4-6. Each vector originates at the initial buoy location. These years had good buoy coverage in the study area and exhibited a well-developed mean Canada Basin low. In 1979

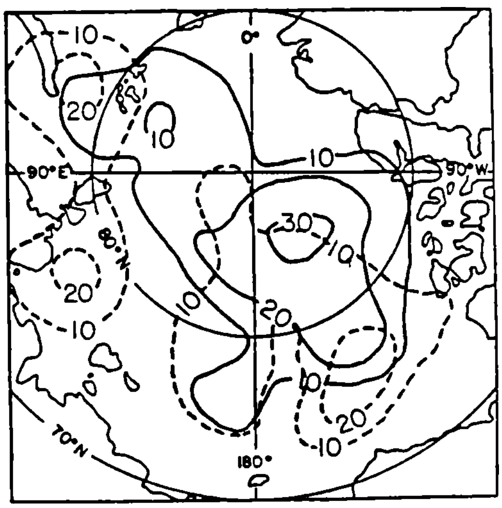

Fig. 3. Same as Figure 2, but for summer (Jul.-Sept.), 1979-85.

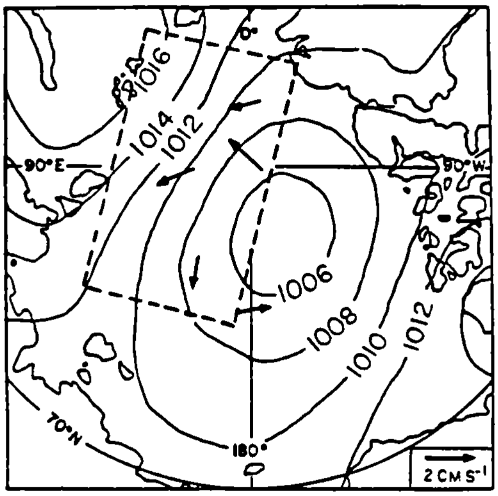

Fig. 4. Mean buoy velocities and pressure field (contours in mb) for Jun. 28 - Jul. 27, 1979.

(Figure 4), three of the five vectors indicate eastward to southeastward ice motion, counter to the long-term mean drift in this region [Colony and Thorndike, 1984]. In 1980 (Figure 5), the mean low dominated almost the entire Arctic Basin, and like 1979, the velocity vectors indicate a drift away from Fram Strait. A relatively large number of buoys were located within the study area in 1981. This season provides the best example of the drift reversal, with all buoys indicating an eastward to southeastward drift (Figure 6), in accordance with the mean pressure distribution. Of the remaining years, the mean pressure field during peak cyclonic activity in 1984 resembled that of Figure 6, however, buoy coverage was poor. In 1982 the cyclonic pattern was weaker and in 1983 it was displaced southward. In 1985, the pressure gradients in the study area were slack and the available buoys show no evidence of a reversal.

Geostrophic currents, estimated from the vectors <c> [Thorndike and Colony, 1982; Moritz and Colony, 1988] for 1979-81 show no clear pattern, but do not follow the ice motion during the time intervals studied, suggesting that the drift phenomenon is limited to a shallow surface layer.

Discussion

The buoy data reports of Thorndike and Colony [1980], subsequently through Colony and Muñoz [1986], reveal many days, in all seasons, when buoy motion in the TPDS is reversed, and Moritz and Colony [1988] show large variances in ice motion between the Fram Strait and North Pole. Zwally and Walsh [1987], using the Hibler [1979] model with observed geostrophic winds, show a near disappearance of the TPDS in our study area for Nov. 26-Dec. 23, 1978, with very little net ice motion. However, large-scale seasonal shifts in sea ice motion in this part of the TPDS have not been previously suggested as a frequent summer phenomenon.

August 1981 provides the strongest case of reversed ice motion in the TPDS observed during 1979-85. Considering both the sensitivity of ice motion to winds in the study region and the distribution of surface pressure in summer, it is likely that with additional buoys, the phenomenon would be more obvious in 1979 and especially 1980 (Figure 5). Mean pressure patterns for Jun. 25-Jul. 25, 1984, are also suggestive of strong eastward ice drift in the TPDS.

Concluding Remarks

Our results suggest that in summer when the atmospheric circulation is persistently cyclonic, reversed ice motion in the TPDS may become pronounced. The primary key is the existence of low pressure in the vicinity of Canada Basin. Reversed ice motion in the TPDS can therefore be expected generally to coincide with reversals of ice motion in the Beaufort Gyre identified by McLaren et al. [1987] and Serreze et al. [1989]. An important next step is to assess the frequency of these reversals. Serreze et al. [1989], through examination of the published Daily Series Synoptic Weather Maps, for 1950-70 suggest that reversals of ice motion in the Beaufort Gyre occurred in the majority of those years. If so, attendant effects in the TPDS of the type examined here should also frequently recur.

More detailed investigations using daily digital NMC surface pressure and upper-air fields for 1950-84 are

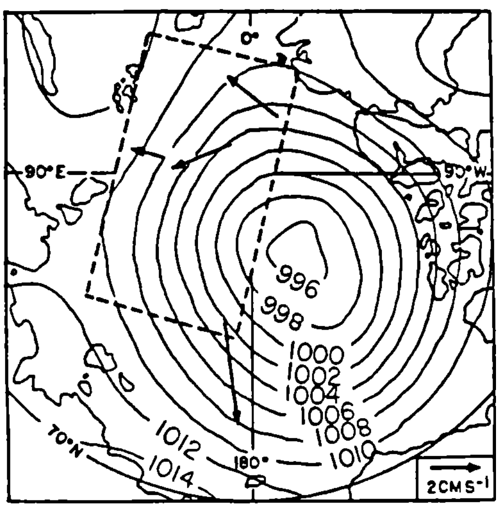

Fig. 5. Same as Figure 4, but for Aug. 13 - Sept. 11, 1980.

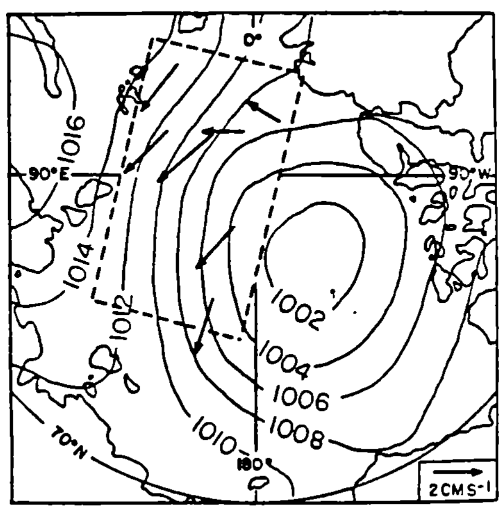

Fig. 6. Same as Figure 4, but for Jul. 28 - Aug. 26, 1981.

currently underway. The possibility that these circulation patterns in the TPDS influence the ice flux through Fram Strait [cf. Englebretson and Walsh, 1989] with effects on the mass balance of the icepack, remains to be investigated.

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THE ARCTIC SUBMARINE : ITS EVOLUTION AND SCIENTIFIC AND COMMERCIAL POTENTIAL

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ABSTRACT

The author presents in this relatively short paper as definitive a history as possible of the evolution of the Arctic submarine. Woven within this history are many of the scientific and commercial insights which accompanied this development. He traces the Arctic submarine's origins from the mid-1600s, and the sporadic, yet gradual, development over three centuries of concepts, events and operational experiences which culminated in the development of the first true Arctic submarine, the nuclear-powered USS *Nautilus*. The author then discusses the many voyages of exploration by nuclear submarines of the U.S.A., Great Britain and Soviet Union which followed.

The paper closes with a presentation of the Arctic submarine's scientific accomplishments and potential, and its commercial potential, and some conclusions the author has drawn from his long study of the subject.

RÉSUMÉ

Le sous-marin arctique : son évolution et ses potentialités scientifiques et commerciales

Les régions polaires se révèlent aujourd'hui d'une importance considérable pour l'ensemble des nations du monde, sur le plan scientifique comme sur le plan commercial. Scientifiquement, en effet, l'Océan arctique détient la clef de nombreux mystères, son influence sur le climat terrestre par exemple; commercialement, ces régions recèlent la majeure partie des ressources mondiales non encore exploitées.

Le sous-marin arctique tel que nous le connaissons aujourd'hui tire son origine d'un vaisseau militaire. Les nombreuses expéditions, couronnées de succès, menées à bord de sous-marins nucléaires américains depuis une trentaine d'années, prouvent leur parfaite adaptation aux conditions arctiques et ce, en toutes saisons. Le temps est venu aujourd'hui d'appliquer cet énorme potentiel à des objectifs scientifiques et commerciaux.

L'auteur retrace ici l'historique du sous-marin arctique, des origines (milieu du XVII^e) au premier vrai sous-marin arctique, l'USS Nautilus *à propulsion nucléaire. Puis il évoque les nombreuses expéditions américaines, britanniques et soviétiques qui suivirent, avant d'énumérer les réalisations et les potentialités scientifiques et commerciales des sous-marins actuels.*

INTRODUCTION

This paper examines the evolution of the Arctic submarine and the ever increasing scientific and commercial potential which have accompanied this evolution over the past 340 years. It is a sporadic history of Arctic submarine ideas, concepts and actual experiences with vessels at sea. It happens to be a history that is largely American, with important additions as a result of the experiences of the Germans, Soviets and the British, particularly during World War II. Finally, it is a history in which five early visionaries in particular stand out : Bishop John Wilkins of England, Jules Verne of France, Professeur Anschutz-Kampfe of Germany; the submarine designer, Simon Lake of the United States — whose influence extended over four decades until well into the 20th century : and Sir Hubert Wilkins of Australia.

This paper will deal with the development of submarines specifically intended for polar expeditions and under-ice operations, and with actual submarine experiences in the Arctic environment whether or not the submarines were originally intended for such. Like so many other areas of technology and exploration, the progress of the Arctic submarine has been far from systematic. The lessons and experiences from one generation have not always been passed on, or learned from by the next. The developments have in the main been discontinous, and those by one nation or state were often not appreciated or incorporated into the thinking and designs of others, even those whose national interests lay in the polar regions.

While this paper cannot remedy these oversights and historical discontinuities, it does systematically present what information is available. The author's observations on various developments and experiences are sometimes over and above the observations and conclusions that were drawn at a particular time in history. The author will not, in this paper, address many recent developments in

Pôle Nord 1983
Éditions du CNRS, Paris, 1987

submarine technology, which nevertheless are highly applicable to improved capabilities in the Arctic and contiguous marginal sea ice areas.

Finally, it will be observed that throughout the history of Arctic submarine development, technological capability often did not keep pace with vision. It is interesting to observe that today the opposite is very much the case : vision had not kept pace with technological capability. This is particularly true in regard to the development of a submarine for commercial purposes in the Arctic.

EARLY CONCEPTS

Bishop John Wilkins

The basic concept of an Arctic submarine, as well as the recognition of its potential for scientific and commercial advantage is at least 335 years old. It appears to have originated with a founder of the Royal Society of London, Bishop John Wilkins. In 1648, he published *Mathematical Magic or, The Wonders That May Be Performed By Mechanical Geometry.* Chapter V of the second book of this work addresses « *the possibility of framing an ark for submarine navigations* ».

Wilkins had obviously been profoundly influenced by Dr. Cornelius van Dreble's successful experiments with underwater boats in the Thames River over two decades earlier, about 1623 (Burgess, 1975). He opens the chapter by stating « *that such a contrivance is feasible and may be effected, is beyond all question, because it hath been already experimented here in England by Cornelius Dreble* » (Wilkins, 1648). Bishop Wilkins stated that the main problem was « *how to make it serviceable for remote voyages, the carrying of a considerable number of men, with provisions and commodities...* ». He then proceeded to outline some major difficulties which had to be overcome, and offered some solutions. His discussion included : the achievement of a method of « *letting out or receiving in of anything as there shall be occasion without threatening the vessel's watertight integrity;* » and, in some depth, special problems relating to submerged navigation and atmosphere control. Finally, he discussed the potential scientific and commercial advantages of a « *submerged ark* ». Among those relevant to this paper, are :

> « *A man may... go to any coast of the world invisibly... Tis safe; from the certainty of tides, and the violence of tempests, which do never move the sea above five or six paces deep... and from ice and great frosts, which do so much endanger the passages toward the Poles. It may be of unspeakable benefit for submarine experiments and discoveries such as determination of the sources and directions of deep ocean currents and springs, and the nature and kind of fishes* ».

In a commercial sense, Wilkins discussed various uses of a submarine for the catching of fish and for the discovery and exploitation of such underwater treasures as « *racks, pearls, coral mines with innumerable other things of value* ».

Wilkins concluded by discussing the use of attached « *cabinets for observation* » which would be capable of being raised to the surface or lowered to the bottom remote from the submarine, and he also foresaw the results of all the underwater observations being both written up and even printed within the submarine (Wilkins, 1648).

PRE-WORLD WAR I
VERNE, ANSCHUTZ-KAMPFE, AND LAKE

More than two centuries elapsed before serious attention was again turned to the notion of an Arctic submarine. During this period some 130 to 140 submarines designs were known to have been considered, and as many as 50 of these built (Lipscomb, 1970). Interest intensified in the mid-1800s. Jules Verne's *Twenty Thousand Leagues Under the Sea*, published in 1869, seems to have been a major stimulus for this interest. Also contributing, was the fact that year-after-year Arctic explorers were finding it virtually impossible to find a way past a massive barrier of ice between them and the North Pole (Reclus, 1873). Many early submarine pioneers were inspired to envision their inventions in Arctic waters, among them being a Belgian engineer, Palmaerts. He wished to « *plunge into the three dimensions of the ocean and reach the Pole by submarine* » in 1880 (quoted in Wallace, 1981). An Italian engineer, Peche, suggested that submarines might be used for Arctic research (Gorlatov and Gakkel, 1965). And, an American, Simon Lake, made public his ideas for the utilization of a submarine for Arctic exploration in the *New York Journal* in early 1898.

Lake immediately followed this announcement with the preparation of designs for a submarine capable of navigation, exploration and scientific study in ice-covered waters (Lake, 1918). Certain features of Lake's basic design were apparently prompted by the need to overcome many of the problems which had been encountered by the famous Norwegian explorer, Fridtjof Nansen. These had been brought to Lake's attention by Alfred Riedel, one of Nansen's closest associates. Simon Lake's subsequent design for an under-ice submarine which he presented before the faculty of John Hopkins University in 1889, possessed the following major characteristics :

(1) A large storage battery which would enable the submarine to travel submerged some 150 miles between charges.
(2) The capability to break through thin ice or to bore through thick ice in order to obtain access to air for running the engines in order to recharge the batteries.
(3) A telescopic conning tower capable of cutting its way through up to 14 feet of ice enroute to the surface in order to permit crew access to the surface while the submarine remained submerged beneath the ice.
(4) The ability to use small mines to blow holes through the ice of sufficient size for the submarine to surface within them.
(5) The use of guide wheels or « runners » on top of the hull, which would enable the submarine to slide or wheel along the underside of the ice pack (Lake, 1918).

Lake applied for and received U.S. Patent 638 342 for these designs (Lake, 1931). In 1902, he constructed the *Protector* (Fig. 1) which he especially fitted out for under-ice operations (i.e., with an inverted toboggan built over its conning tower). During the winter of 1903, it successfully navigated under an 8-inch thick ice field in Narragansett Bay (Lake, 1918), and became, on January 20, 1904, the first submarine in history to surface through ice.

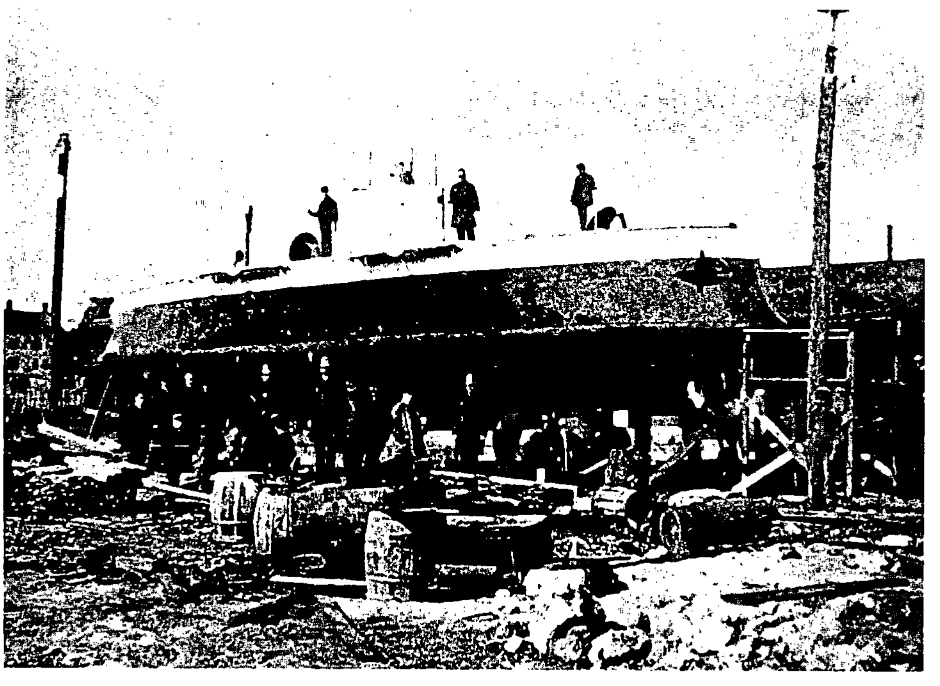

FIG. 1.— The *Protector* (After Lake, 1918).

At roughly the same time, D.I. Mendeleyev suggested a project to the Russian government for a submarine especially designed for navigation in the polar regions (Gorlatov and Gakkel, 1965). In 1901, both the *Geographical Journal* and the *Scottish Geographical Magazine* published the plans of a veteran of several Arctic expeditions (Dunkel, 1931), Professor Anschutz-Kampfe, for reaching the North Pole by submarine. He had previously presented these plans to the Vienna Geographical Society, and an 800 to 900 ton submarine of a design similar to the 1897 French « Narval » Class was supposedly being built for the expedition at Wilhelmshaven (Mäybaum, 1903). Anschutz-Kampfe's basic idea had, in turn, probably originated with the Swedish submarine designer, Theodore Nordenfeldt, 15 years earlier (*Illustrated Naval and Military Magazine*, 1886). Anschutz-Kampfe's submarine was to be capable of traveling 15 hours at 5 knots fully submerged, with a capability to break through thin ice to the surface with the aid of a special bottom propeller designed to assist with vertical ascents. Other features of the submarine included an automatic depth control system, a quite modern system of atmosphere control and even an ambient light meter for the estimation of ice thickness overhead (Mäybaum, 1903). Nothing further came of the project due to lack of support in his own country. Nevertheless, Anschutz-Kampfe's expedition plans — which called for a departure from Spitzbergen during the summer, and « polynya hopping »* the 600 nautical miles to the North Pole — and estimation of the under-ice environment which might be encountered in the Arctic was surprisingly accurate, even by today's standards. His plans to overcome the difficulties posed were similarly sophisticated. It is interesting to note that Professor Anschutz-Kampfe later developed the gyro compass. He calculated that it could be used to overcome many of the major course determination difficulties of Arctic navigation (compasses, particularly magnetic ones, lose their directive accuracy as higher latitudes are approached). Later voyages confirmed his prediction.

Meanwhile, Simon Lake was busy interesting the Russian Admiralty in the idea of under-ice navigation. He suggested to them that it would be easier and safer to send « *large submarines across the Arctic and off the north coast of Russia and Siberia* » than by conventional routes to the Pacific (Lake, 1931). In 1905-06, Lake submitted his plans for a submarine especially suited for under-ice navigation to the Admiralty. The Russian Navy subsequently not only purchased the *Protector*, but also six more Lake-designed submarines of a later class. Several of theses, such as the *Kefal* and *Kaiman* (Fig. 2) were successfully operated in ice-covered waters off Vladivostok and the Gulf of Finland in the years immediately preceding World War I (Lake, 1918). It is interesting to note that Lake was also asked by the Chief Engineer of one of the Canadian railways to submit plans for an under-ice cargo-carrying submarine capable of not only transporting mail and freight, but passengers as well, between Vancouver and an open harbor on the Island of Victoria (Lake, 1918).

Lake's writings during this period indicate that he strongly believed that cargo-carrying submarines fitted to under run ice fields would shorten trade routes by opening up to navigation not only the Northwest Passage, but also new ports in northern Europe and Asia. He suggested that such submarines could also provide an outlet for Siberian grown wheat and other northern products which were not being utilized because of lack of transportation (Lake, 1918, 1931). Lake also suggested that submarines only were capable of economically obtaining soundings at

* Polynyas are areas of open water which occur with some regularity in Arctic pack ice.

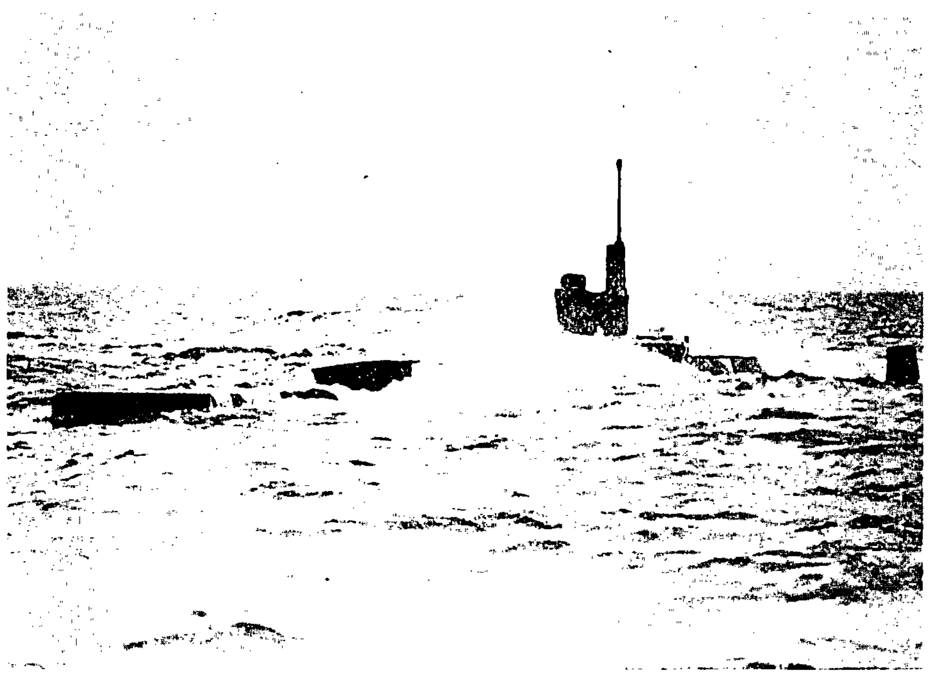

FIG. 2.— *Kaiman* in the Gulf of Finland (After Lake, 1918).

sufficient frequent intervals to adequately correct hydrographic charts then in use in navigation. As well, Lake's writings during this period made frequent reference to the value of submarines for « *investigation of the geological formations of sea bottoms, the sea's flora and fauna, and the location and salvage of valuable wrecks* ». Finally, he devoted considerable attention to the various use of underwater photography, and the value of artificial lights therein (Lake, 1918).

WORLD WAR I

Although very little information is available on the subject, the Germans were believed to have operated a few submarines in the ice of the northern Barents Sea off Spitzbergen during World War I (Mathiesen, 1954). Certainly submarines of the British (particularly the E class) and of the German and Russian navies gained experience in operating in ice-covered waters in the Baltic Sea during this war (Gray, 1971; Lake, 1918).

In the United States, Simon Lake submitted, in 1917, plans and models for two types of cargo carrying submarines to the U.S. Shipping Board (Fig. 3). These were for 11 000 and 13 000 tons (larger than the present Fleet Ballistic Missile Submarines), and designed to be capable of navigating across the Arctic from the Atlantic to the Pacific. His proposal to build a fleet of theses submarines was seriously considered by two successive heads of the Board, but construction was never initiated (Lake, 1931).

In Canada, the wartime Prime Minister, Sir Robert Borden, considered the use of submarines to aid and open commerce in northern areas such as Hudson Bay (Stefansson, 1931).

POST WORLD WAR I - WILKINS

In the years which followed World War I, interest in and support for Arctic submarine operations declined. Nevertheless, Admiral Peary did make brief mention of the possibility during a speech before the National Geographic Society in 1919 (Peary, 1919). It was Vilhjalmur Stefansson who kept the idea alive in his discussions of the advantages of submarine trans-Arctic commerce, carried on in various international editions of his *Northwest Course of Empire*. But it was not until 1928, when Sir Hubert Wilkins returned from his successful flight across the Arctic, that serious attention was again given to the « Arctic submarine ».

Inspired by discussions held with Stefansson during a 1913-1916 Arctic expedition, and apparently following a program outlined by the Royal Meteorological Society in 1919 (Wilkins, 1934), Wilkins was now convinced it was the time to attempt to reach the North Pole and to explore the depths of the polar sea by submarine (Miller, 1930). In 1930 he announced his plan to methodically and leisurely use a submarine for polar exploration (Stefansson, 1931) and began extensive preparations for what was to subsequently become the world's first submarine expedition to the Arctic Ocean. This voyage was not only for exploration, but also for scientific and commercial purposes. Amazingly, it remains to date the only Arctic submarine expedition conducted with commercial intent.

Two of the main objectives of Wilkin's expedition are of particular interest in this regard :

To demonstrate dramatically the fact that submersible vessels may be used for opening up and development of the Hudson Bay district and other northern areas.

To demonstrate that submersible vessels may be used to transport at cheaper rates North American products —

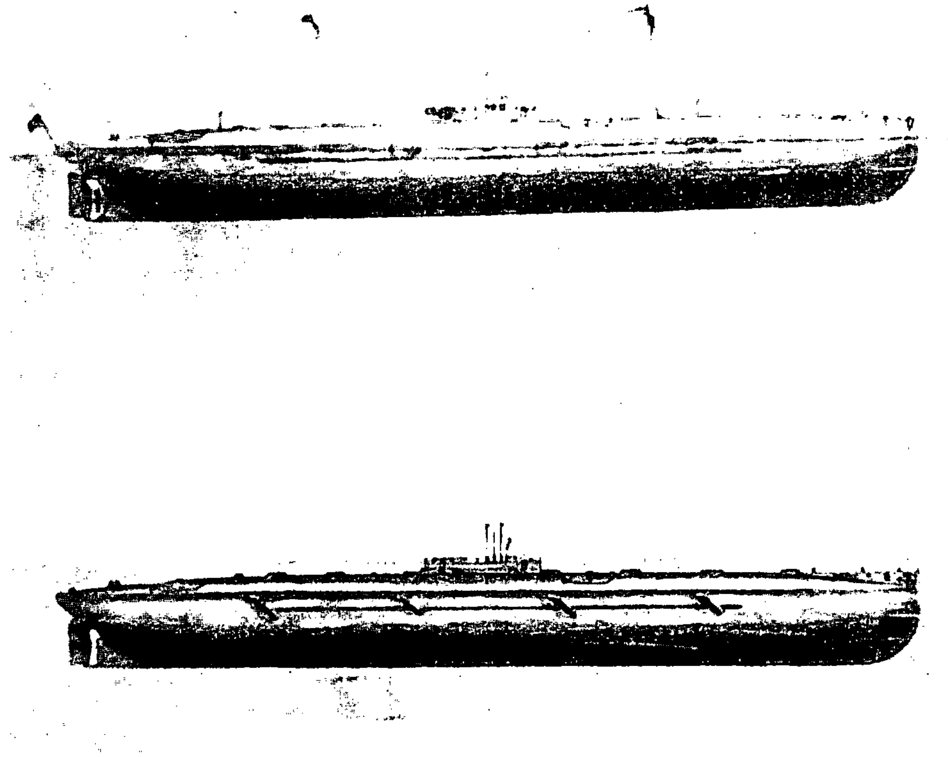

FIG. 3.— Lake's Cargo Carrying Submarine Design (After Lake, 1918).

through the Hudson Bay route or across the Arctic — to Europe, and so benefit primary producers and industrialists (Wilkins, 1931).

Lake was particularly interested in seeing such a voyage made, as he believed that the trip would jolt the public into realizing that the submarine's place in the scientific and commercial fields would be as important as in the military field (Lake, 1931). He foresaw that it would « *open up to civilization a vast Arctic territory which only needs proper transportation facilities to make it one of the most productive of the Earth's surface* ». He predicted that « *if it were successful, in a few years thereafter, regular cargo-carrying submarines of large size would be taking the shorter Arctic route during five of six months of the year* » (Lake, 1931).

Thanks to the courtesy of the U.S. Navy Department and the U.S. Shipping Board, the submarine 0-12 was placed at his disposal and the constructor of the vessel (1918), Simon Lake, undertook to rebuild it and make it suitable for travelling underneath the Arctic pack ice (Sverdrup, 1933 ?). His plans included number of controversial modifications for the 0-12 : a « sled runner » that permitted the submarine to glide along the underside of the ice, and « ice drill » to cut through 13 feet of ice, and (more successfully) an airtight chamber with a bottom hatch through which scientific instruments and collectors could be raised and lowered. Joining Wilkins in his venture to cross the Arctic Ocean from Atlantic to Pacific via the North Pole were Sloan Danenhower as prospective commanding officer, a former U.S. submarine officer; and Professor Harald Sverdrup as chief of the scientific staff (Wilkins, 1931).

Upon completion of the rebuilding, in the spring of 1931, the 0-12 was christened the *Nautilus* (Fig. 4). *Nautilus* was 175 feet long, displaced 550 tons submerged, and was estimated to have the capacity to cruise 125 nautical miles, completely submerged for up to three days. Wilkin's basic plan called for cruising submerged for 16 out of every 24 hours, and then breaking or boring through ice to recharge batteries, and for navigation and scientific observations (Danenhower, 1931; Sverdrup, 1933 ?).

Wilkin's expedition scientific plan, as prepared by Sverdrup, placed its main emphasis on meteorological and physical oceanography observations, as they were convinced the greatest impact of the polar regions on the peoples of the world was its effect on climate (Miller, 1930). Their scientific equipment included a diving chamber with hydrographic winch in the foremost compartment of the submarine. It was from here that deep sea oceanographic observations were to be taken (Sverdrup, 1931). Sverdrup, in particular, felt that determination of the bottom topography of the polar basin — through the use of their new sonic depth sounder — would be indispensable to the study of world ocean currents. He also felt that the data would be essential for understanding changes and the solution of many problems of (world) economic importance (Sverdrup, 1931).

Although Wilkin's expedition was well planned, it did not meet its goals. It did, however, prove that an extensive scientific program could be carried out under the conditions on board a submarine (Sverdrup, 1933 ?). Certainly Sverdrup made a considerable amount of observations concerning the physical oceanography of the region north of Spitzbergen. Unfortunately, the submarine was old and

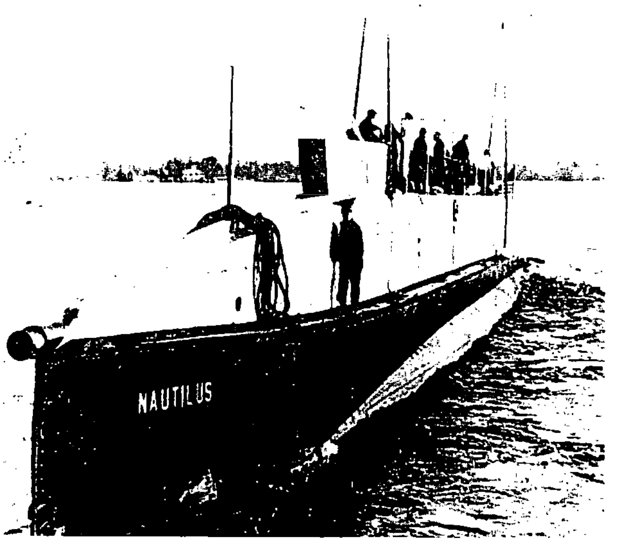

FIG. 4.— *Nautilus* (US Navy).

inadequate. A series of severe material failures in combination with probable sabotage and damage which occured in a dive under ice, added to a quite late start for the ice pack (i.e., 18 August) meant that Wilkins had to turn back after only three weeks (*New York Times*, September 6, 8, 20, and 25, 1931).

Nonetheless, public interest in Arctic submarines was aroused; and at least for a while future support was promised. Wilkins, in fact, submitted to contractors in 1934 plans for a brand new submarine, especially built for operating in polar regions. He hoped such a submarine could be built during the following year (Wilkins, 1934). In conclusion, it can be said that the concepts, techniques, and data which were developed and collected as a result of this pioneer expedition did much to ensure that submarines would one day be capable of operating in collecting valuable scientific data throughout the polar basin (Lyon, 1963).

Interest in the use of submarines for under ice navigation and scientific work continued in the Soviet Union during the remainder of the 1930s. Plans were considered for their use during a polar expedition in 1934, and for the rescue of the crew of the ice crushed steamship *Chelyushkin* in the Chukchi Sea. And in February 1938, three Soviet submarines, D-3, Shch-403, and Shch-404 took part in an expedition to remove personnel from Ivan Papanin's « North Pole » drifting ice floe « scientific expedition ». This particular voyage is considered by some Soviet authorities to have provided the impetus for ultimately working out the necessity plans for a Soviet submarine specially designed for underice navigation (Gorlatov and Gakkel, 1965).

DEVELOPMENTS DURING WORLD WAR II

Military needs and combat experiences during World War II stimulated the next significant advances in the steadily evolving technologies of the Arctic submarine.

According to several authorities, the Soviet submarines Shch-311 and Shch-324 operated under considerable stretches of ice within the Gulf of Bothnia during late January 1940, with the Shch-324 traveling some 31.2 nautical miles (nm) under and then surfacing through ice on 19 January 1940 (Gorlatov and Gakkel, 1965). According to the same authorities, V.U. Vize, in May 1941, suggested the use of submarines to transport cargo between Murmansk and the Soviet Far East during the winter months.

There is no doubt that significant numbers of Soviet submarines of the D, K, L, M-IV, S, and Shch classes, such as the D-5, K-21, K-51, L-3, and Shchs-311, 320, 323 and 402 conducted extensive intelligence collection and combat operations. They did so under severe conditions within, under, or in close proximity to ice in the following geographical areas : the northwestern Black Sea, the Baltic Sea, the Gulfs of Bothnia and Finland, fjords along the northern Norwegian coast, the northern and eastern Barents Sea and the entrance to the White Sea (Gorlatov and Gakkel, 1965; Achkasov and Pavlovich, 1981). U-boats such as U-255, U-354, U-601, U-711, U-739, U-960 and U-957 rounded northern Novaya Zemlya and transited the Kara and Vilkitski Straits enroute to and from some very successful operations (U.S. Office of Naval Intelligence, 1951; Showell, 1973; Doenitz, 1959; Achkasov and Pavlovich, 1981). They also placed automatic weather equipment in Northwest Spitzbergen, Northeast Greenland and Franz Josef Land, and supported manned shore stations in these places.

They operated in the Denmark Strait during the winter months and even conducted, from beneath the pack ice off northeast Greenland, an unsuccessful attack on a U.S. Coast Guard cutter (U.S. Hydrographic Office, 1950). The collective conclusions of some of the most experienced German captains, such as Lieutenant Lange of U-711, are most interesting :

> *A submarine is never helpless in the ice... because it can submerge, proceed under the ice, select an open area in the ice with the aid of its high-angle periscope, come to the surface, recharge the battery... and submerge again. It can dive and pass under all ice obstacles with the expection of the ice masses lying in shallow water* (quoted in U.S. Office of Naval Intelligence, 1951).

Other observations, and needs cited by the German submariners, such as for under-ice acoustic detection equipment and special hull strengthening, resulted in the development of the basic requirements for a special Arctic submarine able to conduct « *non-combat operations in the Arctic regions* » (U.S. Office of Naval Intelligence, 1951). Interestingly, most of the requirements have now been fully incorporated into modern nuclear submarines.

Finally, it should be mentioned that the Japanese operated midget submarines out of Kiska Island in the Aleutians (Morgan, 1983).

In closing this section, it is interesting to note that World War II saw the first major building and use of submarines for cargo carrying purposes. Starting with the basic design of the famous World War I cargo carrying submarine *Deutschland*, the Axis powers designed and built several different classes of submarine tankers, transports, and submarine towed cargo carriers during this period.

The best known of these were the long-range Type IXC and Ds used to transport petroleum and strategic materials from Japan and the famous 1900 Ton Type XIV *Milch Cow* submarine tanker which was capable of reprovisioning and refueling up to five U-boats at sea. Less well known are the well-worked out designs of the Type XX and the long-range, high speed Type XXID, XXIE, and XXIT classes of which only the prototype Type XXI got to sea before the end of World War II (Rossler, 1981). None of these submarine cargo carrying submarines, however, were apparently designed for or intended for operations in ice-covered waters. Nonetheless, they, too, would have an influence on post-World War II underice cargo submarine concept designs and proposals. Thus, the military needs of World War II contributed greatly to the advance of submarine technology in general; and to experience, and knowledge in regard to both Arctic and cargo submarines in particular.

POST WORLD WAR II : THE DEVELOPMENT OF A « TRUE » ARCTIC SUBMARINE

The years immediately following World War II saw increased interest in the Arctic regions. They also saw the initiation of several important projects by the United States Navy, which were to have profound implications for the eventual development of a « true » Arctic submarine.

Operations with Conventional Submarines

From 1946 to 1953, under the direction of Dr. Waldo Lyon, Head of the Submarine Arctic Research Laboratory, the U.S. Navy conducted a series of operation in the Arctic, using conventionally powered submarines built during World War II. These operations were for scientific research and to develop under-ice operating techniques and equipment. The USS *Atule* (SS-403) operated the first upward-beamed fathometer — to determine ice thickness above the submarine — in 1946 between Baffin Island and Greenland (U.S. Naval Undersea Center, 1974); and during the Antarctic summer of 1946-47, the USS *Sennett* (SS-408) developed techniques for acoustically tracking pieces of floating ice (*Sennett*, 1947). This cruise was particularly significant in that it resulted in the first delineation of what should constitute a basic under-ice acoustic navigation and piloting system for U.S. submarines (*Sennett*, 1947).

The USS *Boarfish* (SS-327) made the first excursion of some 12 miles under pack ice in August 1947, in the Chukchi Sea; and obtained excellent profiles of the underside of the ice canopy overhead with her upward beamed fathometer (*Boarfish*, 1947). In September 1948, the USS *Carp* (SS-338) made a 54 mile penetration inside the Chukchi ice pack. During this time she developed techniques for making vertical ascents into the leads and polynyas of open water which dotted the pack ice; and for resubmerging beneath the ice (*Carp*, 1948; Lyon, 1959). In the summers of 1952 and 1953, the USS *Redfish* (SS-395) (Fig. 5) further perfected these operational techniques and additionally conducted extensive oceanographic projects in the Beaufort Sea, as far as to Banks Island on one voyage.

These voyages completed the series of experiments with conventional submarines and resulted in the first formal proposal for development of a U.S. polar submarine (*Redfish*, 1953).

In 1955, Captain Robert McWethy, the Technical Assistant to the Chief of Naval Operations, formally recommended that « *a submarine be assigned for experimental under-ice operations, particularly as related to future modifications of submarines for ice operations* » (U.S. Naval Undersea Center, 1974).

Early Nuclear Submarines

During this same period, 1946-1953, a U.S. Navy group at Oak Ridge, Tennessee, headed by Captain (now

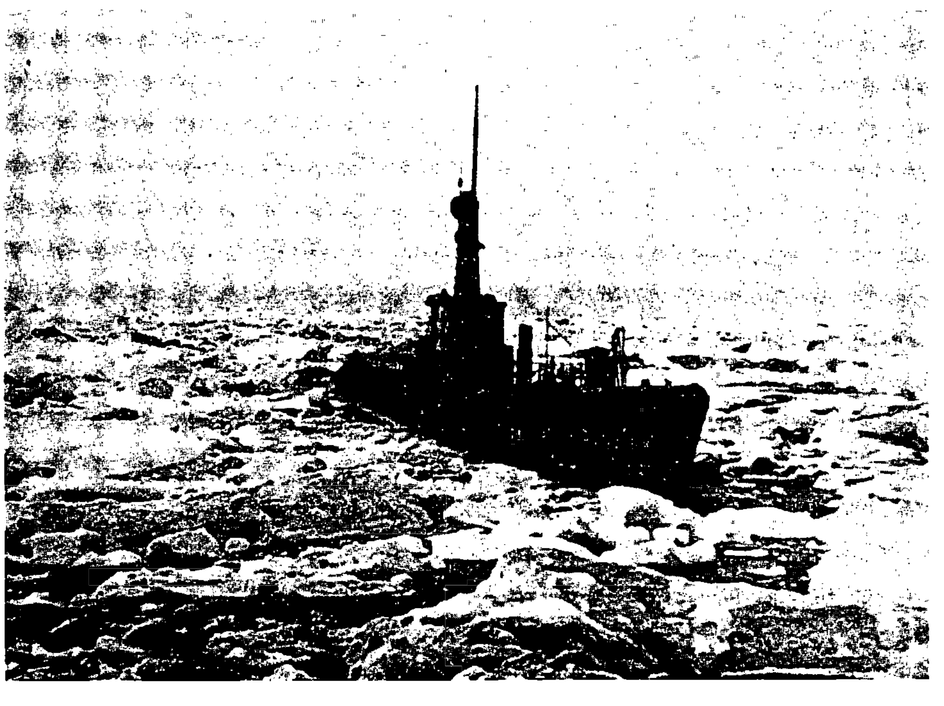

FIG. 5.— *Redfish* in the Beaufort Sea (US Navy).

Admiral) H.G. Rickover made the decision to create the world's nuclear power plant for submarines. Their goal was to achieve a « true submarine », one that would be capable of cruising anywhere within the world's ocean depths for months at a time. A special « Naval Reactors » organization with authority in both the Atomic Energy Commission and the U.S. Navy was established in 1947. Under its auspices a prototype submarine reactor plant, STR Mark I, was produced in 1953. It was capable of a simulated, non-stop, full-power crossing of the Atlantic Ocean (Kintner, 1959). An operational version, STR Mark II, was subsequently installed in a specially-built submarine and on January 17, 1955, the world's first nuclear submarine, USS *Nautilus*, was underway (Anderson, 1959).

In the late summer of 1957, *Nautilus* accompanied by the conventionally powered submarine *Trigger*, and outfitted with the under-ice acoustic equipment of the *Redfish* departed Spitzbergen for the first of three deep penetrations beneath the Arctic ice. This first voyage took her to 87° North and within 180 miles of the North Pole. There, a power failure to both gyro compasses forced *Nautilus* to turn back. Dr. Lyon, the embarked senior scientist, was able to assist *Nautilus* in determining her navigational positions on the way out by correlating bathymetric and temperature profile observations with those obtained by Sverdrup in 1931 (Lyon, 1963).

Nautilus other two voyages were conducted with the aid of an inertial navigation system, a high resolution mine detection sonar for under-ice work and a sail strengthened for breaking through ice. Although in June, 1958, lack of an effective ahead-looking under-ice piloting sonar caused her to turn back on her first attempt at a transpolar crossing, *Nautilus* succeeded a month later in passing beneath the ice pack north of Alaska and entering the Arctic Basin. This voyage culminated in the first crossing of the Arctic Basin via the North Pole. It was accomplished in just 96 hours, and *Nautilus* on 3 August 1958, became the first ship in history to reach the North Pole (Anderson, 1959).

Nautilus thus became the first « true » Arctic submarine and ushered in a new era of submarine under-ice voyages for exploratory and research purposes. In the words of Dr. Waldo Lyon, the senior scientist on this and all future cruises, « *The trans-Arctic submarine, which five years ago was often called fantastic, is now a demonstrable fact, and consequently the Arctic Ocean becomes an operating area for the submarine* » (quoted in McWethy, 1958).

Of the voyages which immediately followed, those by the USS *Skate* (SSN-578) in 1958 and 1959 were particularly important. Carrying navigational equipment which enabled her to maneuver at will in high latitudes while still maintaining an accurate position, *Skate* not only achieved the North Pole nine days after *Nautilus*, she also became the first ship to attain the « *Pole of Inaccessibility* » (Calvert, 1960). Moreover, *Skate* conducted the first winter operation in the Arctic, and on Saint Patrick's Day, 1959, became the first ship in history to surface — through 12 inches of ice — at the North Pole (Calvert, 1960).

In early 1960, the USS *Sargo* (SSN-583) departed on what most experienced submariners consider the most difficult under-ice expedition ever conducted. *Sargo* entered the Arctic Basin by successfully traveling 1,450 km across the shallow ice covered Bering-Chukchi Sea shelf. *Sargo* conclusively proved the nuclear submarine's capability to safely navigate between deep ice keels, in some cases extending nearly to the bottom, through the use of a newly developed under-ice piloting sonar (Lyon, 1963). *Sargo* spent a total of 31 days in the Arctic during February and March, 1960; and surfaced some 16 times through thick ice in total darkness (Nicholson, 1965). *Sargo* thus demonstrated an outstanding ability to conduct shallow water operations under the worst of ice conditions (Nicholson, 1965). *Sargo* also conducted the first submerged transit survey of the M'Clure Strait, the Beaufort Sea entrance to the Northwest Passage (McLaren, 1982b), therein truly demonstrating the capabilities of the nuclear submarine for polar exploration.

During the summer of 1960, a fourth nuclear submarine, the USS *Seadragon* (SSN-584), became, in Baffin Bay, the first submarine to ever closely examine and pass beneath icebergs, many of quite deep draft and exceeding several million tons.

Seadragon was also the first submarine to traverse the classic Northwest Passage, from Baffin Bay to the Beaufort Sea, via the Parry Channel. Of particular commercial significance is that *Seadragon*'s under-ice navigation and piloting capabilities enabled her to locate and survey a safe all-season deep water passage through the ice clogged Barrow Strait (Steele, 1962).

This era came to a dramatic conclusion during the summer of 1962 when *Skate*, coming from the Atlantic by way of the Nares Strait and the Lincoln Sea (the first submarine transit and survey of these waters), rendezvoused with *Seadragon*, which had come from the Pacific, at the North Pole (Lyon, 1963). On her return, *Skate* made the first west-to-east transit of the Northwest Passage, by way of the Parry Channel (Boyle, 1969).

During the period from 1957 to 1962, United States' nuclear submarines had traveled over 50,000 km under the Arctic ice (Sater, 1969). By 1963, as Dr. Waldo Lyon (1963) stated : « *The Arctic Ocean has become the private sea of the submariner who is free to move in any direction and at any speed under the ice covering the sea* ».

The *Sturgeon* Class of Nuclear Submarines

In 1963, construction began on a new « Sturgeon » Class of nuclear attack submarine. Thirty-seven were built, all capable of year-round Arctic operations. Their special features are summarized in McLaren (1981) :

> *The top of the sail and the rudder is strengthened (with HY 80 steel), the masts have special protective ice caps, and the sail planes can be rotated to a vertical position for surfacing through ice. The « Sturgeon » Class also possesses a recessed secondary propulsion motor that can be lowered and used for precise maneuvering. (See Fig. 6). The general characteristics of the under-ice piloting sonar can be seen in Fig. 7. In a typical surfacing evolution, a polynya of the requisite length is located, course is reversed, depth is decreased, and the submarine is maneuvered into a hovering position beneath its center. The secondary propulsion motor is used to make last-minute adjustments to ensure avoidance of large blocks of ice overhead. Once the topsounders (Fig. 6) indicate « all clear », or indicate ice sufficiently thin overhead, a vertical ascent is commenced into the polynya.*

The first of these all-year Arctic submarines to test its capabilities was the USS *Queenfish* (SSN-651) (Fig. 8). She departed for the Davis Strait and Baffin Bay in January 1967 and spent a week in ice-covered, iceberg-infested

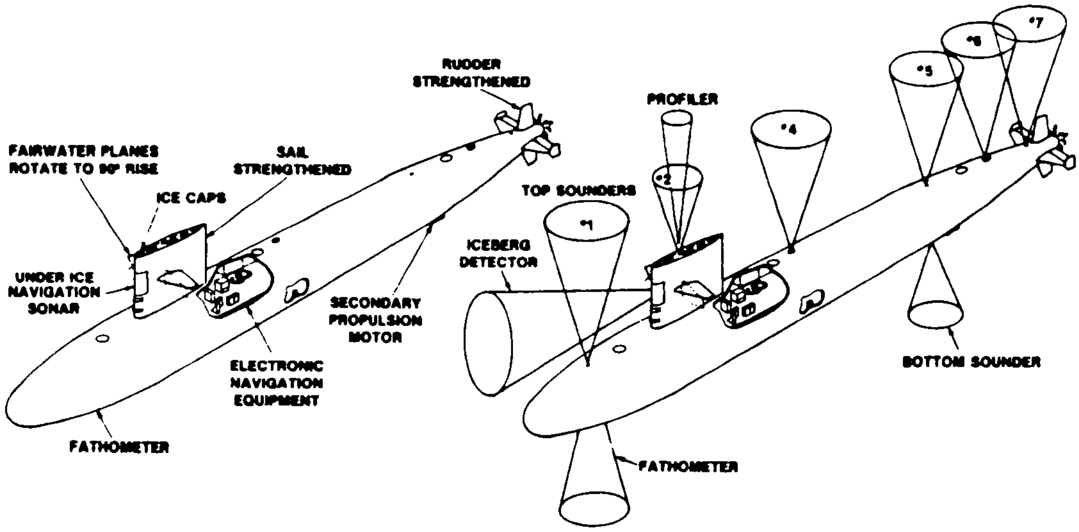

FIG. 6.— « Sturgeon » Class Special Under-Ice Operating Features (After McLaren, 1981).

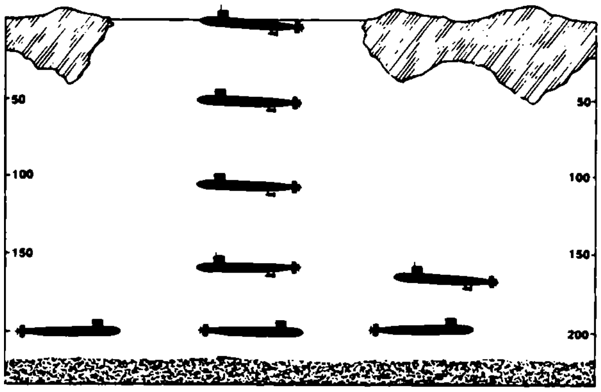

FIG. 7.— Diving and Surfacing in the Arctic (After McLaren, 1981).

waters. The shakedown cruise concluded with a successful surfacing through ice (McLaren, 1983a).

The voyages that followed were all made by submarines with virtually identical operational characteristics and capabilities for scientific research. The principal polar cruises of US and British submarines during the period 1967-83 are presented in Table 1. Before discussing some of their scientific attainments and potential for the future, however, brief mention should be made of what is known concerning Arctic operations by Soviet submarines during the same period.

Soviet Submarine Under-Ice Operations

Very little published information, much less in a translated form, is available concerning the operations of Soviet submarines in the Arctic during this period.

In the mid-1950s, a Soviet Professor of Science, G.F. Pokrovssy, discussed in the journal *Knowledge is Strength* the advantages of carrying goods and passengers across the Arctic aboard large nuclear submarines (Bartl, 1967). It is also known that three conventionally powered submarines of the post-war « Zulu IV » Class were converted for oceanographic research, and that two « Zulu Vs » were disarmed and used for fishing research (Moore, 1976). It can be assumed with certainty that all of these were subsequently operated within ice-covered waters. One Soviet authority, in particular, reported that valuable data had been collected by the Soviet experimental submarine, *Northerner* (probably one of the « Zulu IVs ») during eight voyages between 1959 and 1964 into the North Atlantic, Norwegian and Barents Seas (Bartl, 1967).

It is particularly interesting to note that the Soviet Minister of Defense, Marshal Malinowsky, declared as early as 1961, that,

« ... *we consider our nuclear submarines have mastered under-ice navigation in the Arctic...* » (quoted in Bartl, 1967).

The only Soviet under-ice expedition to be widely published to date was the voyage of *Lenin Komsomol* to the North Pole, where it surfaced in the summer of 1962. The *Lenin Komsomol* was a « November » Class nuclear attack submarine (Gorlatov and Gakkel, 1965; Bartl, 1967). It is interesting to note that the Soviet journal *Izvestia* in announcing this voyage on 27 January 1963, stated that, « *The honour of being the first voyagers under the severe ice of the Arctic Basin belongs to Soviet sailors, and that Soviet nuclear submarines sailed in the high latitudes of the Arctic Basin long before American ones* » (quoted in Bartl, 1967). It would be interesting to examine the facts which support this statement.

Subsequent voyages to the North Pole have been mentioned (Gorlatov and Gakkel, 1965; Bartl, 1967). During one, a series of automatic meteorological stations were set up. The Soviet authority, Bartl, briefly describes a circumglobal voyage in 1966 made by a group of Soviet nuclear submarines. Of special interests is the fact that he states that they not only rounded the southern tip of South America, but they also operated within both the Arctic and Antarctic Circles, and in close proximity to ice and icebergs.

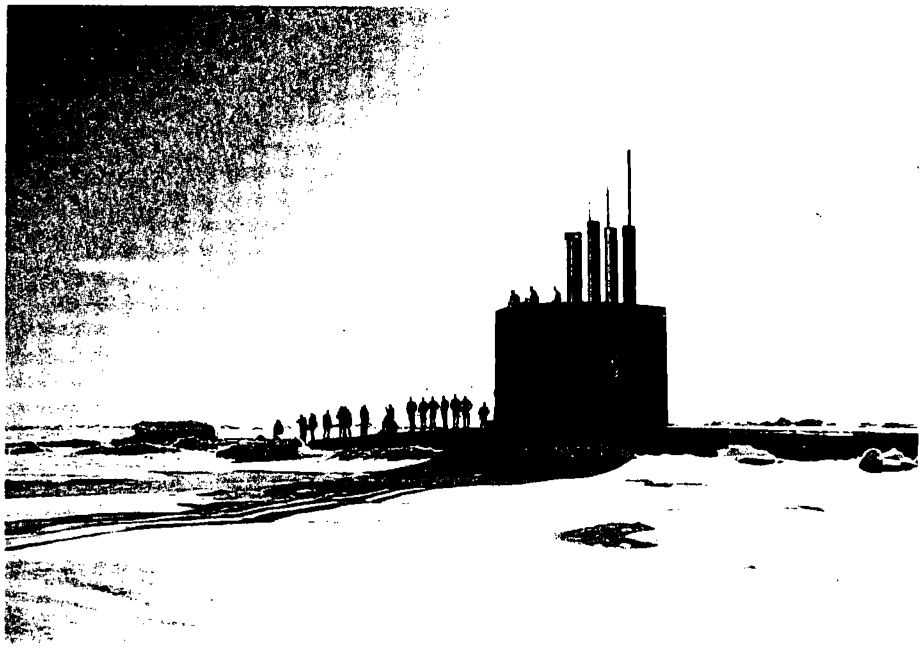

FIG. 8.— USS *Queenfish*, August 1970 (US Navy).

TABLE 1. — *Principal Polar Cruises of US and British Submarines, 1967-1983*

Date	Submarine	Area	Major Accomplishment
1967 Feb	USS *Queenfish*	Baffin Bay	First single-screw nuclear submarine operations in and under the ice
1969 Apr-May ..	USS *Whale* USS *Pargo* USS *Skate*	Arctic Basin	Surfacing through thick ice and "ridge busting" experiments
1970 Aug...........	USS *Queenfish*	Arctic Basin, Siberian Continental Shelf	Extensive shallow water operations using satellite navigation
1970 Nov...........	USS *Hammerhead*	Nares Strait, Arctic Basin	First autumn cruise
1971 Mar...........	HMS *Dreadnought*	Arctic Basin, North Pole	First UK Arctic operation
1971 Feb-Mar....	USS *Trepang*	Denmark Strait, Greenland Sea	*
1972 Mar-Apr....	USS *Hawkbill*	Northern Bering Sea	Shallow water operations
1975 Mar...........	USS *Bluefish*	Arctic Basin, Greenland Sea	*
1976 Mar...........	USS *Gurnard*	Arctic Basin, Beaufort Sea	Extensive shallow water operations
1976 Sept...........	HMS *Sovereign*	Arctic Basin, Greenland Sea	
1977 Mar...........	USS *Flying Fish*	Arctic Basin, Greenland Sea	*
1978 Oct	USS *Pintado*	Arctic Basin, Kara Sea	*
1979 Mar...........	USS *Archerfish*	Baffin Bay, Nares Strait	*
1979 May	HMS *Sovereign*	Greenland Sea	*
1981 Nov...........	USS *Silversides*	Greenland Sea	The 100th nuclear submarine
1982 Nov...........	USS *Aspro* USS *Tautog*	Arctic Basin	First submerged rendezvous through ice at the North Pole

* Because of security constraints, details on these operations cannot be given.

(After McLAREN, 1982a).

Finally, it has also been generally noted that Soviet conventional and nuclear submarines of various classes have utilized both the Northern Sea Route and the Trans-Polar Route to transfer from their Northern to Pacific Fleet (inference from Preston, 1982).

Scientific Attainments and Potential of U.S. Arctic Submarines

The U.S. submarine voyages listed in Table 1 have resulted in the collection of an enormous amount of physical oceanographic data which are still being analyzed. Each voyage has contributed to the growing knowledge of the characteristics and limits of pack ice and of icebergs. Knowledge of the special characteristics of contiguous marginal sea ice zones has been gained. And, through sound velocity, temperature and salinity measurements, and passive and active acoustic observations, such things as new subsurface currents have been discovered. Furthermore, they have assisted in more accurately delineating the layered nature and characteristics of those currents already known, such as the Arctic Surface Layer and the Atlantic Layer immediately beneath it. These results have stimulated new theory and mathematical models.

In the areas of applied science and technology, the experiences of these cruises have resulted in improved research capability. For example, capabilities developed for measuring the variability of sound speed due to changing temperatures, density, salinity and pressure will enable future cruises to more accurately delineate and measure the magnitude and direction of currents, internal waves, tides, and large scale fronts and eddies. The Arctic submarine's various scientific collection and acoustic tracking capabilities could also be of considerable assistance in the solving of northern waters ecological impact problems, such as the tracking and determining of effects of oil spills, and the effect of man-generated low frequency noise pollution or emissions on marine life, particularly mammals. Another new, and virtually unexplored area which the passive acoustic capabilities of a modern Arctic research submarine could encompass would be the development of techniques for interception, recording, and interpretation of subsurface transient acoustic emissions. This capability would be of particular value in the location, identification, and sizing of marine mammal populations. It might also be of potential value in the detection, location, and classification of icebergs, ice islands and the myriad types, thicknesses and ages of sea and pack ice.

Finally, with its present and potential scientific collection capabilities, the polar research submarine is vital for the collection of the information necessary for the modeling and analysis of the complexities of ocean circulation patterns and dynamics. And, in conjunction with data obtained through remote sensing techniques, the information could one day result in knowing what role, if any, the Arctic Ocean plays in the world's climate.

Commercial Potential of the Arctic Submarine

Because the author has published several recent articles and one thesis on the subject (McLaren, 1982b, 1983a, 1983b), he will not discuss the subject in any great detail in this paper. He will note, however, that certainly the most rapidly emerging need for the Arctic submarine as a commercial vessel is in the offshore petroleum fields of the Beaufort Sea and Canadian Islands. These fields are expected to be fully ready to go into production in the late 1980s and early 1990s. No method of transportation has as yet been developed for this purpose, much less shows any promise of being ready in time. Production in these areas will most certainly be followed by production in fields yet to be developed within promising sites in the Chukchi and Bering Seas and offshore eastern Greenland, to name a few.

Although transportation means such as icebreaker tankers and pipelines are currently under consideration by Dome Petroleum Limited, the Arctic Pilot Project and the Polar Gas Project, they may never become as economically viable and ecologically sound as the Arctic submarine, which has already demonstrated its capability to conduct operations in all these areas year-round. In the author's opinion, the time is already considerably overdue for action on some of the several submarine tanker and cargo carrier concept plans which have been recently proposed. These include the giant submarine tanker proposed by General Dynamics (McLaren, 1982b, 1983a) which, despite lingering problems, might be eventually most suitable for the more accessible deeper offshore areas, and the small Arctic submarine tanker and tows (McLaren, 1982b, 1983b) which would be most suitable for the shallower and/or less accessible areas. For as Admiral I. Galantin of the United States Navy noted in 1958 :

A fully laden tanker ploughing a rough sea is virtually a submarine constrained to the surface for the sake of top hamper on its few remaining feet of freeboard. It requires little imagination and very simple engineering to go all the way in putting the ship underwater and producing a simpler, more efficient hull, one which can escape the stresses of surface operation and which can maintain a higher economic speed (Galantin, 1958).

CONCLUSION

The evolution of the true Arctic submarine has been a lengthy, varied, and quite eventful one as this paper has shown. Although there has never been much hesitancy on the part of various nations in availing themselves of the submarine's many scientific capabilities, the vision of the world's maritime nations and particularly those with significant national interests in the polar regions has not, however, kept pace with the rapidly increasing commercial potential, much less the need for an Arctic submarine dedicated to commercial purposes.

As I stated in a previous research paper (McLaren, 1983b), hesitancy on the part of governments and commercial firms to consider the potential of the Arctic submarine as a vessel of commerce may well be based on other than rational grounds, for as Simon Lake stated in 1918 : « *It is the novelty of the enterprise and the mystery surrounding the submarine that makes it so difficult to the layman* ». There is no doubt that submarines — let alone submarines under ice — are still beyond most people's understanding of reasonable and safe transportation. That « visibility », for example, may with modern technology be better under water than at the surface does not occur to most landsmen, nor does the notion that a far less obstructed passage exists below the ice than on or through it on the surface. Nonetheless, the time has now come to develop a commercial submarine for the Arctic because the day will soon arrive when it will be urgently needed to assist in the development of not only the Arctic's non-renewable resources, such as petroleum and minerals, but also its renewable marine resources as well.

E.F. Roots of Environment Canada summed up the situation very well in 1979 when he said :

The development of a marine transportation system in the Arctic is a problem whose dimensions are set by the environment... If we succeed in adapting not only our *technology, but also our modern management practices and policies, to the Arctic environment, we may be able to take full advantage of the unique assets of the Northern environment.*

To this, the author would add the expansion of vision and the consequent changes which this would bring in decision-making.

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DEPARTMENT OF THE ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY, CORPS OF ENGINEERS
HANOVER, NEW HAMPSHIRE 03755-1290

CECRL-TD

8 February 1990

Honorable Albert Gore, Jr.
United States Senate
393 Russell Senate Office Building
Washington, DC 20510-4202

Dear Senator Gore:

This is in response to your 16 January 1990 letter to Mr. Steve Ackley, U.S. Army Engineer, Cold Regions Research and Engineering Laboratory, concerning polar regions impacts in climate change.

We would be pleased for Mr. Ackley to participate on your suggested panel of scientists. He has extensive experience in both the Arctic and Antarctic and is a national authority on sea ice characteristics and the atmosphere-ocean-ice interface. The Corps is concerned about the potential impacts of climate change (warming) in the polar regions from the perspectives of the integrity of strategic facilities in the Arctic (built on permafrost) and the changes in the water regime to include coastal processes (sea level change), navigation (impacted by changing flow volumes), wetlands (impacted by changes in precipitation patterns) both in the Arctic and the Continental U.S. Your panel will offer an excellent opportunity to collaborate with other experts on the most effective path to a better understanding of the climate change process and a focused effort to address an important piece of the puzzle.

The distinguished panel would also benefit by interactions with Navy polar oceanographic and sea ice scientists. We accede to Navy security concerns and recognize their prerogatives for release of classified information. It is also important to understand the role that the Navy sea ice data might play in understanding ice-ocean-atmosphere dynamics.

Ice characteristics (including thickness) are potentially an important component to our understanding of the role of polar regions in climate change. However, there are important caveats. The Navy sea ice data referred to in the article attached to your letter is primarily data on the number and depth (below water) of sea ice pressure ridges. These features are formed by a complex process that include both the thermal effects of the atmosphere and winds and currents. The variability of these features over time may not be a simple reflection of a climate change. Also, melting of the ice cover in the Arctic Ocean would have little impact on sea level since the ice forms from sea water and the total volume of the ocean (water and ice) does not change.

There are two important factors the panel should consider. First, the study suggested is very important, however, it is but one piece of a complex picture and must be interpreted in light of all important processes. Second, the basic data on sea ice analyzed to date has required the commitment of substantial resources for both data reduction and eventual analysis. I suggest identification of levels and sources of resources be one of the initial objectives of the panel.

Your recognition of this important global issue and Mr. Ackley's ability to contribute to this effort are appreciated. We look forward to cooperating with your office, the panel and the Navy to ensure its successful conclusion.

Sincerely,

LEWIS E. LINK, Ph.D.
Technical Director

Copies Furnished:
Chief of Naval Research
Ofc of Oceanographer of Navy/Hayes
Ofc Under Secretary of Defense/Cress
Ofc Assistant Secretary of Army for
Research, Development & Acquisition/Sterrett
Corps of Engineers/Strachn
CRREL/Ackley

UNIVERSITY OF WASHINGTON
SEATTLE, WASHINGTON 98195

Department of Atmospheric Sciences, AK–40

return to Rick

January 25, 1990

The Honorable Albert Gore, Jr.
United States Senate
393 Russell Senate Office Building
Washington DC 20510-4202

Attn.: Mr. Leon Fuerth
Mr. Rick Adcock

Dear Senator Gore:

Thank you for your letter of 16 January concerning your efforts to motivate the Navy to release arctic sea ice thickness data. Being a veteran of nearly three decades among the people trying to get that information from the Navy I am most gratified by your interest in this matter and will be glad to help in whatever way I can.

Since the first under-ice crossing of the Arctic Basin by the USS Nautilus in 1957, the Navy has amassed a large amount of sonar profiles of the ice bottom that indicate thickness, roughness, and areas of open water. Occasional samples of these data have been released and have contributed to our knowledge of the morphology of the sea ice. I believe that some of the recent press has unjustly accused the Navy of purposely withholding crucial information for some sinister reasons.

Some of this information is clearly sensitive because it reveals the time and location where the submarines were, and it is not surprising that in the political climate of the sixties and seventies certain types of information were monopolized by the "cold warriors." At the same time we should recognize that the Navy, through its Office of Naval Research, has supported basic and unclassified research in the arctic geosciences at a higher and more sustained level than any other federal agency.

While the present situation clearly calls for a relaxation of the classification criteria, the issue has several other aspects which, in my view, may be summarized as follows :

(1) Under-ice sonar profiles are generally taken for operational and safety purposes. It seems fair to assume that they are not as carefully annotated and archived as would be the case if they had been taken for scientific purposes.

(2) The designs and performance specifications of upward-looking submarine sonars have changed over the years. So it must be assumed that data acquired over a period of 30 years will have problems of compatibility.

(3) All sonars require frequent performance checks and calibrations. We cannot doubt that sonars serving navigation and target acquisition are submitted to these checks, but it may in some instances be difficult to determine in retrospect if this was also done to the ice profiling sonars.

What this adds up to is a large pile of data ranging in quality from excellent to useless, laced with secret elements, whose disentanglement and summation will require a massive effort. The Navy has obviously not seen the need to undertake that effort for their own purposes. My guess is that at least a few person-years of funding would be required to sort out that data base.

Perhaps an expeditious way to proceed would be to request the release of sonar profiles from the Central Arctic Basin over deep water only, and far removed from the continental shelves where secrecy is more likely to be an issue. The location of the submarine tracks would have to be known only approximately and the time only to within plus or minus two weeks.

I believe we should be cautious about assuming that these sea ice thickness data will reveal anything about global climate change. If a thinning trend over the past two or three decades should be detected, it may not be due to a warming of the Arctic atmosphere but to changes in the circulation of the underlying ocean. But even if there is no overall trend in ice thickness, the data in question would be extraordinarily useful for an improved understanding of the mechanisms that maintain the present ice cover and the changes that would result from a different climatic environment.

Yours respectfully,

N. Untersteiner

Norbert Untersteiner
Professor and Chairman

NU:dem

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Phone: 206-543-6438
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25 January 1990

Senator Albert Gore
United States Senate
393 Russell Senate Office Building
Washington DC 20510-4202

Dear Senator Gore;

In response to your letter of January 16, I would be happy to work with you and the Navy on the methodology for the analysis and release of submarine polar ice cover data to the public. I am pleased that your office is taking the initiative in obtaining the release of the data.

As far as a grid for the released data, we might consider using the National Meteorological Center (NMC) octagonal grid for the northern hemisphere, which has grid points with a spacing of about 350 km. This is a well-known grid, which is used for the reduction of meteorological and climate data. Alternatively, we might consider finer meshed version of this grid.

In closing, the re-analysis of this Navy data could provide a valuable counterpart to the ice extent time series derived by NASA from satellite data. I am off to Japan for two weeks, but will be available for further work on this project after my return on February 14.

Sincerely yours,

SM

Seelye Martin
Professor

→ CC: Dr. Claire Parkinson
Oceans and Ice Branch
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

National Aeronautics and
Space Administration

Goddard Space Flight Center
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20771

NASA

Reply to Attn of 671

January 25, 1990

Senator Albert Gore, Jr.
393 Russell Senate Office Building
United States Senate
Washington, DC 20510-4202

Dear Senator Gore:

Thank you for your letter of January 16. I would be pleased to be on the team examining the sea-ice thickness data of the Navy. Such data can be an extremely important complement to the data more readily obtainable from space satellites, namely, the data on ice compactness and extent; and I applaud you in your initiative in encouraging the Navy to make these data available. I feel that I should caution you, however, that the thickness data will not be able to reveal as much information as might be expected from reading the article on "Global warming: National security?" that was enclosed with your letter. In particular, the article claimed that: "it is surely true that if we know the rate at which ice is melting we can calculate the rate at which the atmosphere is warming." This unfortunately is not the case. Sea ice thickness is a complicated function of many variables, including ocean temperature, winds, currents, and salinity as well as air temperature. Consequently, knowledge of the rate of ice melt could not be used by itself to determine air temperature changes unequivocally. However, ice thickness is still an important climate variable, and thus the study you suggest could be of great value in adding to the growing evidence of climate change. This will be especially true if there is a long time series of data and good spatial coverage. I look forward to working with you and your staff and to examining the ice thickness data.

Sincerely,

Claire L Parkinson

Claire L. Parkinson
Oceans and Ice Branch/Code 671
Laboratory for Oceans

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To Rick Adcock
(Senator Gore's office)

UNIVERSITY OF WASHINGTON
SEATTLE, WASHINGTON 98195

Department of Atmospheric Sciences, AK-40

January 25, 1990

The Honorable Albert Gore, Jr.
United States Senate
393 Russell Senate Office Building
Washington DC 20510-4202

Attn.: Mr. Leon Fuerth
Mr. Rick Adcock

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Yours respectfully,

N. Untersteiner

Norbert Untersteiner
Professor and Chairman

NU:dem

UNIVERSITY OF WASHINGTON
DEPARTMENT OF ATMOSPHERIC SCIENCES

FAX COVER SHEET

DATE: 25 January 1990

TO: The Honorable Albert Gore, Jr.
United States Senate
Attn: Mr. Rick Adcock
Washington, D.C.

FAX: (202) 224-0580

FROM: Norbert Untersteiner
Professor and Chairman
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Comments:

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland
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NASA

January 25, 1990

Reply to Attn of 671

Senator Albert Gore, Jr.
393 Russell Senate Office Building
United States Senate
Washington, DC 20510-4202

Dear Senator Gore:

Thank you for your letter of January 16. I would be pleased to be on the team examining the sea-ice thickness data of the Navy. Such data can be an extremely important complement to the data more readily obtainable from space satellites, namely, the data on ice compactness and extent; and I applaud you in your initiative in encouraging the Navy to make these data available. I feel that I should caution you, however, that the thickness data will not be able to reveal as much information as might be expected from reading the article on "Global warming: National security?" that was enclosed with your letter. In particular, the article claimed that: "it is surely true that if we know the rate at which ice is melting we can calculate the rate at which the atmosphere is warming." This unfortunately is not the case. Sea ice thickness is a complicated function of many variables, including ocean temperature, winds, currents, and salinity as well as air temperature. Consequently, knowledge of the rate of ice melt could not be used by itself to determine air temperature changes unequivocally. However, ice thickness is still an important climate variable, and thus the study you suggest could be of great value in adding to the growing evidence of climate change. This will be especially true if there is a long time series of data and good spatial coverage. I look forward to working with you and your staff and to examining the ice thickness data.

Sincerely,

Claire L Parkinson

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January 25, 1990

The Honorable Albert Gore, Jr.
United States Senate
393 Russell Senate Office Building
Washington DC 20510-4202

Attn.: Mr. Leon Fuerth
Mr. Rick Adcock

Dear Senator Gore:

Thank you for your letter of 16 January concerning your efforts to motivate the Navy to release arctic sea ice thickness data. Being a veteran of nearly three decades among the people trying to get that information from the Navy I am most gratified by your interest in this matter and will be glad to help in whatever way I can.

Since the first under-ice crossing of the Arctic Basin by the USS Nautilus in 1957, the Navy has amassed a large amount of sonar profiles of the ice bottom that indicate thickness, roughness, and areas of open water. Occasional samples of these data have been released and have contributed to our knowledge of the morphology of the sea ice. I believe that some of the recent press has unjustly accused the Navy of purposely withholding crucial information for some sinister reasons.

Some of this information is clearly sensitive because it reveals the time and location where the submarines were, and it is not surprising that in the political climate of the sixties and seventies certain types of information were monopolized by the "cold warriors." At the same time we should recognize that the Navy, through its Office of Naval Research, has supported basic and unclassified research in the arctic geosciences at a higher and more sustained level than any other federal agency.

While the present situation clearly calls for a relaxation of the classification criteria, the issue has several other aspects which, in my view, may be summarized as follows :

(1) Under-ice sonar profiles are generally taken for operational and safety purposes. It seems fair to assume that they are not as carefully annotated and archived as would be the case if they had been taken for scientific purposes.

(2) The designs and performance specifications of upward-looking submarine sonars have changed over the years. So it must be assumed that data acquired over a period of 30 years will have problems of compatibility.

(3) All sonars require frequent performance checks and calibrations. We cannot doubt that sonars serving navigation and target acquisition are submitted to these checks, but it may in some instances be difficult to determine in retrospect if this was also done to the ice profiling sonars.

What this adds up to is a large pile of data ranging in quality from excellent to useless, laced with secret elements, whose disentanglement and summation will require a massive effort. The Navy has obviously not seen the need to undertake that effort for their own purposes. My guess is that at least a few person-years of funding would be required to sort out that data base.

Perhaps an expeditious way to proceed would be to request the release of sonar profiles from the Central Arctic Basin over deep water only, and far removed from the continental shelves where secrecy is more likely to be an issue. The location of the submarine tracks would have to be known only approximately and the time only to within plus or minus two weeks.

I believe we should be cautious about assuming that these sea ice thickness data will reveal anything about global climate change. If a thinning trend over the past two or three decades should be detected, it may not be due to a warming of the Arctic atmosphere but to changes in the circulation of the underlying ocean. But even if there is no overall trend in ice thickness, the data in question would be extraordinarily useful for an improved understanding of the mechanisms that maintain the present ice cover and the changes that would result from a different climatic environment.

Yours respectfully,

N. Untersteiner

Norbert Untersteiner
Professor and Chairman

NU:dem

UNIVERSITY OF WASHINGTON
DEPARTMENT OF ATMOSPHERIC SCIENCES

FAX COVER SHEET

DATE: 25 January 1990

TO: The Honorable Albert Gore, Jr.
United States Senate
Attn: Mr. Rick Adcock
Washington, D.C.

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