Submarine Upward Looking Sonar Ice Draft Profile Data and Statistics

Summary

This data set consists of upward looking sonar draft data collected by submarines in the Arctic Ocean. It includes data from both U.S. Navy and Royal Navy submarines. Maps showing submarine tracks are available. Data are provided as ice draft profiles and as statistics derived from the profile data. Statistics files include information concerning ice draft characteristics, keels, level ice, leads, un-deformed and deformed ice. Data from the U.S. Navy's Digital Ice Profiling System (DIPS) have been interpolated and processed for release as unclassified data at the U.S. Army's Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. Data from the analog draft recording system were digitized and then processed by the Polar Science Center, Applied Physics Laboratory, University of Washington. Data from British submarines were provided by the Scott Polar Research Institute, University of Cambridge. All data sources used similar processing methods in order to ensure a consistent data set.

Access to the Submarine Upward Looking Sonar Ice Draft Profile Data and Statistics data set is unrestricted, but users are encouraged to register for the data. Registered users will receive e-mail notification about any product changes.

Citing These Data

National Snow and Ice Data Center. 1998, updated 2006. *Submarine upward looking sonar ice draft profile data and statistics.* Boulder, Colorado USA: National Snow and Ice Data Center/World Data Center for Glaciology. Digital media.

To broaden awareness of our services, NSIDC requests that you acknowledge the use of data sets distributed by NSIDC. Please refer to the citation below for the suggested form, or contact NSIDC User Services for further information. We also request that you send us one reprint of any publication that cites the use of data received from our Center. This helps us to determine the level of use of the data we distribute. Thank you.

Overview Table

Category	Description
Data format	Data files are ASCII (text) format.
Spatial coverage and resolution	Arctic Ocean (see Table 1)
Temporal coverage and resolution	1975-2000 (see Table 1)
File size	The entire data set is 150 MB.
Parameter(s)	Sea ice deformation Sea ice draft/thickness Sea ice roughness Leads
Procedures for obtaining data	Data are available via FTP.

Table of Contents

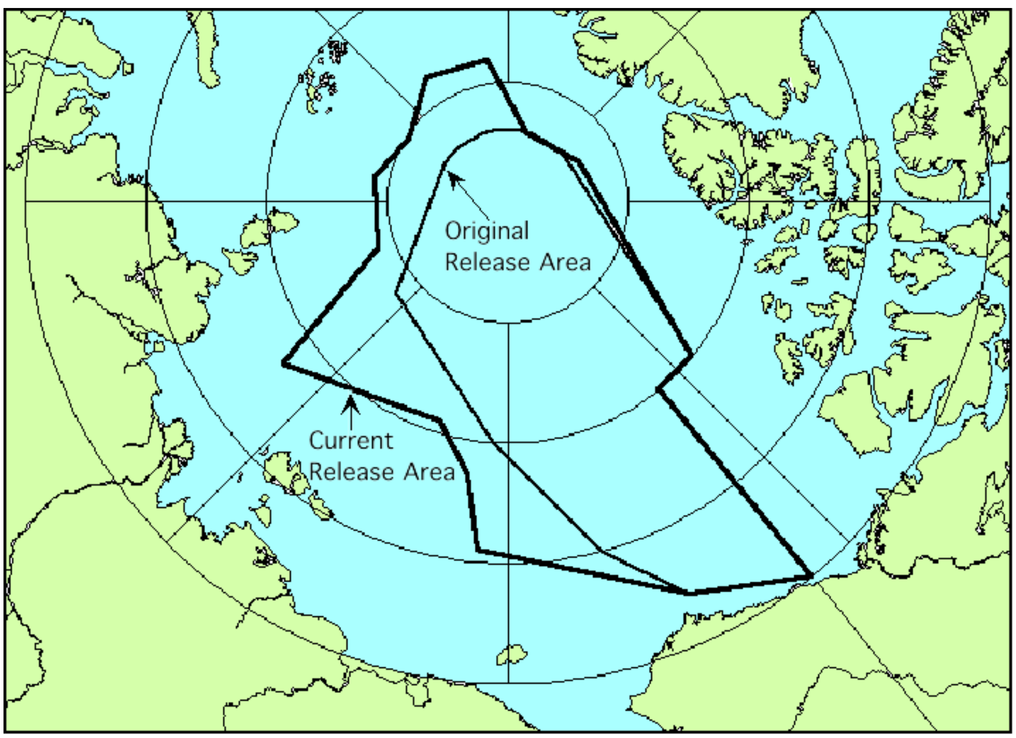
1. Contact

NSIDC User Services
National Snow and Ice Data Center
CIRES, 449 UCB
University of Colorado
Boulder, CO 80309-0449 USA
phone: +1 303.492.6199
fax: +1 303.492.2468
form: Contact NSIDC User Services
e-mail: nsidc@nsidc.org

2. Overview

Background

This data set includes submarine data collected in the Arctic Ocean by U.S. Navy and Royal Navy submarines. U.S. Navy guidance has stated that previously classified, submarine-collected ice draft data may be declassified and released according to set guidelines. Those guidelines include restrictions stating that positions of the data must be rounded to the nearest 5 minutes of latitude and longitude, and date is to be rounded to the nearest third of a month. The guidelines also specify a region in which the data may be released. The Chief of Naval Operations has expanded the release area beyond the original "Gore Box" (so called because of Vice President Gore's advocacy for releasing the data). See the map below (click on the image to see the full size map).



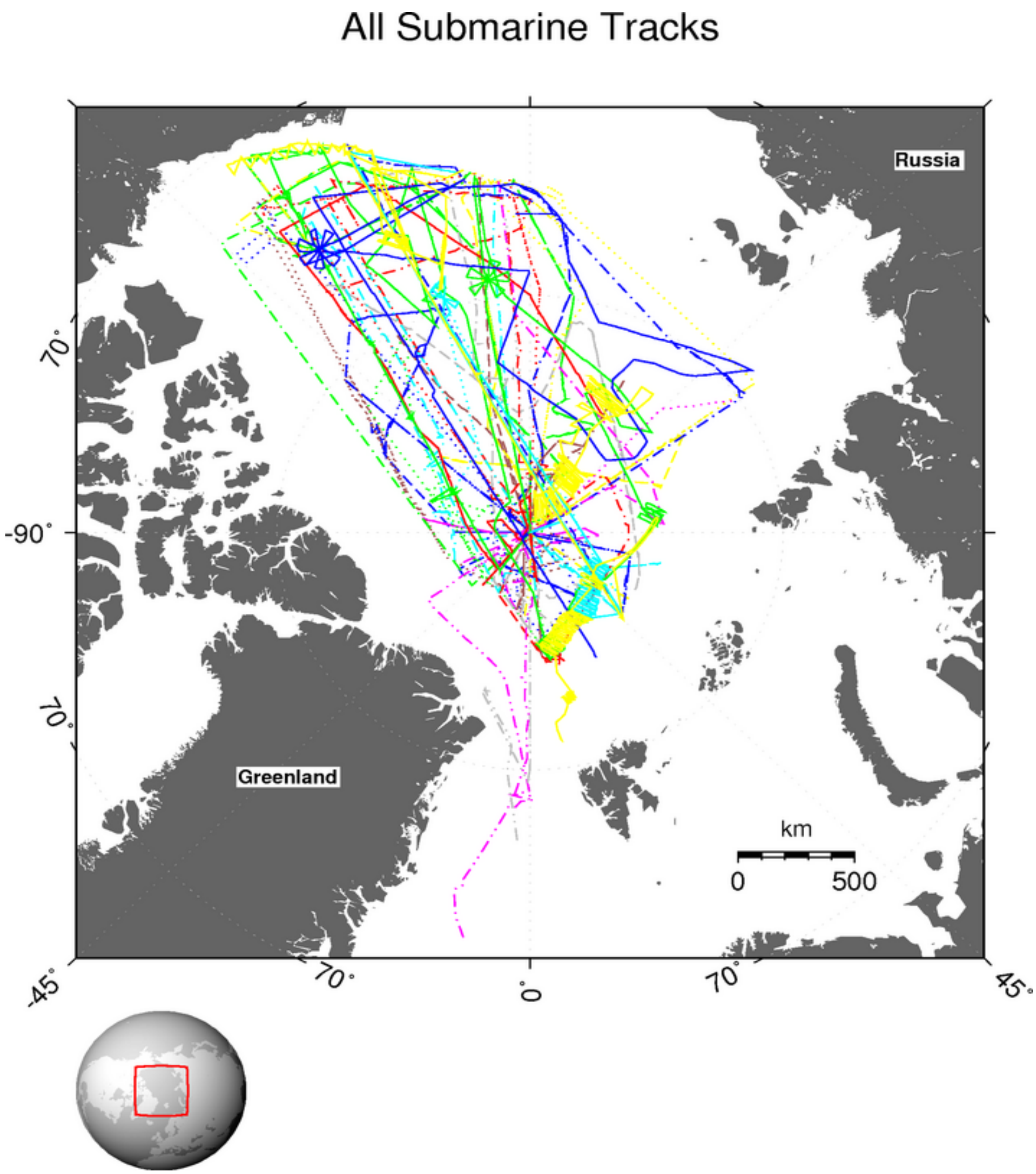
The SCience ICe EXercise (SCICEX) is a program that uses U.S. Navy submarines for research. SCICEX data are not classified and do not have restrictions on reporting the precise location and date for the data; therefore the SCICEX ice draft data in this collection are reported with their date of acquisition, and position is reported to six decimal places.

Since 1967 U.S. submarines have employed a narrow beam sonar transducer. Since 1976 data have usually been recorded digitally on U.S. Navy submarines with the Digital Ice Profiling System (DIPS). All U.S. Navy data in this data set come from the DIPS system, unless they are part of the analog portion. In processing, data are corrected for depth errors, erroneous drafts are removed, and data are spatially interpolated. The interpolation routine integrates submarine speed and position to obtain drafts at uniform spatial intervals. This is a labor-intensive interactive process, during which segments in which the submarine changed depth or course must be removed from the data. The majority of the cruise data were interpolated and processed for release as unclassified data at the U.S. Army's Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. SCICEX-97 and SCICEX-98 data were processed at the University of Washington, Polar Science Center, in cooperation with CRREL and using similar processing steps.

Data from British submarines were processed by the Scott Polar Research Institute (SPRI), University of Cambridge, in the same way as were the U.S. submarine data.

ULS draft data acquired on U.S. submarines prior to 1976 were recorded only as traces on paper rolls. In 1976 and thereafter, data were recorded both on analog paper roles and using DIPS. Polar Science Center investigators developed a method to scan and digitize the analog draft data so that they are as equivalent to the digitally recorded DIPS data as possible (Wensnahan and Rothrock, 2005). These data were added in 2006. This portion of the collection is referred to as the analog portion.

The map below shows submarine tracks from the non-analog portion of the data set (click on the image to see the full size map). To access the map legend, click here.



3. Detailed Data Description

Background

Data are in two types of files, one for ice draft profiles, and the other for statistics derived from the profile data. Ice draft files include a header that gives date and location information followed by a sequential list of drafts spaced at 1.0 m intervals that comprise the bottom-side sea-ice roughness profile. Data in each file fall along a straight-line (great circle) track between the two end points given in the header. The length of the profile in any given file can be up to 50 km, but may be shorter if data dropouts create gaps greater than 0.25 km, or if changes in course cause deviations from a straight-line track. Statistics files include information on ice draft characteristics, keels, level ice, leads, un-deformed, and deformed ice. For background information on scientific uses of ice draft data such as these statistical measures of ice deformation, see Analysis of Arctic Ice Draft Profiles Obtained by Submarines, a note provided by W. Tucker and S. Ackley, CRREL, Hanover, NH, in July 1998.

Table 1 shows the cruise reference name (click to see cruise track), dates, number of segments, the size of the directory containing the data (after uncompressing and untarring), and examples of naming conventions for the data files. NSIDC is told how we may refer to each cruise by the data providers. We have agreed to adhere to this naming convention. Therefore NSIDC cannot provide the submarine names for all cruises to users of this data set. Note that permission was obtained to release some SCICEX-99 data acquired outside the previously mentioned release box. A legend for the submarine cruise tracks is also available.

Table 1

Cruise Reference Name	Start Date	End Date	Number of Draft Segments	Size of Untarred/ Uncompressed File Directory	File Name Convention/ Examples	Provided to NSIDC for publication by*	Date published by NSIDC	Raw data source
1975 (analog)	May 1975	May 1975				Wensnahan June 2006	September 2006	USchart
UK-76 (Gurnard)	07 April 1976	10 April 1976	27	22.0M	0476drft.002 0476stat.013	Davis February 1999	May 1999	UKDIPS
1976 (analog)	April 1976	April 1976				Wensnahan June 2006	September 2006	USchart
1979 (analog)	April 1979	April 1979				Wensnahan June 2006	September 2006	USchart
1981 (analog)	October 1981	October 1981				Wensnahan June 2006	September 2006	USchart
1982a (analog)	November 1982	November 1982				Wensnahan June 2006	September 2006	USchart
1983a (analog)	August 1983	August 1983				Wensnahan June 2006	September 2006	USchart
1984b (analog)	September 1984	September 1984				Wensnahan June 2006	September 2006	USchart
1984c (analog)	November 1984	November 1984				Wensnahan June 2006	September 2006	USchart
1984d (analog)	October 1984	November 1984				Wensnahan June 2006	September 2006	USchart
1986a	May 1986	June 1986	111	19.1M	1986adrft.053 1986astat.090	February 2001 (?)	December 2001	USDIPS
1986b	02 April 1986	03 April 1986	82	21.0M	1986bdrft.001 1986bstat.001	Tucker February 2001 (?) (original)	March 2001	USDIPS
						Tucker May		

						2004 (corrected)	July 2004	
UK-87 (analog)	08 May 1987	26 May 1987	130	82.8M	0587drft.a41 0587stat.b13	Davis February 1999	May 1999	UK, A/H**
1987	02 April 1987	03 April 1987	64	17.7M	1987drft.035 1987stat.035	February 2001	March 2001	USDIPS
1987c (analog)	May 1987	June 1987				Wensnahan June 2006	September 2006	USchart
1988a	03 May 1988	03 May 1988	32	10.5M	1988drft.050 1988stat.064	Tucker March 2000 (original)	May 2000	USDIPS
						Tucker May 2004 (corrected)	July 2004	
1988b	01 August 1988	03 August 1988	47	12.9M	1988bdrft.018 1988bstat.018	February 2001	March 2001	USDIPS
1988c (analog)	April 1988	May 1988				Wensnahan June 2006	September 2006	USchart
1989b	September 1989	September 1989	47	13.6M	1989bdrft.018 1989bstat.099	Tucker April 2002	June 2002	USDIPS
1990	March 1990	April 1990	35	5.3M	1990drft.131 1990stat.143	Tucker November 2001	December 2001	USDIPS
1990c (analog)	September 1990	September 1990				Wensnahan June 2006	September 2006	USchart
UK-91 (analog)	20 April 1991	22 April 1991	16	11.6M	0491drft.012 0491stat.021	Davis February 1999	May 1999	UK, A/H**
1991	03 March 1991	02 May 1991	142	20.2M	1991drft.047 1991stat.107	Tucker March 2000	May 2000	USDIPS
Grayling-1992	April 1992	April 1992	9	2.9M	g92drft.032 g92stat.0431992a	Tucker February 1998 (original)	February 1998	USDIPS
						Tucker May 2004 (corrected)	July 2004	
1992a	May 1992	May 1992	17	2.9M	1992adrft.015 1992astat.021	Tucker September 2001	December 2001	USDIPS
1992b	August 1992	September 1992	38	8.8M	1992badrft.038 1992bstat.027	Tucker September 2001	December 2001	USDIPS
L2-92	02 April 1992	02 April 1992	64	16.5M	L292drft.010 L292stat.052	Eppler October 1998	November 1998	USDIPS
SCICEX-93	01 September 1993	12 September 1993	139	43.2M	sc93drft.041 sc93stat.131	Eppler October 1998	November 1998	USDIPS
						Tucker		

1993	02 April 1993	03 April 1993	86	24.1M	1993drft.034 1993stat.034	Tucker February 2001	March 2001	USDIPS
1993c (analog)	April 1993	April 1993				Wensnahan June 2006	September 2006	USchart
1994	01 April 1994	01 April 1994	85	30.1M	1994drft.146 1994stat.161	Tucker September 1999	October 1999	USDIPS
1994b (analog)	September 1994	September 1994				Wensnahan June 2006	September 2006	USchart
SCICEX-96	20 September 1996	22 October 1996	217	64.9M	sc96drft.095 sc96stat.141	Eppler February 1999 (original) Tucker May 2004 (corrected)	March 1999 July 2004	USDIPS
SCICEX-97	03 September 1997	02 October 1997	217	64.9M	sc97drft.111 sc97drft_sheba.15 sc97stat.054 sc97stat_sheba.167	Yu September 1999 (original) Yu June 2002 (corrected)	October 1999 June 2002	USDIPS
SCICEX-98 Note	02 August 1998	16 August 1998	129	44.2M	sc98drft.020 sc98drft_sheba.036 sc98stat.116 sc98stat_sheba.028	Yu May 2002	June 2002	USDIPS
SCICEX-99	02 April 1999	13 May 1999	41 (plus subsegments)	119.0M	sc99drft.404_002.002 sc99stat.404_002.002	Tucker November 2004	June 2005	USDIPS
2000a (analog)	October 2000	October 2000				Wensnahan June 2006	September 2006	USchart

*Also see acknowledgements

**Analog/Hand-digitized

The description of the data in this section is applicable to the non-analog portion of the data set. The analog portion of the data set is described in a document provided by M. Wensnahan (see Documentation for G01360 Analog Portion, a .doc file. This documentation will be integrated with the rest of the product documentation when resources allow.).

File Naming Convention

For non-analog U.S. Navy cruise data, the file name begins with four characters denoting the cruise. The next four characters are either "drft" (for draft files) or "stat" (for statistics files). Each file name is followed by a three-digit extension that corresponds to an ice segment. The extensions were assigned in the order in which the segments were acquired by the submarine. Each draft file contains data for one ice segment. Each statistics file contains data (19 parameters) for one ice segment. For SCICEX-97 and SCICEX-98 data, data files for segments acquired in the vicinity of the SHEBA (Surface Heat Balance of the Arctic Ocean) experiment have "_sheba" added to their names. For SCICEX-99 data, the naming convention is as follows: "sc99drft.404_002.002" indicates data collected on April 4 (404), and this is the second segment processed for this day (_002). The segment required processing in parts, and this is the second (.002) part of the segment.

See Notes on U.K. Data Files, and Documentation for G01360 Analog Portion, a .doc file, for information on the naming convention for Royal Navy and U.S. Navy analog portion files.

Format

Data files are ASCII (text) format.

File Header Format and Information

File headers at the beginning of the draft and statistics files give the following information concerning the data segment from which information in the archive file was generated (Fig. 1): a) the name of the source file from which the data were generated, b) date information consisting of the exact date (year, month, and day) the data were acquired, for SCICEX data; in the case of previously classified data, the year, month, and the third of the month (1=Days 1 to 10, 2=Days 11 to 20, 3=Days 21 to 31) in which the data were acquired, c) geographic coordinates of the first and last drafts in the file; in the case of previously classified data, the coordinates are rounded to the nearest 0.1° north latitude and east longitude, d) the number of drafts in the profile segment, e) the length of track included in the profile segment in kilometers, and f) the length and location within the draft file of any gaps that exceed 10.0 m in length. Profile length is the great circle distance between unrounded latitude-longitude coordinates of the first and last drafts, for both SCICEX and previously classified data. Individual draft measurements are equally spaced at approximately 1.0 m intervals along the great circle arc.

Note that the number of draft values at 1.0 m spacing can sometimes be greater or less than the profile length in meters. Two reasons for this are rounding error (draft values are nominally every 1 meter, but may be slightly more or less), and the fact that minor turns or turns of short duration in the submarine track may not have been edited from the data record.

```
              SOURCE FILE: lnall.026

                --------DATE--------

                          Year: 1992

                         Month:  APR

                Third of Month:    2

                --------------------

           -----SEGMENT DESCRIPTION-----

             Beginning Latitude:  80.8

            Beginning Longitude: 210.3

                Ending Latitude:  81.2

               Ending Longitude: 210.2

              Number of Drafts:   49999

           Length of Track (km):  49.999

           -----------------------------

        __________________________________

             DATA GAPS IN DRAFT FILE

          (The following gaps greater than

             0.010 km were detected.)

        ----------------------------------

          0.012 km gap follows draft 35328

        ----------------------------------
```

```
3.45
2.99
2.92
3.27
2.89
2.62
3.02
2.99
2.75
2.91
.
.
.
.
.
```

Figure 1. Ice draft file showing header and first 10 drafts in meters

Notes on U. K. Data Files

The header file for the U.K. data (the equivalent of Fig. 1) has a slightly different format. The naming convention for the U.K. files is XXYYzzzz.xyy, where XX designates month, YY is the year, zzzz is drft or stat, for draft or statistics file, x is a placeholder that designates which survey of the cruise the data are from when a cruise has more than one survey, and yy is the segment number.

The 1976 SPRI data are from USS Gurnard in the Beaufort Sea with approximate latitude/longitude coordinates supplied. Centroids were not determined. An experimental narrow-beam sonar was used (Wadhams and Horne, 1980).

The 1987 SPRI data are from the HMS Superb in the Greenland Sea & Eurasian basin. Data are in two legs (a and b). Segments a03 and b46 have insufficient data for analysis. For segments b45, b55, b58, b60 and b61 the ice regime is not conducive to standard analyses; therefore, these segments were processed with level ice slope of 0.05 and minimum lead width set to zero.

File Size

The entire data set is 150 MB.

4. Data Acquisition and Processing

The description of the data in this section is applicable to the non-analog portion of the data set. The analog portion of the data set is described in a document provided by M. Wensnahan (see Documentation for G01360 Analog Portion, a .doc file. This documentation will be integrated with the rest of the product documentation when resources allow.).

Please also see Processing of the SCICEX '98 Submarine Data, by Y. Yu and S Dickinson, Applied Physics Laboratory, University of Washington. This document describes how SCICEX 98 data were corrected for errors caused by a stuck depth gauge.

Ice Draft Files In order to statistically analyze these data, they were interpolated to even spatial intervals. The raw, digital data contain information only about ice draft and time, which is not useful for statistical, fractal, or spectral analysis. To obtain ice drafts at uniform spatial intervals, the speeds and positions of the submarine were integrated with the interpolation routine. Segments of the data during which the submarine changed course and/or depth were removed. For some cruises, only segments greater than 10 km in straight-line length were retained for this data set.

Raw top-sounder profiles, from which data presented here are derived, were created by sampling ice draft with top-sounder profilers at intervals spaced equally in time as the submarine moved beneath the ice cover. Adjacent drafts in the raw profile, though recorded at intervals that are constant in time, represent spot measurements separated by non-constant distances, the length of which vary with changes in vessel speed. In this raw format, profiles from different tracks (or even from different segments of the same track) are not directly comparable because the same feature (keel, lead, etc.) sampled twice will have a different shape depending on whether the sensor platform was moving rapidly or slowly. Keels and other roughness elements in raw top-sounder profiles thus appear compressed at high speeds, and stretched out at low speeds. Such apparent differences in sampling rate bias summary statistics (mean draft, variance, etc.) and spectral characteristics (Fourier transforms, auto- and cross-correlation, etc.) because the bottom-side ice profile represented in one section of data is over- or under-sampled with respect to that in another section.

To eliminate this problem, interpolated profiles composed of drafts spaced equally in distance (as opposed to time) are created. Navigation data combined with speed and bearing information give good estimates of the geographic location of each draft. Great circle distances between points, calculated from geographic coordinates using standard mapping equations, provide a basis for interpolating a derivative set of equidistant drafts using a cubic spline algorithm [spline( ) and splint( )] (Press et al. 1992). The interpolated profiles that result, consisting of drafts spaced equally with respect to distance (nominally 1.0 m apart), form the basis of this data archive (Fig. 1).

Individual ice draft files represent data acquired continuously over straight-line tracks that span distances up to 50 km in length. Data acquired while the vessel was turning have been removed. Gaps within archived profiles, resulting from dropouts and other sensor malfunctions, are shorter than 0.25 km; their length and location within the profile is noted in header information described above. When gaps greater than 0.25 km in length were encountered, one file was closed and the next opened. Draft measurements are given in meters, and the distance between consecutive drafts is 1.0 m.

Ice Statistics Files Ice Draft PDF and General Statistics Basic statistical analysis was performed on the processed, interpolated data. Data of lengths 10 km to 50 km were retained. Although 50 km segments are preferable (Wadhams 1984), shorter segments were included because they add value to the data set, especially in regions where the ice morphology changes rapidly. Because these shorter segments were included, caution must be exercised when analyzing regional, seasonal, and interannual variations. The statistics data files are ASCII text files. Probability density functions (pdfs) (Fig. 2) are derived from the frequency distribution of all drafts in the track segment. Bin width is 0.1 m. Counts in each bin are normalized by the total number of drafts in the segment to give the probability of occurrence of drafts of any given depth. Bins for which no drafts occur have probability of 0.0 and are omitted from the listing to save storage space (see, for example, BIN 276 for drafts between 27.5 and 27.6 m, Fig. 2). This convention is used for all other pdfs in the statistics archive.

General statistics calculated for ice drafts in each segment include standard parametric descriptors of central tendency and dispersion (mean and median draft, variance, standard and average deviation, standard error, skewness, kurtosis, and root-mean-square draft, see Fig. 3). Note that the mean is that of all ULS measurements, including open water.

```
    PROBABILITY DENSITY
 -FUNCTION OF ICE DRAFTS-
    Bin Width (m):     0.1
  Number of Bins:    279
 |----|-----|-----------|
       LOWER
       BOUND
   BIN  (m)  PROBABILITY
```

```
|----|-----|-----------|
   1   0.0  0.00630013
   2   0.1  0.00110002
   3   0.2  0.00094002
   4   0.3  0.00062001
   5   0.4  0.00064001
   6   0.5  0.00086002
   7   0.6  0.00264005
   8   0.7  0.00220004
                  .
                  .
                  .
 274  27.3  0.00004000
 275  27.4  0.00006000
 277  27.6  0.00004000
 278  27.7  0.00002000
 279  27.8  0.00002000
|----|-----|-----------|
```

Figure 2. Probability density function (pdf) of ice drafts

```
----GENERAL DRAFT STATISTICS----
               Mean (m):    3.250
             Median (m):    2.200
  Average Deviation (m):    1.700
 Standard Deviation (m):    2.627
     Standard Error (m):    0.012
               Variance:    6.904
               Skewness:    3.263
               Kurtosis:   15.624
          RMS Draft (m):    4.179
--------------------------------
```

Figure 3. Ice draft statistics

Specific formulae used to calculate these values are as follows (code used in these calculations borrows heavily from that given in the moment ( ), select ( ), and middle ( ) functions of Press et al.,1992):

$$Mean = \overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i$$

$$Median = X_{med} = \begin{cases} X_{(N+1)/2} & When \ N \ is \ odd. \\ \left(X_{N/2} + X_{(N/2)+1}\right)/2 & When \ N \ is \ even. \end{cases}$$

$$Variance = \frac{1}{N-1}\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^2$$

$$Std.Dev = \sigma = \sqrt{Variance}$$

$$Avg.Dev. = \frac{1}{N}\sum_{i=1}^{N}\left|X_i - \overline{X}\right|$$

$$Std.Err = \frac{\sigma}{\sqrt{N}}$$

$$RMS_{draft} = \sqrt{\frac{\sum_{i=1}^{N} X_i^2}{N}}$$

$$Skewness = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{X_i - \overline{X}}{\sigma}\right]^3$$

$$Kurtosis = \left\{\frac{1}{N}\sum_{i=1}^{N}\left[\frac{X_i - \overline{X}}{\sigma}\right]^4\right\} - 3$$

Autocorrelation

Function Autocorrelation measures the correlation between pairs of consecutive drafts within a profile. Pairs may consist of adjacent drafts, or drafts separated by a particular distance (lag). This process compares the ice draft profile with itself. Successive comparisons with increasing values of lag in effect slide the profile past itself and allow one to determine whether periodicities exist that lead to higher correlations at some offsets than at others. Such periodicities, if they exist, may arise from periodic noise in the profile, or may reflect geophysical phenomena that produce recurring features.

First-order autocorrelation considers correlation between the set of all pairs of adjacent drafts:

(X1, X2), (X2, X3), (X3, X4), ..., (Xi-1, Xi), ..., (Xn-1, Xn).

This assumes that the distance between consecutive drafts is constant; drafts used here are interpolated to a nominal spacing of 1.0 m, so this requirement is met. Higher order autocorrelations are calculated in sequence by comparing pairs of drafts separated by successively greater distance or lag. In the case where lag=2, for example, the set of adjacent pairs is represented by:

(X1, X3), (X2, X4), (X3, X5), ..., (Xi-2, Xi), ..., (Xn-2, Xn),

and for lag=5:

(X1, X6), (X2, X7), (X3, X8), ..., (Xi-5, Xi), ..., (Xn-5, Xn).

Autocorrelation r as a function of lag is defined as:

$$r_{lag} = \frac{\sum_{i=(lag+1)}^{n} (X_{i-1} - \overline{X})(X_i - \overline{X})}{\sum_{i=lag}^{n} \left(X_i - \overline{X}\right)^2}.$$

The analog to this procedure in conventional correlation analysis is calculation of a correlation coefficient associated with the cluster of points produced by plotting, in a scatter diagram, all possible pairs of drafts that are separated by a given lag. The statistics archive lists autocorrelation as a function of lag from 0 to 150, inclusive (Fig. 4). Inasmuch as the spatial separation between individual draft measurements is 1.0 m, this corresponds to a range of lags from 0.0 m to 150.0 m. In addition, a variable called Correlation Length, defined as the lag at which r_{lag} less than or equal to 1/e, is given as a basis for making general comparisons between autocorrelation functions calculated for different profile segments.

```
               ---------------
               AUTOCORRELATION
               ---------------
        Evaluated Lags From 0 To 150
Criterion for Correlation Length = 0.367879
           Correlation Length = 45
               |----|--------|
                  LAG  R[LAG]
               |----|--------|
                    0  1.00000
                    1  0.98696
                    2  0.96349
                    3  0.94327
                    4  0.92245
                    5  0.90072
                    6  0.87947
                    7  0.85825
                    8  0.83758
                    9  0.81778
                          .
                          .
                          .
```

Figure 4. Autocorrelation function

Keels

Keel detection is accomplished using an algorithm developed by A.W. Lohanick (unpublished). Lohanick's routine, which was originally written to detect ridges in laser profilometer data acquired during Project Birdseye, uses a Rayleigh criterion to identify local maxima (or, in the case of ice draft data, minima) that correspond to ridges (or keels). To qualify as a keel, an ice draft must be at least twice as deep as the local minimum draft measured from an undeformed ice datum (2.5 m), it must be the deepest draft among all local drafts, and it must be deeper than 5.0 m. Two or more keels that occur adjacent to each other are identified as independent features if they are separated by at least one draft that is less than half the depth of the first keel in the pair, as measured from the undeformed ice datum (2.5 m). Otherwise they are identified as a single feature with a draft equal to the local maximum.

Keels detected using this routine are listed in a table giving the record number at which the keel occurs in the draft file, the depth of the keel, and the distance to the previous keel (Fig. 5). Additional tables give pdfs of keel depths with a bin width of 1.0 m (Fig. 6) and of spacings between adjacent keels with a bin width of 50.0 m (Fig. 7). Summary statistics calculated for keel depths and keel spacings using equations given above for draft statistics give mean, median, maximum and minimum draft and spacing, average and standard deviation, and variance, skewness, and kurtosis (Fig. 8).

KEELS

Number of Drafts Examined:	49999
Number of Keels Detected:	306
Minimum Keel Depth Cutoff:	5.00 m
Undeformed Ice Datum:	2.50 m

LIST OF DETECTED KEELS

RECORD NUMBER	KEEL DEPTH (m)	KEEL SPACING (m)
15	8.04	44.12
59	9.16	87.39
147	17.09	25.45
172	9.19	363.12
535	9.01	74.66
610	6.82	16.12
626	6.06	121.32
747	8.05	16.97
764	8.97	263.86
1028	5.24	55.99
1084	5.92	878.11
1962	8.68	244.34
2206	8.07	43.27
2249	8.58	53.45

---PDF OF KEEL DEPTHS---

Bin Width (m):	1.0
Number of Bins:	27

BIN	LOWER BOUND (m)	PROBABILITY
6	5.0	0.21895425
7	6.0	0.21895425
8	7.0	0.14052288
9	8.0	0.13398693
10	9.0	0.06535948
11	10.0	0.04248366
12	11.0	0.05555556
13	12.0	0.02941176
14	13.0	0.02614379
15	14.0	0.01307190

```
2303  10.36   215.49
2518  11.25   145.07
2663   6.31   617.62
3281   5.45   266.39
3547   7.34   466.60
4014   5.29   112.83
4127   6.21   719.42
4846  10.37   100.11
4946   6.36   399.58
5344   5.01   246.03
5590   7.48    78.90
5669   5.03   525.14
          .
          .
          .
          .
          .
```

Figure 5. List of keels

```
  16  15.0  0.00653595
  17  16.0  0.00980392
  18  17.0  0.00980392
  19  18.0  0.00653595
  20  19.0  0.00326797
  22  21.0  0.00653595
  23  22.0  0.00326797
  26  25.0  0.00653595
  28  27.0  0.00326797
|----|-----|-----------|
```

Figure 6. Probability density function of keel depths

```
---PDF OF KEEL SPACINGS---
--------------------------
   Bin Width (m):   50.0
  Number of Bins:     28
|----|-------|-----------|
       LOWER
       BOUND
  BIN   (m)   PROBABILITY
|----|-------|-----------|
    1     0.0  0.26470588
    2    50.0  0.26470588
    3   100.0  0.15686275
    4   150.0  0.07516340
    5   200.0  0.04575163
    6   250.0  0.04575163
    7   300.0  0.02941176
```

```
                 KEEL STATISTICS
------------------------------------------
                        KEEL        KEEL
     STATISTIC      DEPTH (m)  SPACING (m)
------------------|-----------|-----------
              Mean       8.50       163.74
            Median       7.38        89.93
           Minimum       5.01         5.09
           Maximum      27.86      1411.66
```

8	350.0	0.01960784
9	400.0	0.01960784
10	450.0	0.00326797
11	500.0	0.01633987
12	550.0	0.00326797
13	600.0	0.01960784
14	650.0	0.00653595
15	700.0	0.00653595
17	800.0	0.00326797
18	850.0	0.00980392
23	1100.0	0.00653595
29	1400.0	0.00326797

Figure 7. Probability density function of keel spacings

Average Deviation	2.56	132.80
Standard Deviation	3.63	198.89
Variance	13.15	39556.33
Skewness	2.23	2.71
Kurtosis	6.39	9.18

Figure 8. Keel depth and spacing statistics

Level Ice Segments

Level ice segments are defined as a series of consecutive drafts spanning a distance greater than 10 m in length over which the slope between any two adjacent drafts is less than or equal to 0.050 (Fig. 9). The magnitude of individual drafts is not a criterion. Level ice defined on this basis thus does not necessarily indicate thin ice or lead ice but can occur (and occasionally does occur) within thick first-year ice, multiyear ice, and regions of heavily deformed ice. Parameters given for each level ice segment include the record number within the draft file at which the segment begins, segment length, the mean of drafts within the segment, the mean of slopes between adjacent drafts within the segment, and the distance (spacing or separation) from the end of the previous level ice segment to the start of the current segment. Separate tables list pdfs of mean draft (Fig. 10), level ice spacing (Fig. 11), and level ice segment length (Fig. 12). The bin width used for mean draft pdfs is 0.5 m, for mean spacing pdfs is 50.0 m, and for mean level ice segment length is 10.0 m.

-------------LEVEL ICE SEGMENTS-------------

Criteria Used to Define Level Ice Segments:

Maximum draft-to-draft slope: 0.050

Maximum ice draft: NONE

Minimum segment length: 10.0 m

FIRST RECORD NUMBER	SEGMENT LENGTH (m)	MEAN DRAFT (m)	MEAN SLOPE	DISTANCE TO PREVIOUS SEGMENT (m)
879	14.01	2.28	0.0043	0.00
1667	11.01	1.97	0.0082	773.98
1747	11.01	2.09	0.0082	68.95

PDF: LEVEL ICE MEAN DRAFT

Bin Width (m): 0.5

Number of Bins: 6

BIN	LOWER BOUND (m)	N	PROBABILITY
1	0.0	7	0.09333333

3199	10.01	2.07	0.0110	1441.47
3415	10.01	1.20	0.0090	205.94
3443	14.01	0.09	0.0071	18.01
3474	18.01	0.05	0.0089	17.01
3659	17.01	2.01	0.0106	167.02
3679	14.01	1.97	0.0093	3.00

.
.
.

Figure 9. List of level ice segments

1	0.0	7	0.09333333
2	0.5	2	0.02666667
3	1.0	4	0.05333333
4	1.5	35	0.46666667
5	2.0	26	0.34666667
7	3.0	1	0.01333333

Figure 10. Probability density function of mean draft in level ice segments

PDF: LEVEL ICE SEGMENT SPACINGS

Bin Width (m): 50.0

Number of Bins: 108

BIN	LOWER BOUND (m)	N	PROBABILITY
1	0.0	14	0.18666667
2	50.0	9	0.12000000
3	100.0	2	0.02666667
4	150.0	3	0.04000000
			.
			.
			.
46	2250.0	1	0.01333333
53	2600.0	1	0.01333333
109	5400.0	1	0.01333333

Figure 11. Probability density function of separation between level ice segments

-PDF: LEVEL ICE SEGMENT WIDTHS-

Bin Width (m): 10.0

Number of Bins: 7

BIN	LOWER BOUND (m)	N	PROBABILITY
2	10.0	70	0.93333333
3	20.0	2	0.02666667
4	30.0	2	0.02666667
8	70.0	1	0.01333333

Figure 12. Probability density function of the width of level ice segments

Leads

Leads are defined as a series of consecutive drafts, all of depth less than 0.3 m, that span a distance 10.0 m or greater in length. Parameters given for each lead segment include the record number within the draft file at which the segment begins, lead width, the mean of drafts within the segment, and the distance (spacing or separation) from the end of the previous lead to the start of the current lead (Fig. 13). Separate tables list pdfs of mean draft within leads (Fig. 14) and distance between adjacent leads (Fig. 15). The bin width used for pdfs of mean lead draft is 0.05 m, and for mean spacing pdfs is 50.0 m.

```
----------------LEADS---------------

   Criteria Used to Define Leads:

        Maximum ice draft:   0.3 m

        Minimum ice draft:   0.0 m

        Minimum width:  10.0 m
```

FIRST RECORD NUMBER	LEAD WIDTH (m)	MEAN DRAFT (m)	DISTANCE TO PREVIOUS SEGMENT (m)
3438	25.02	0.094	0.00
3469	26.02	0.046	6.00
9209	93.96	0.020	5716.49
27943	18.02	0.166	18636.52
27964	12.01	0.177	3.00
28495	38.04	0.012	518.93
32759	22.02	0.042	4221.41
33409	18.02	0.048	627.98
36596	42.04	0.040	3179.51
42019	50.04	0.019	5377.14

Figure 13. List of leads

```
PDF: LEAD ICE MEAN DRAFT
-----------------------------

 Bin Width (m):    0.1

 Number of Bins:      3
```

BIN	LOWER BOUND (m)	N	PROBABILITY
1	0.000	7	0.70000000
2	0.050	1	0.10000000
4	0.150	2	0.20000000

Figure 14. Probability density function of mean draft in leads

```
------PDF: LEAD SPACINGS-------
-------------------------------

     Bin Width (m):   50.0

     Number of Bins:    372

|----|-------|----|-----------|

          LOWER

          BOUND
```

BIN	(m)	N	PROBABILITY
1	0.0	3	0.30000000
11	500.0	1	0.10000000
13	600.0	1	0.10000000
64	3150.0	1	0.10000000
85	4200.0	1	0.10000000
108	5350.0	1	0.10000000
115	5700.0	1	0.10000000
373	18600.0	1	0.10000000

Figure 15. Probability density function of distances between leads

The depth criterion used to define lead segments effectively excludes ice that has undergone significant deformation. Adjacent lead segments separated by short distances, although listed here as separate features, thus may be part of the same lead. In the absence of sound criteria with which to distinguish ridged ice within a lead from thick ice between two adjacent but separate leads unambiguously, we leave it to the user community to establish their own rules to be applied to the draft profiles and lead statistics for discriminating between these two cases.

Undeformed and Deformed Ice Undeformed ice is defined as a series of consecutive drafts, all of depth less than 5.0 m, that span a distance 10.0 m or greater in length over which the slope between adjacent drafts does not exceed 0.050; deformed ice is all ice that is not classified as undeformed on the basis of these criteria. Undeformed and deformed ice segments are listed in different tables of the same format. Parameters given include record numbers within the draft file at which segments begin and end, segment width, the mean of drafts within the segment, the mean of slopes between adjacent drafts within each segment, and the distance (spacing or separation) from the end of the previous segment to the start of the current segment (Fig. 16). Separate tables list pdfs of mean draft within undeformed and deformed ice segments (Fig. 17), distance between adjacent segments (Fig. 18), and segment lengths (Fig. 19). The bin width used for pdfs of mean draft is 0.5 m, for mean spacing pdfs is 50.0 m, and for segment length is 10.0 m.

--------------UNDEFORMED ICE SEGMENTS--------------

Criteria Used to Define Undeformed Ice Segments:

Maximum draft-to-draft slope: 0.050

Maximum ice draft: 5.0 m

Minimum segment length: 10.0 m

RECORD NUMBER (STRT)	(END)	SEGMENT LENGTH (m)	MEAN DRAFT (m)	MEAN SLOPE	DISTANCE TO PREVIOUS SEGMENT (m)
878	892	14.01	2.28	0.0043	0.00
1666	1677	11.01	1.97	0.0082	773.98

PDF: UNDEFORMED ICE MEAN DRAFT

Bin Width (m): 0.5

1746	1757	11.01	2.09	0.0082	68.95
3198	3208	10.01	2.07	0.0110	1441.47
3414	3424	10.01	1.20	0.0090	205.94
3442	3456	14.01	0.09	0.0071	18.01
3473	3491	18.01	0.05	0.0089	17.01
3658	3675	17.01	2.01	0.0106	167.02
3678	3692	14.01	1.97	0.0093	3.00
3712	3730	18.01	1.85	0.0067	19.90
4151	4164	13.01	1.51	0.0108	420.99
4782	4798	16.01	2.17	0.0113	618.04
5269	5281	12.01	1.89	0.0092	472.92
6873	6897	24.02	2.07	0.0067	1592.02
7657	7670	12.90	2.14	0.0094	760.58
8088	8102	13.90	1.95	0.0101	418.09
8658	8669	11.01	1.12	0.0091	556.09
9214	9292	77.95	0.00	0.0022	544.97

.
.
.
.
.

Figure 16. List of undeformed ice segments (List of deformed ice segments given in identical format)

Number of Bins: 4

BIN	LOWER BOUND (m)	N	PROBABILITY
1	0.0	7	0.09459459
2	0.5	2	0.02702703
3	1.0	4	0.05405405
4	1.5	35	0.47297297
5	2.0	26	0.35135135

Figure 17. Probability density function of mean draft within undeformed ice segments

PDF: UNDEFORMED ICE SEGMENT SPACINGS

Bin Width (m): 50.0

Number of Bins: 108

BIN	LOWER BOUND (m)	N	PROBABILITY
1	0.0	14	0.18918919
2	50.0	9	0.12162162
3	100.0	2	0.02702703
4	150.0	3	0.04054054

5	200.0	7	0.09459459
6	250.0	2	0.02702703
7	300.0	1	0.01351351
9	400.0	5	0.06756757
10	450.0	3	0.04054054
11	500.0	1	0.01351351
12	550.0	2	0.02702703
13	600.0	1	0.01351351
15	700.0	2	0.02702703
16	750.0	2	0.02702703
17	800.0	1	0.01351351
18	850.0	1	0.01351351
21	1000.0	2	0.02702703
23	1100.0	1	0.01351351
26	1250.0	2	0.02702703
27	1300.0	1	0.01351351
29	1400.0	3	0.04054054
32	1550.0	1	0.01351351
35	1700.0	1	0.01351351
38	1850.0	1	0.01351351
39	1900.0	1	0.01351351
41	2000.0	1	0.01351351
45	2200.0	1	0.01351351
46	2250.0	1	0.01351351
53	2600.0	1	0.01351351
109	5400.0	1	0.01351351

Figure 18. Probability density function of distance between adjacent undeformed ice segments

PDF: UNDEFORMED ICE SEGMENT WIDTHS

Bin Width (m): 10.0

Number of Bins: 7

BIN	LOWER BOUND (m)	N	PROBABILITY
2	10.0	69	0.93243243
3	20.0	2	0.02702703
4	30.0	2	0.02702703
8	70.0	1	0.01351351

Figure 19. Probability density function of the width of undeformed ice segments

Note on Data Intervals and Segment Length

The following information was added to the documentation on 21 August 2003. It was provided by D. Eppler, Bronson Hills Associates, on 27 September 1999 in response to a user's question regarding why the track distance based on track endpoints is sometimes less or greater than would be expected based on number of meter-spaced data values in that segment. The text provided by D. Eppler was edited slightly by F. Fetterer:

> There are three possible explanations for why the track distance based on track endpoints is sometimes less or greater than would be expected based on number of meter-spaced data values in that segment. Two of the explanations arise from certain aspects of these data that cannot be changed. The third explanation involves errors we may have introduced by failing to detect turns in what we otherwise thought were long straight-line course segments.
>
> 1. Rounding Error: We create the profiles using an algorithm that converts time and speed in the raw data

set to distance, which in turn allows us to apply a cubic spline technique to interpolate a series of equally spaced points (drafts) that are located 1.0 m apart. This entails a series of non-trivial calculations involving trig functions, square roots, and other library functions that introduce rounding errors. The nominal spacing between adjacent drafts thus is 1.0 m, but the actual spacing may be slightly greater than or less than this. I would expect that the sum of all errors over a long profile would approach 0.0 m, but this might not be the case. If, for example, the error tends to be negative more often than it is positive, the outcome would be a profile with more drafts in it than you would otherwise expect if the spacing was exactly 1.0 m between consecutive drafts. I do not think that the this type of imprecision in the exact location of a draft will have significant impact on most end-users of the data set, especially where the user is interested in summary statistics calculated for all drafts in an entire segment.

2. Navigation Uncertainty: We determine the location of drafts in the profile using a set of tie points taken from navigation logs provided to us by the Arctic Submarine Laboratory. At best, these points are recorded 30 minutes apart, but in some cases the time gap between successive points is on the order of an hour or more. That is to say that in the ideal case, we know exactly where the boat was twice in an hour; but we really don't know with certainty where the boat was in between successive navigation tie points. In the absence of conflicting information (from navigation notes, bearing or information recorded in the raw profile data set) we assume the course taken is a straight line between the successive tie points. As a check on this we look at the ship's heading that is recorded in the raw profile data provided us. If we see a course change, we break off the current straight-line segment and begin a new one after the turn ends. Recognize, however, that even a straight-line course typically deviates a bit--plus or minus two or three degrees from a mean heading is typical. Barring deviations greater that this we assume that a straight course is followed.

The straight line course between navigation points is of course the shortest distance between them. Given that we know the actual course is not perfectly straight, it is likely that many profiles will have more points in them than would be expected if the nominal spacing is absolutely constant at 1.0 m. A 50 km segment thus may in fact end up with slightly more than 50,000 drafts because, in reality, the boat sailed a distance further than 50 km to get to the next tie point.

3. We erred in creating the segments: Occasionally we err when we put together a segment by including data taken while the boat was turning. Abrupt, tight 360 degree turns where the boat changes course, circles, and then comes back immediately to it's previous course heading are common in some of the cruises. If we miss such momentary excursions from a straight line course, this leads to segments in which there are many more points than there should be for the distance supposedly traveled. We believe we removed most if not all of these bad segments, but some may have been overlooked.

5. Data Access and Related Collections

Data Access

Data are available via FTP.

Related NSIDC Data Collections

- AWI Moored ULS Data, Weddell Sea (1990-1998)
- AWI Moored ULS Data, Greenland Sea and Fram Strait, 1991-2002
- See Moored Upward Looking Sonar Data
- The Environmental Working Group (EWG) Joint U.S.-Russian Arctic Sea Ice Atlas also contains formerly classified ULS data collected by U.S. Navy submarines from 1977 to 1993. Ice draft profiles and statistics, including probability density and cumulative distribution functions, are provided for over 200 individual track segments. Note that submarine cruise data in the EWG data set and in this data set were processed differently; ice draft profiles and statistics from the same cruise may differ in the two data sets. The EWG data were processed at the University of Washington Applied Physics Laboratory (APL) using APL software modified in 1994 by the addition of two routines (BSQTIME3 and BSQSPAC2) from Bronson Hills Associates (BHA) -- hereafter referred to as the APL software. The Submarine Upward Looking Sonar Ice Draft Profile Data and Statistics data were processed at CRREL using a suite of all-BHA software. APL software processing is nearly automatic, while BHA processing requires extensive interactive analysis. BHA allows data viewing, but it can potentially recover up to 30% more ice draft profiles. The Environmental Research Institute of Michigan (developers of the EWG data set) and Bronson Hills Associates compared the two processing methods at APL using SCICEX-93 ice draft data collected on September 4, 6, and 11 in the eastern Chukchi Sea, Beaufort Sea, and the North Pole regions. Results were as follows:

Segment length: Differences were always less than 6 m and most were less than 3 m. APL and BHA routines were consistent with respect to distances calculated from the raw top sounder data records.

Ice draft statistics: The mean and standard deviation compared well, but values of RMS draft departed significantly because the two software packages used different formulae for the RMS calculation.

Keel location: APL software selects more keels than the BHA software. Most discrepancies appear to arise from keel picks associated with broad keels characterized by multiple closely spaced peaks. APL software identifies these as separate keels and the BHA software a single keel.

Keel statistics: The APL software consistently provided mean keel drafts that exceeded the BHA values by 2.0 to 2.5 m. Standard deviations were consistent. This difference is thought to have occurred from the slightly different application of the Rayleigh criterion used for keel detection and APL interpolation methods (Fred Tanis, ERIM International, Yanling Yu, University of Washington, and Dennis Farmer, Bronson Hills Associates, provided this information.).

Other Related Collections

Mooring data from the Beaufort Gyre Exploration Project

6. References and Related Publications

References

Press, W.H., S.A. Teukolsky, W.T. Vetterling, and B.P. Flannery, 1992. Numerical recipes in C: the art of scientific computing. Cambridge University Press, 994.

Rothrock, D. A. and M. Wensnahan, 2006. The Accuracy of Sea-Ice Drafts Measured from U.S. Navy Submarines, J. Ocean. and Atmos. Tech., Submitted

Wadhams, P., and R.J. Horne, 1980. An analysis of ice profiles obtained by submarine in the Beaufort Sea, J. Glaciol., 25, 401-424.

Wadhams, P., 1984. Arctic sea ice morphology and its measurement, Arctic Technology and Policy, I. Dyer and C. Chryssostomidis, eds., Washington, D.C., Hemisphere Publishing Corp., 179-195.

Wensnahan, M., and D. A. Rothrock, 2005. Sea-ice draft from submarine-based sonar: Establishing a consistent record from analog and digitally recorded data, Geophys. Res. Lett., 32, L11502, doi:10:1029/2005GL022507.

Related Publications

(This short bibliography of upward looking sonar references was compiled in 2000 and has not been substantially added to since then.)

Ackley, S.F., W.D. Hibler III, F.K. Kugzruk, A. Kovacs, and W.F. Weeks, 1976. Thickness and roughness variations of Arctic multiyear sea ice, CRREL Report 76-18, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 25 pp.

Alam, A., 2000. Surface turbulent fluxes over arctic leads. Ph.D. Thesis, University of Colorado, 234 pp.

Alam A., J.A. Curry, and M.A. Tschudi, 2001. A parameterization of the lead-width distribution and turbulent surface heat flux for arctic sea ice, J. Geophys. Res., in press, (SHEBA special issue).

Bourke, R. and C. Garrett, 1987. Sea ice thickness distribution in the Arctic Ocean, Cold Reg. Sci. and Technol. 13, 259-280.

Bourke, R.H., and R.G. Paquette, 1989. Estimating the thickness of sea ice, *J. Geophys. Res*. 94, 919-923.

Bourke, R.H. and A.S. McLaren, 1992. Contour mapping of Arctic Basin ice draft and roughness parameters. *J. Geophys. Res*. 97, 17,715-17,728.

Comiso, J.C., P. Wadhams, W.B. Krabill, R.N. Swift, J.P. Crawford, and W.B.T. III, 1991. Top/bottom multisensor remote sensing of arctic sea ice, *J. Geophys. Res.*, 96 (C2), 2693-2709.

Davis, N. R. and P. Wadhams, 1995. A statistical analysis of arctic pressure ridge morphology, *J. Geophys. Res.*, 100, C6 10915-10925.

Drucker, R., S. Martin, and R. Moritz. 2003. Observations of ice thickness and frazil ice in the St. Lawrence Island polynya from satellite imagery, upward looking sonar, and salinity/temperature moorings. *J. Geophys. Res.*, 108: C5, 3149, doi:10.1029/2001JC001213.

Kerman, B., P. Wadhams, D. Norman, J. Comiso, 1999. Informational equivalence between synthetic aperture radar imagery and the thickness of Arctic pack ice. J. Geophys. Res. 104 29,721-29,731.

Kvambekk, A.S., and T. Vinje, 1992. Upward looking sonar ice draft series from the Greenland Sea. In Report of the Sea Ice Thickness Workshop (A.S. Thorndike, C. Parkinson, and D.A. Rothrock, eds.), Polar Science Center, University of Washington, Seattle, WA, B25-B28.

LeShack, L.A., W.D. Hibler III, and F.H. Morse, 1971. Automatic processing of Arctic pack ice data obtained by means of submarine sonar and other remote sensing techniques, in Propagation Limitations in Remote Sensing, (J.B. Lomax, ed.), AGARD Conference Proceedings No. 90, NATO Advisory Group for Aerospace Research and Development.

Lyon, W.K., 1984. Submarine exploration of the North Pole region; history problems, positioning and piloting, J. of Navigation, 37 (2), 155-179.

McLaren, A.S., P. Wadhams, and R. Weintraub, 1984. The sea ice topography of M'Clure Strait in winter and summer of 1960 from submarine profiles, Arctic, 37, 110-120.

McLaren, A.S., 1988. Analysis of the under-ice topography in the arctic basin as recorded by the USS Nautilus during August 1958, Arctic, 41 (2), 117-126.

McLaren, A.S., 1989. The under-ice thickness of the Arctic Basin as recorded in 1958 and 1970, J. Geophys. Res., 94, 4971-4983.

McLaren, A.S., R.G. Barry, and R.H. Bourke, 1990. Could Arctic ice be thinning? Nature, 345, 762.

McLaren, A.S., J.E. Walsh, R.H. Bourke, R.L. Weaver, and W. Wittmann, 1992. Variability in sea-ice thickness over the North Pole from 1977 to 1990, Nature, 358, 224-226.

McLaren, A.S., R.H. Bourke, J.E. Walsh, and R.L. Weaver, 1994. Variability in Sea-Ice Thickness Over the North Pole From 1958 to 1992, in The Polar Oceans and Their Role in Shaping the Global Environment, pp. 363-371, The American Geophysical Union.

Melling, H., and D.A. Riedel, 1996. Development of seasonal pack ice in the Beaufort Sea during the winter of 1991-1992: A view from below, J. Geophys. Res., 101, no. C5, , 11,975-11,991.

Moritz, R.E., 1992. Sampling the temporal variability of sea ice draft distribution, In Report of the Sea Ice Thickness Workshop (A.S. Thorndike, C. Parkinson, and D.A. Rothrock, eds.), Polar Science Center, University of Washington, Seattle, WA, B29-B38.

Rothrock, D.A., Y. Yu and G.A. Maykut, 1999. Thinning of the Arctic Sea-Ice Cover Geophys. Res. Let., 26, no. 23, 3469.

Rothrock, D.A., J. Zhang, and Y. Yu. 2003. The arctic ice thickness anomaly of the 1990s: A sonsistent view from observations and models. J. Geophys. Res. 108(C3): 3083. doi:10.1029/2001JC001208.

Thorndike, A.S., C. Parkinson, and D.A. Rothrock (eds.), 1992. Report of the Sea Ice Thickness Workshop, Polar Science Center, University of Washington, Seattle, WA, 41pp + App.

Tucker, W.B. III, and W.D. Hibler III, 1986. Variability of Arctic sea ice drafts, In Proc. of Second Workshop on Ice Penetration Technology, CRREL Special Rpt. 86-30, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 237-256.

Tucker, W., R. Anderson, J. Newton, C. Wales, G. Newton, and T. Luallin, 1992. Accuracy of submarine ice draft measurements. In Report of the Sea Ice Thickness Workshop (A.S. Thorndike, C. Parkinson, and D.A. Rothrock, eds.), Polar Science Center, University of Washington, Seattle, WA, B22-B24.

Tucker, W.B. III, J.W. Weatherly, D.T. Eppler, D. Farmer and D.L. Bentley, 2001. Evidence for the rapid thinning of sea ice in the western Arctic Ocean at the end of the 1980s, Geophys. Res. Let., 28, no. 14, 2851-2854.

Wadhams, P., and R.J. Horne, 1980. An analysis of ice profiles obtained by submarine in the Beaufort Sea, J. Glaciol., 25, 401-424.

Wadhams, P., 1981. Sea-ice topography of the Arctic Ocean in the region 70°W to 25°E, Philos. Trans. R. Soc. London, Ser. A, 302, 45-85.

Wadhams, P., 1984. Arctic sea ice morphology and its measurement, In Arctic Technology and Policy (I.Dyer and C. Chryssostomidis, eds.) Washington, DC, Hemisphere Publishing Corp., 179-195.

Wadhams, P., A.S. McLaren, and R. Weintraub, 1985. Ice thickness distribution in Davis Strait from submarine profiles, J. Geophys. Res., 90, 1069-1077.

Wadhams, P., and T. Davy, 1986. On the spacing and draught distributions for pressure ridge keels, J. Geophys. Res., 91, 10,697-10,708.

Wadhams, P., 1990. Evidence for thinning of the Arctic ice cover north of Greenland, Nature, 345, 795-797.

Wadhams, P., N. R. Davis, J. C. Comiso, R. Kutz, J. Crawford, G. Jackson, W. Krabill, C. B. Sear, R. Swift and W. B. Tucker, 1991. Concurrent remote sensing of arctic sea ice from submarine & aircraft. Intnl. J. Remote Sensing, 12, 9, 1829-1840.

Wadhams, P., 1992. Sea ice thickness distribution in the Greenland Sea and Eurasian Basin, May 1987, J. Geophys. Res., 97, 5331-5348.

Wadhams, P., W.B. Tucker III, W.B. Krabill, R.N. Swift, J.C. Comiso, and N.R. Davis, 1992. Relationship between sea ice freeboard and draft in the Arctic Basin and implications for ice thickness monitoring, J. Geophys. Res. 97, 20,325-20,334.

Wadhams, P. and N. R. Davis, 1994. The fractal properties of the underside of sea ice. In Marine, Offshore and Ice Technology (Murthy, Wilson and Wadhams, eds.), 353-363. Fifth International Conference on Computer Aided Design, Manufacture and Operation in the marine and Offshore Industries, Incorporating the Fourth Ice Technology Workshop. Computational Mechanics Publications, Southampton & Boston.

Wadhams, P., 1995. Arctic sea ice extent and thickness. Phil. Trans. R. Soc. Lond. A 352, 301-319.

Wadhams, P., 1997. Ice thickness in the Arctic Ocean: the statistical reliability of experimental data. J. Geophys. Res. 102, 27,951-27,959.

Wadhams, P., and N.R. Davis, 2000. Further evidence of ice thinning in the Arctic Ocean. Geophysical Research Letters 27 (24): 3973-3975.

Wadhams, P., and R. J. Horne. 1978. *An analysis of ice profiles obtained by submarine sonar in the AIDJEX area of the Beafort Sea.* Scott Polar Research Institute Technical Report 78-1. Cambridge: SPRI.

Walsh, J.E., R.S. Weaver, R. Colony, A.S. McLaren, and R.H. Bourke, 1995. Correlation of ice thickness variability to atmospheric circulation over the North Pole 1958-1992. In Proc. of Fourth Conf. on Polar Meteorol. and Oceanography 15-20 Jan. 1995, Dallas, TX, Am. Met. Soc. 156-161.

Wesnahan, W., D. Rothrock, and P. Hezel. 2007. New Arctic sea ice draft data from submarines. *EOS* 88: 5, 55-56.

Williams, E., C. Swithinbank, and G. de Q. Robin, 1975. A submarine study of Arctic pack ice,. Glaciol., 73, 349-362.

Williams, M.D., 1998. Submarines under ice: the U.S. Navy's polar operations. Naval Institute Press, Annapolis, MD, xii, 223.

Winsor, P., 2001. Arctic sea ice thickness remained constant during the 1990s. Geophysical Research Letters 28 (6): 1039-1041.

7. Ackowledgements

The National Science Foundation Office of Polar Programs project "Analysis of Arctic Ice Draft Profiles Obtained by Submarines," W. B. Tucker III and S. F. Ackley, principal investigators, supported preparation of data for those cruises identified in Table 1 as provided to NSIDC by Tucker or Eppler. The upward looking sonar data were interpolated and processed for release as unclassified data at the U.S. Army's Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. The U.S. Navy's Arctic Submarine Laboratory (ASL) provided the original data to CRREL. ASL approved declassification on behalf of the Chief of Naval Operations. Software and processing algorithms for these data were developed by D. Eppler and D. Farmer of Bronson Hills Associates, Hanover, NH. Bronson Hills Associates also provided technical documentation.

Preparation of the U.K. data (identified in Table 1 as provided to NSIDC by Davis) was funded by a subcontract under the same National Science Foundation Office of Polar Programs project "Analysis of Arctic Ice Draft Profiles Obtained by Submarines." The data were processed by the Scott Polar Research Institute, University of Cambridge, with the cooperation of the Royal Navy and the U.K. Hydrographic Office. N.R Davis and P. Wadhams were involved in the production of the U.K. data. SCICEX-97 and SCICEX-98 data were provided by D.A. Rothrock and Y. Yu with the support of National Science Foundation (OPP-9617343). These are identified in Table 1 as provided by Yu. The original data were provided by the U.S. Navy's Arctic Submarine Laboratory and were subsequently processed at the Polar Science Center, Applied Physics Laboratory, University of Washington. The software and processing algorithms were provided by B. Markham of ASL and by Bronson Hills Associates, making the data compatible with other submarine data archived previously by NSIDC. SCICEX-99 data were delivered to NSIDC by T. Tucker, and were processed by Bronson Hills Associates (D. Farmer) through the support of the Applied Physics Laboratory, University of Washington, and NSF grant OPP-9910331.

The U.S. analog data were processed at the Polar Science Center at the University of Washington and provided with documentation by M. Wensnahan and D. A. Rothrock (identified in Table 1 as provided to NSIDC by Wensnahan). These data were prepared with funding from NSF Office of Polar Programs grant OPP-9910331.

Researchers making use of these invaluable data owe a debt of gratitude to the present and past staff of the Arctic Submarine Laboratory, San Diego, California, for their long-term stewardship of the data. Without guidance from ASL, and in particular without the collaboration of D. Bentley, J. Gossett, and T. Luallin release of these data to the scientific community would not be possible. The Arctic Submarine Laboratory holds raw data from all U.S. submarine cruises beginning with the first cruise under the ice in 1958.

This data set is maintained at NSIDC with support from the NOAA NESDIS National Geophysical Data Center.

8. Document Information

Document Authors

This documentation was originally drafted by NSIDC’s M. Marquis, based on information and incorporating written documentation provided by D. Eppler, Bronson Hills Associates. Supplementary documentation (information linked in the documentation) was provided by Y. Yu and S.Dickinson (Processing of the SCICEX '98 Submarine Data, on 14 May 2002), by W. Tucker and S. Ackley, (Analysis of Arctic Ice Draft Profiles Obtained by Submarines on 6 July 1998) and by M. Wensnahan (Documentation for G01360 Analog Portion, 17 July 2006).

Document Creation Date

24 July 1998

Document Revision Date

The documentation was minimally revised as data from several additional cruises were provided by CRREL and the Polar Science Center after the initial 1998 release. In 2006, NSIDC’s F. Fetterer extensively edited and reformatted the documentation. This revision to the documentation coincided with the addition of the analog portion of cruise data. L. Ballagh fixed three broken links in Table 1 in Feb. 2007. L. Ballagh added new submarine track images created by B. Raup in April 2008.

Document URL

http://nsidc.org/data/docs/noaa/g01360_upward_looking_sonar/index.html