DRAFT AND MOVEMENT OF PACK ICE IN THE BEAUFORT SEA: A TIME-SERIES PRESENTATION
APRIL 1990 – AUGUST 1999

H. Melling and D. A. Riedel

Science Branch - Pacific Region
Institute of Ocean Sciences
P.O. Box 6000, Sidney, BC
Canada   V8L 4B2

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H. Melling and D. A. Riedel

Fisheries and Oceans Canada
Institute of Ocean Sciences
9860 West Saanich Road
Sidney BC V8L 4B2
E-mail: MellingH@dfo-mpo.gc.ca

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ABSTRACT

Melling, H. and Riedel, D.A.. 2004. **Draft and Movement of Pack Ice in the Beaufort Sea: A Time-Series Presentation April 1990 – August 1999**. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 238. v + 24 p.

A long-term study of the movement and draft of sea ice over the continental shelf of the eastern Beaufort Sea was initiated in April 1990 and continues at present. The objectives are to: (1) determine the character and recurrence of ice features hazardous to the offshore industrial activity, specifically the exploitation of hydrocarbon reserves and (2) determine the impact of climate variability and change on the Beaufort Sea ice regime. Observations are made using two types of self-contained sonar moored near the seafloor. A four-beam Doppler sonar measures the velocity of ice drift and a narrow-beam ice-profiling sonar measures its draft. Ten sites on the Mackenzie and Banks Island shelves have been instrumented to meet various objectives during this period. However, long time series have been maintained at only three locations, namely the middle shelf and shelf edge north of the Mackenzie delta and the shelf edge to the north-west of Amundsen Gulf. In a typical year, pack ice covers the sites except in late summer. Approximately 2000 km of pack ice are surveyed annually by each installation.

This report provides:

1) Documentation of the mooring sites and periods of observation
2) Documentation of the sonar characteristics and operating parameters
3) Description of the procedures for data processing
4) Description of the procedures for data calibration
5) Time series of ice draft sub-sampled to approximately 4-minute intervals to meet international archival standards
6) Monthly statistical measures of ice draft derived from these time series – histogram, mean, standard deviation, 20-percentile, 80-percentile

Key words: Arctic, Beaufort, sea ice, draft, drift, sonar, climate.

RÉSUMÉ

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Une étude à long terme du mouvement et du tirant d’eau de la banquise sur le plateau continental à l’est de la Mer de Beaufort a été initié en avril 1990 et continue présentement. Les objectifs sont de: (1) déterminer le caractère et la réapparition des caractéristiques de glaces qui peuvent causer un risque aux activités côtières industrielles, plus précisément l’exploitation des réserves d’hydrocarbones et (2) déterminer l’impact de variations et de changements climatique sur le régime de glace de la Mer de Beaufort. Des observations ont étés effectués en utilisant deux types de sonar indépendants amarrés au fond de la mer. Un sonar à quatre faisceaux mesure la vélocité de la dérive de glace tandis qu’un sonar de profile de glace à faisceaux mince mesure le tirant d’eau de la glace. Dix sites sur les plateaux des îles Mackenzie et Banks ont subit l’emplacement d’instruments pour atteindre plusieurs objectifs durant cette période. Cependant, de longues séries temporelles de données ont été maintenues seulement à trois endroits; au milieu et à la bordure nord du plateau continental du Delta du Mackenzie, et la bordure nord-ouest du plateau du Golfe d’Amundsen. En une année typique, la glace pack couvre ces sites exceptés à la fin de l’été. À peu près 2000 Km de glace pack est surveillés à chaque année par chaque installation.

Ce rapport fournit :

1) La documentation des sites amarrés et les périodes d’observation
2) La documentation des caractéristiques des sonars et les paramètres d’opération
3) La description des procédures de traitement de données
4) La description des procédures de calibration de données
5) Les séries temporelles de données du tirant d’eau de la glace, échantillonnées aux intervalles d’environ 4 minutes pour conformer au standard international d’archive
6) Les statistiques de mesure mensuelle du tirant d’eau de la glace provenant des séries temporelles de données – histogramme, moyenne, écart-type, percentile 20, percentile 80

Mot clés : Arctique, Mer de Beaufort, banquise, tirant d’eau de la glace, dérive de la glace, sonar, climat

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INTRODUCTION

Sea ice grows in vast featureless sheets of uniform thickness if not disturbed by wind and current. An equilibrium thickness is attained when the heat conducted up through the ice from the ocean is adequate to balance the energy loss at the atmospheric interface. As this budget varies seasonally, so does the equilibrium thickness. Calculations show that the annually averaged thickness of Arctic sea ice, when subject only to thermodynamic forcing, is about 3 m (Maykut and Untersteiner, 1971).

The constant movement of sea ice in response to winds and currents generates stresses which cause ice sheets to break apart into floes separated by leads of open water. Under cold conditions these leads develop a new cover of thinner ice. Where moving floes collide, ice is broken into fragments and piled into sinuous mounds called ridges. By these processes, the ice pack is quickly deformed into a rough and geometrically complex ‘landscape’ both above and below the sea surface. In the southern Beaufort Sea in late winter, first-year sea ice typically ranges in thickness from zero to about 2 metres. However, ridges accumulate to very much greater total thickness. The deepest free-floating ridge keel recorded to date extended to almost 50 m depth (Kovacs *et al.*, 1973).

The geometrical properties of an ice field may be summarized by a number of statistical parameters. For thickness, these include the mean, the standard deviation and the probability density $g(h)$ (Thorndike *et al.*, 1975). These parameters are best calculated over a region for which the area R is large relative to the area of recognizable features in the pack. The size of R is not well defined, but in the Arctic Ocean might reasonably be 50-100 km across. If $dA(h, h+dh)$ is the area within R covered by ice having thickness in the range $(h, h+dh)$, then:

$$g(h)\,dh = \frac{1}{R}\,dA(h, h+dh),$$

where $g(h)$ includes open water area as ice of zero thickness. The mean ice thickness is given by the first moment of $g(h)$:

$$\overline{h} = \int_0^\infty h \cdot g(h)dh.$$

In general, $g(h)$ will be a function of both space and time.

Sonar operated from underwater ships or from moorings can presently provide only measurements related to ice thickness along a line. In the context of such observations, the definition of $g(h)$ should be modified by replacing R with L, where L is a distance, which again is not well defined but again probably of order 50-100 km.

In most studies that have used moored sonar, statistical parameters have been calculated from observations spaced regularly in time, not distributed uniformly along a line or over an area. The distribution in space of regularly timed observations is a set of points at varying (including zero) separations along a meandering survey line dictated by the varying speed and direction of ice drift.

Modified definitions are used for time-series statistics. The statistical parameters are defined over an interval T which is long relative to the time required for recognizable features in the pack to pass over the mooring. The value of T is not well defined, but in the Arctic Ocean might range between 3 and 30 days. If $d\tau(h, h+dh)$ is the interval during T when the instrument is covered by ice having thickness in the range $(h, h+dh)$, then:

$$g_T(h)\,dh = \frac{1}{T}\,d\tau(h, h+dh),$$

where $g_T(h)$ includes open water area as ice of zero thickness. The mean ice thickness is given by the first moment of $g_T(h)$:

$$\overline{h_T} = \int_0^{\infty} h \cdot g_T(h)\,dh.$$

In general, $g_T(h)$ will be a function of both space and time. In general, $g_T(h) \neq g(h)$.

Over time, the thermodynamic processes of freezing and melting tend to narrow $g_T(h)$ to a small band of ice thicknesses about the equilibrium for the region. Conversely, the dynamic processes of lead opening and ridging broaden the function by creating open water (zero ice thickness) at one end of its range and by creating thick ridged ice at the other.

Data acquired by upward-looking sonar mounted on nuclear submarines have been used since the late 1950s to observe the draft and ridging of pack ice in the basins of the Arctic Ocean (Bourke and Garrett, 1987). However, there are few observations from this era over the shallow Arctic continental shelves.

Moored, self-contained, upward-looking sonar are ideal for measurement of sea-ice draft in shallow seas. Observations are acquired at a fixed location, but the natural movement of the pack brings new ice into the sonar’s field of view. In the southern Beaufort Sea, approximately 2000 kilometres of ice can be profiled annually in this way. Observations of this type were first acquired by prototype instruments in the late 1970's and early 1980's, in the Beaufort Sea (Hudson, 1990; Pilkington and Wright, 1991). Observations made with second-generation instruments have been presented in earlier reports (Melling and Riedel, 1993, 1994), but are also incorporated in this archive.

OBSERVATIONAL PROGRAMME

The study is focused in the eastern Beaufort Sea. Its initial motivation was the acquisition of a statistical description of pack ice in the area, particularly in relation to features of extreme draft (ridge keels) and their rate of drift. From 1976 to 1987 there was very active exploration for oil within the zone of drifting pack ice. Since 2001 there has been a resurgence of interest in exploration, with emphasis this time on natural gas within the zone of land-fast ice.

Pressure ridges are the most severe commonplace ice hazard to offshore structures and shipping. Icebreaking ships and drilling platforms typically reach their design limits when transiting ice ridges. Grounded ridges gouge deeply into the seabed in the Beaufort Sea, thereby threatening sub-sea well completions and pipelines. Accurate data are needed for the cost-effective and safe design of the offshore infrastructure (surface piercing platforms, seabed installations, sub-sea pipelines, icebreaking ships, environmental constraints on operations, etc.).

In the early 1990s, the Frozen Sea Research Group at the DFO Institute of Ocean Sciences deployed sonar at locations within and just north of potential areas for hydrocarbon production: DFO sites 1 and 2 are at the middle shelf and shelf edge in the Kugmallit sea valley and span the transition zone between seasonal and perennial ice. Unfortunately perennial ice, of special interest as the most severe hazard to offshore structures, was not observed frequently at these locations. To acquire better data on hazard from old ice, instruments were installed at progressively greater distances to the north-east, at site 4 in 1991, site 5 in 1996 and site 6 in 1997. The locations chosen embody a compromise between the scientific objective to observe old ice and the practical constraints imposed by such ice on the practicality of deploying and recovering sub-sea moorings.

Unfortunately, too much old ice at sites 5 and 6 seriously hindered the retrieval of instruments deployed there in the second half of the 1990s. In an effort to avoid unacceptably high concentrations of old ice, these moorings were moved southward to sites 8 and 7 in 1998. Site 7 was discontinued in 1999 because of difficulty in access. Operations at site 8 by the *CCGS Sir Wilfrid Laurier* were seriously hindered by ice in 1999, 2001 and 2003 and completely blocked in 2002.

Site 9, in waters south of site 1 that are generally ice-free in summer, was activated in 2001 for the trial deployment of a sonar prototype designed to measure both ice and storm waves. This instrument was moved north-eastward to site 10 in 2003.

Map of mooring sites: IPS_mooring_sites_Beaufort.jpg

Figure 1. Locations of ice sonar moorings in the Beaufort Sea, 1990-2003.

Initially, while instruments were under evaluation, moorings were deployed in April using aircraft-based techniques from the ice surface (Moorhouse and Melling, 1987) and recovered and redeployed using conventional techniques from icebreaking ships in September. Deployments were approximately 6 months in duration. Following detection and correction of faults in the early versions of the instruments and their operating controls, we were confident in doubling the duration of deployments to 12 months, April to April.

Aircraft used to support oceanographic mooring, Beaufort Sea in April: Twin & helo with rafting.jpg

Figure 2. Aircraft used to support the recovery of sonar moorings through the pack ice of the Beaufort Sea in April.

Melting an access hole through first-year ice: Hole melting.jpg

Figure 3. An access hole 1.1-m in diameter is melted through the ice to retrieve instruments now floating beneath it.

Retrieval of an ADCP mooring through ice: ADCP mooring on ice.jpg or Mooring retrieved.jpg

Figure 4. An ADCP breaks the surface in the final stage of a through-ice mooring recovery.

Retrieval of an IPS3 mooring through ice: IPS3, with the crew, at a through-ice recovery.jpg

Figure 5. The surfacing of an IPS mooring through first-year ice is celebrated by the recovery team.

The expense and difficulty of maintaining moored instruments in ice-covered seas are unremitting motivators for innovation. By 1996, we had re-engineered our sonar to operate for two years and our transponding releases for three, so that deployments of 24-month duration were practical. The first long deployment was at site 5 (1996-1998). Since 1999, the difficult sites 2 and 8 have been on a 24-month rotation.

The deterioration of governmental logistic support for wintertime science in the North required discontinuation of aircraft-based operations after the 1996 field season. Although wintertime work is physically demanding, success in the deployment and recovery of moorings through the ice is more predictable, since the ice is used for the operations rather a hindrance to them. In summer, ice can be a significant impediment to the progress of even an icebreaking ship, and a significant challenge to the recovery of moorings under summertime conditions (melt ponds, thaw holes, open leads, etc.). Heavy ice has prevented ship-based operations at one or more sites of this programme in five (1991, 1997, 1999, 2001, 2002) of the ten summers (1990-1992, 1997-2003) when icebreakers were in used.

CCGS Sir Wilfrid Laurier, an ice-breaking buoy tender: SWL in a ridge.JPG

Figure 6. CCGS Sir Wilfrid Laurier, an ice-breaking buoy tender, has provided effective support to the mooring programme since 1997.

This project has carried various names: Ice Subsurface Characterization (ISC) project, Ice Type and Thickness (ITT) project, Ice Thickness and Climate (ITC) project and Beaufort Marine Hazards (BMH) project. These names survive in the acronyms used to designate the sites of moorings over the years.

INSTRUMENTATION

MOORINGS

Typically an ice-profiling sonar (IPS) for the measurement of ice draft, and an acoustic Doppler current profiler (ADCP) for the measurement of ice motion have been moored at each site. Exceptions are the use of a WASP sonar instead of IPS for ice-draft observation at site 2 in 1991-92, and the deployment of IPS without ADCP at sites 9 and 10 during 2001-2004, where the primary emphasis was on the measurement of wind waves.

Table 1. History of sonar deployments at sites 1 and 2. Light type denotes failed deployments. Underlining denotes qualified success.

Table, mooring history, sites 1-2

Table 2. History of sonar deployments at sites 3-10. Light type denotes failed deployments. Underlining denotes qualified success

Table, mooring history, sites 3-10

Positions in all years of deployment were determined using the Global Positioning System (GPS). It is noted that the GPS was subject to 'selective availability' up until May 2000. In general, the positional uncertainty associated with 'selective availability' is about twice that (±15 m) associated with sideways drift of the mooring as it falls to the seabed following its release at the surface. Positions are reported in the NAD83 datum. Soundings were estimated from the National Resource Series Charts 26508 and 26602, and from unpublished field survey sheets of the Canadian Hydrographic Service.

The recovery of data from deployments has been less than 100% of expectation. There were several failed deployments in the early 1990s during the development and testing of the IPS. Other losses were attributable to logistic failures caused by ice. Fractional data recovery between April 1990 and September 2003 (13.5 years) has been 81% for IPS and 94% for ADCP.

Table 3. Summary of interruptions in the ice-draft time series, 1990-2003.

Table of time-series interruptions

Ice is absent for some time in summer at most of the sites and in most years. The lack of observations of pack ice at these times reflects natural seasonal cycles, not failure in the programme. Figures provide a schematic representation of the observations presently available from IPS and from the ADCP. The former figure indicates the periods of ice-free conditions at the mooring sites.

Data available from IPS

Figure 7. Schematic representation of the observations presently available from IPS. The periods of ice-free conditions at the mooring sites are also indicated.

Data available from ADCP

Figure 8. Schematic representation of the observations presently available from ADCP.

The deployment-history tables indicate the type of mooring used by code: '0' for an unconventional mooring, '1' for a stand-alone mooring for IPS, '2' for a stand-alone mooring for ADCP and '3' for a mooring supporting both IPS and ADCP.

The type '1' is a taut-line configuration, as short as practical to minimize hazard from drifting ice in shallow water (less than 40-m depth). Five plastic floats (Viny 12B3) support the in-water weights of the instrument and the acoustic transponding releases (4 floats are sufficient for the smaller 420-kHz IPS). Viny floats provide an excellent buoyancy-to-drag ratio; the drag of this float is only 6% of buoyancy with 0.5 m/s current. With this design, the IPS maintains a zenithal orientation within ±2° and moves vertically by less than two centimetres in such a current. The instrument is contained within a 316-stainless steel frame, which provides attachment points for other devices and grappling points for under-ice recoveries. The frame may be fitted with a low-frequency radio beacon (Pieps 457) and a pinger, both of which switch on only following release in response to lower ambient pressure. The deactivation of these beacons at working depth prevents interference with the sonar and conserves battery power over long deployments. The mooring is equipped with two transponding releases, connected in parallel for redundancy. The anchor weight is built from clumped chain, permitting the weight used to be no more than necessary. This economy is necessary when aircraft are used for transport to deployment sites. The mooring is assembled on the ice or deck and deployed anchor first by free-fall to the seabed.

Mooring for IPS

Figure 9. Schematic drawing of the type '1' mooring used for the ice-profiling sonar.

Type 1 mooring (IPS2) before deployment

Figure 10. A type '1' for IPS3 mooring is raised from the deck of the CCGS Henry Larsen in preparation for deployment.

The type '2' is very similar to type '1'. Four plastic floats are sufficient here, since the zenith-pointing constraints on the ADCP are much less severe than those for the IPS (±5° at 0.5 m/s current). The principal differences are a vane on the instrument frame and a swivel beneath it. By aligning with the flow, the vane reduces azimuthal oscillations of the instrument that are associated with vortex shedding. Azimuthal stability simplifies the correction of the time-averaged ADCP headings for compass non-linearity, since the necessary correction is well defined. This is not so if the ADCP rotates appreciably over the averaging interval. When moorings type '1' and type '2' have been used at a site, they have been placed no closer than the depth of water (50-80 m) to avoid acoustic cross-talk. In order that the two instruments view as closely as practical the same ice, the separation of moorings has rarely exceeded 250 m.

Mooring for ADCP

Figure 11. Schematic drawing of the type '2' mooring used for the acoustic Doppler current profiler.

Type 2 mooring (NB-ADCP) before deployment

Figure 12. A type '2' mooring for ADCP is raised from ice in preparation for deployment in winter.

The type '3' is essentially a mooring of type '1' connected above a mooring of type '2' by approximately 50 m of line. Since the IPS interferes with ADCP operation if too close (less than 30 m) this mooring can be used in water deeper than 80 m. More floatation is needed if the depth of water exceeds 120 m. The IPS, which produces the best data if close to the ice, is best positioned deeper than 40 m to avoid impact with drifting ridge keels. A heavier anchor is required for the type '3' mooring and deployment and recovery operations can be more complicated. The vertical stability of the IPS, which is important to the accurate calibration of ice draft, is degraded because the IPS may occasionally be pulled down as much as a metre by the stronger currents in this area. Vertical displacement of the sonar should be tracked by measuring pressure at more frequent intervals when using a type '3' mooring, perhaps every two minutes or less.

Mooring for IPS & ADCP

Figure 13. Schematic drawing of the type '3' mooring used jointly for IPS and ADCP sonar.

In a long-term study, consistency in the placement of moorings is desirable. The actual locations of moorings at nominal sites have varied over the years, subject chiefly to difficulties associated with ice at the time of deployment. Local maps display the relative locations of IPS moorings at sites 1, 2, 4 and 8.

site 1

Figure 14. Detailed map of the changing location of IPS at site 1, 1990-2003.

site 2

Figure 15. Detailed map of the changing location of IPS at site 2, 1990-2003.

site 4

Figure 16. Detailed map of the changing location of IPS at site 4, 1991-1995.

site 8

Figure 17. Detailed map of the changing location of IPS at site 8, 1998-2003

PROFILING SONAR FOR THE MEASUREMENT OF ICE DRAFT

The ice-profiling sonar (IPS) was developed at Institute of Ocean Sciences (Fisheries and Oceans Canada) to measure precise ranges to the ice-water interface (Melling *et al.*, 1992). The IPS is best positioned 30-100 m beneath the ocean surface, looking upward. It transmits an acoustic pulse of selectable duration, and then identifies the echo from the bottom of the ice. Through firmware within the IPS, the received signal is examined and that part of the echo returning from the bottom of sea ice, or from the sea surface in the absence of ice, is selected. The interval between transmission and receipt of this echo is the *travel time*. It is the main parameter measured and recorded internally in the IPS's EPROM memory. The IPS may be programmed to record also the maximum *amplitude* and the *persistence* of the selected echo.

The IPS contains sensors for measuring the tilt of the sonar beam from vertical on two orthogonal axes, total hydrostatic pressure and temperature and a real-time clock. The frequency of the recording of these auxiliary variables may be selected independently of the ping rate. The pitch and roll values allow the calculation of zenithal distance from echo range. The pressure sensor permits calculation of the actual depth of the IPS beneath (unseen) sea level, as the instrument's depth changes in response to storms, tides and mooring motions. Atmospheric pressure, which makes a varying contribution to total pressure, must be obtained by means of independent instrumentation at the surface. Temperature values are used in the calibration of pressure data and provide guidance in the calculation of target range from echo delay.

The IPS views a spot of approximately 1-m diameter at the surface. It relies on drift of the ice to bring new targets into the field of view for measurement. In this way, the sonar acquires data that allow calculation of a cross-section of pack-ice draft along a meandering path. If ice movement between pings is less than the field of view (1 m), then the cross-section will be over-sampled and some of the measurements redundant. If the movement is greater, then the ice profile will be under-sampled and small-scale features of the profile may be misinterpreted as features of larger scale (aliasing). Although high drift speeds are relatively rare, the IPS measures a large fraction of all the ice which it surveys when ice drift is rapid.

Table 4. Fraction of the observation time and of the drift path during which ice speed exceeds the specified value. Values are based on 12 months of ice-drift observation at 70° 20' N 133° 40' W in 1990-91.

Speed exceeds ...	**Fraction of Time**	**Fraction of Path**
Mean speed	30%	84%
0.20 m s^{-1}	14%	60%
0.24 m s^{-1}	10%	49%
0.30 m s^{-1}	8%	41%
0.40 m s^{-1}	4%	27%
Mean speed (m s^{-1})	0.08	
Maximum speed (m s^{-1})	0.99	

The IPS has five adjustable parameters that control identification of the ice-water interface.

Minimum Acceptable Range is the distance above the transducer within which the IPS will ignore all echoes. This parameter is useful for controlling the rejection of potentially large echoes from targets near the instrument.

Maximum Acceptable Range is the distance above the transducer beyond which the IPS will ignore all echoes. This parameter reduces sensitivity to reverberation from the seabed in shallow water.

Echo Start Amplitude is the amplitude that an echo must exceed before the IPS will start the Minimum Persistence check.

Echo Stop Amplitude is the amplitude below which an echo must drop, after that echo has exceeded the Echo Start Amplitude, before the end of that echo is identified. The Echo Stop Amplitude must always be less than Echo Start Amplitude.

Minimum Persistence is the minimum duration of the echo selected by Start and Stop Amplitude that will be permitted from a target. This parameter is useful for rejecting strong, short-lived echoes from small targets in the water column. The Minimum Persistence must exceed the length of the transmitted pulse.

Our current model of the ice-profiling sonar is model 4, developed in 1995 and first used in 1996. Model 1 never delivered useful data. Models 2 and 3 differed only in terms of data storage and fail-safe features in firmware. Model 4 is a version completely re-engineered to reduce energy demand, sensitivity to other targets and cost, and to increase reliability, operating flexibility, operating endurance and data storage. The pendulums used to measure pitch and roll by IPS2 and IPS3 were replaced with solid-state sensors, the operating frequency was increased from 200 kHz to 420 kHz and the data storage from 16 megabytes to 66 and ultimately 132 megabytes. IPS4 operates sequentially in up to eight unique configurations, activated on preset dates. This feature permits optimal use of battery and data capacity as ice conditions change throughout the year. IPS4 has also a burst mode, suited for brief high-resolution surveys or wave measurement.

The IPS4 has been licensed for manufacture and sale to ASL Environmental Sciences Inc of Sidney Canada (*http://www.aslenv.com/index.htm*).

The IPS3s used in the early years of the projects have been updated to IPS4s which operate at 200, not 420 kHz. New prototypes of the IPS4 have firmware switchable gain, to facilitate the measurement of surface waves during ice-free periods. A high-frequency (895 kHz) version of the wave sonar is presently under test.

Tables summarize the general specifications of the IPS family and typical values of IPS4 control parameters used for a two-year deployment eight-phase deployment to meet changing ice conditions in the Beaufort Sea..

Table 5. General technical specifications of the IPS family.

IPS specifications

Table 6. Typical values of IPS4 control parameters used for a two-year, eight-phase deployment to meet changing ice conditions in the Beaufort Sea.

IPS operating parameters

WASP SONAR FOR THE MEASUREMENT OF ECHOES

The WASP is a self-contained echo sounder developed at Institute of Ocean Sciences to record the amplitude of back-scatter from the water column. In 1991, data from a WASP, which had been deployed at site 2 to observe the internal hydraulics of flow beneath ridge keels, were processed to provide ice draft because the IPS1 prototype at the same site had failed. In 1995, a calibrated WASP was used at site 1 to acquire quantitative data on scattering of high-frequency sound from marine ice (Melling, 1998b).

The WASP is deployed beneath the surface looking upward. It measures the amplitude of the echo from a vertically directed ping (to 8-bit resolution) in 500 range bins, and adds (to a 16-bit number) the amplitudes of echoes within each bin over a selectable number of consecutive pings before recording. When 32 echo sums have accumulated in RAM, power is supplied to a hard-disk drive and 32 kilobytes of data are written to storage. This operation takes 15 seconds and interrupts the normal sequence of pings. General specifications of the WASP are summarized in Table 5.

The operating setup used in 1991 is summarized below. Note that the spatial resolution and ping rate are an order of magnitude poorer than for the IPS. This less-than-optimal configuration for ice profiling reflects WASP's setup for a different application.

Table 7. Setup Parameters Used for WASP1 at Site ISC91-2

Minimum Acceptable Range	0.3 m
Maximum Acceptable Range	80 m
Bin Size	16 cm
Ping Interval	3 s
Average Interval	30 pings
Block Interval	48 min
Ping Length	50 cm

There is no algorithm for target detection in the firmware of the WASP. The draft of ice was extracted from the recorded data during post-processing.

Identification of the ice echo within the WASP record was carried out using a custom-built programme WASP2IPS, which mimics the function of firmware used in real time by the IPS. To locate the surface, WASP2IPS examines each binned profile of echo amplitude from the WASP and selects the most persistent of those echoes which exceed minimum amplitude and minimum persistence thresholds. The programme creates an IPS-like file of the ranges, amplitudes and persistence of the selected echo from each WASP echo.

The WASP data record can differ significantly from the original echo because digitized echoes from a number of pings are added before recording. Under rough ice, this addition can cause a 'smearing' of the ice-water interface over a number of range bins, so that an abrupt increase in the echo at the range of the ice is not always found. The summed echo contains information on the *distribution* of the draft of ice during the averaging interval, but the detailed ice profile has been lost.

A software simulation of the impact of WASP's signal processing on a measured ice-draft cross-section demonstrated that a useful value of draft can be obtained with a judicious choice of the detection threshold. With the guidance from simulations, ice was detected in the WASP record from 1991 using the following control parameters: echo start amplitude (52%), echo stop amplitude (2.6%), minimum acceptable range (30 m), maximum acceptable range (79 m), minimum acceptable persistence (1 m: 2x ping length).

These controls provide an ice profile whose common statistical properties are likely to be good estimates of those of the actual ice cover. This profile is the primary data product. However, two additional detections were carried out for special purposes: a 20% level of detection produced a sequence of draft optimized for the determination of maximum keel depths, while a sequence produced at a 99% level of detection allowed reliable identification of the open-water areas essential to the accurate calibration for draft.

DOPPLER SONAR FOR THE MEASUREMENT OF ICE DRIFT

A time series of ice motion at each site is not only of value to the scientific interpretation of the ice-draft observations, but also the means by which the time series of ice draft can be mapped to a pseudo-spatial coordinate. Integration of the ice velocity over time generates a curve of ice displacement that represents the track surveyed IPS across the underside of the pack ice.

The instruments that have been used to measure ice motion are narrow-band acoustic Doppler current profilers (NB-ADCP) manufactured by RD Instruments (*http://www.rdinstruments.com*) of San Diego, California. The ADCP is a microprocessor-controlled echo sounder (actually four echo sounders) which determines the motion of an underwater acoustic target by measuring the Doppler shift of the echo returned from it. The instrument has four separate beams inclined at 30° to the main axis of the instrument and separated in azimuth by 90°. Determination of radial velocities along each beam by application of the Doppler principle allows calculation of the three velocity components of the target at a particular range, under the assumption that the target velocity is uniform over the spread of the beams. Four beams provide an extra degree of freedom which allows the validity of this assumption to be assessed. Within the water column, sound is backscattered to the instrument chiefly from the planktonic organisms located within the narrow beam of the sonar. Backscatter from turbulent microstructure is relatively weak in the operating area.

The ice-water interface presents a very strong target to the sonar, but this interface is not at the same range in each of the beams because of instrument tilt and irregularity in the ice surface. The NB-ADCP has a separate mode of operation (“bottom-tracking mode”) and tracking algorithm that can be used to measure the movement of pack ice. The more common application of this algorithm is tracking the seafloor from a ship, where the sonar beams are pointed downward. Firmware within the instrument scans the echoes in each beam and identifies the strong return from the ice-water interface. It then measures the Doppler shift of this echo, regardless of its range, and computes the velocity of the scattering interface by combining the Doppler shifts determined at the appropriate range in each of the four beams.

Because of the pulsed character of sonar operation, the echo has a wide bandwidth, which generally masks the small Doppler shift. Results from the processing of many independent pings are averaged to produce an estimate of velocity that is sufficiently accurate for oceanographic applications. The nominal accuracy of Doppler velocities obtained during the present deployments is ±0.7 cm/s. A table summarizes the general specifications of the NB-ADCP. Instruments operating at both 307 and 614 kHz have been used in this programme.

Table 8.General technical specifications of the RDI narrow-band ADCP

ADCP specifications

The ADCP also measure the ocean current and the acoustic scattering cross-section within ‘bins’ of a few metres vertical extent distributed between the instrument and the surface. Water-column echoes from within 4 m of the sonar are obscured by ring-down of the transmitter and those from within 10-20 m of the ice by strong returns received at low sensitivity through the zenith-pointing side lobes of the inclined beams. These complementary observations from the ADCP are not discussed here.

Table 9. Typical parameters for the setup of a NB-ADCP for a two-year deployment on a type 3 mooring.

ADCP operating parameters

OTHER DATA

Supplementary observations are needed for the processing and calibration of range and pressure data from ice-profiling sonar to yield pack-ice draft.

The average speed of sound between the IPS and the ice is the conversion factor between travel time and range. Values calculated from vertical profiles of temperature and salinity versus pressure acquired at the times of deployment and recovery are a valuable starting point for calibration. These profiles are also used to calculate the relationship between pressure and depth at the mooring at these specific times.

The IPS measures total hydrostatic pressure, whereas the depth of the IPS must be determined from the component of this pressure that is contributed by the ocean. The missing variable is the atmospheric pressure at sea level. This cannot be measured routinely at a fixed location over an ice covered ocean. Values of sea-level pressure can be interpolated from standard meteorological analyses (every 6 hours) or taken from coastal observations (hourly). We have used the hourly time series from the closest coastal site, without adjustment since these sites have been within 200 km of meteorological stations at the coast. Routine sea-level pressure observations made by observers at Tuktoyaktuk and Sachs Harbour and by automatic stations at Pelly Island, Tuktoyaktuk, Sachs Harbour and Mould Bay were acquired from the Meteorological Service of Canada.

DATA PROCESSING

The *IPS Processing Guide, Version 2.2* (unpublished technical report, November 1998) and its addenda provide more detailed descriptions of the stages in processing sonar data to yield ice draft.

ICE DRAFT FROM ECHO RANGE AND PRESSURE

The steps followed in the processing of recorded time series (echo travel time and pressure) to obtain ice draft are briefly summarized.

Establish the relationships between travel time and range and between pressure and depth using observations made at the times when sonar were deployed and retrieved. These calculations establish the exact depth of the IPS at these times, information that is essential to the calibration of ice draft discussed later. The relationships are based upon on-site observations of sea-level pressure and the values of seawater temperature and salinity within the water column from the surface to the depth of the sonar.

Check the indicated pressures from the IPS both on deck and at operating depth, both at the start and completion of the deployment. Since the pressure port is oil-filled, on-deck measurements must be taken with the IPS vertical and corrected for the weight of the oil. Determine the drift in calibration of the pressure sensor caused by creep during the deployment. Derive a time-dependent calibration for pressure values recorded by the IPS.

Interpolate values of sea-level atmospheric pressure from a nearby station to the times of pressure measurement by the IPS. Station values are hourly and IPS values at intervals of a few minutes. Subtract the sea-level pressure from the IPS pressure and convert the difference to a depth using the pressure-to-depth conversion factor derived earlier.

Interpolate values of depth to the time of each ping, typically at intervals of a few seconds.

Preliminary values of range are calculated using an assumed average sound speed for the upper ocean (typically 1437 m s^{-1}). A time series of corrections to this value must be prepared. A first approximation is based on the sound-speed profiles acquired at deployment and recovery and on the apparent draft of calm, ice-free expanses that are obvious in the data record. The correction is conveniently expressed as a range-correction factor, $\beta(t)$, the ratio of true target range to that calculated using the assumed depth-averaged sound speed.

Verify that the temporal variation of the range-correction factor is consistent with plausible seasonal changes in the temperature and salinity of waters between the sonar and the surface.

Use the preliminary $\beta(t)$ to correct ranges from the IPS at each ping. Subtract the range from the interpolated instrument depth to estimate ice draft at the time of each ping. Scan the entire data record to identify all targets of low apparent draft.

Examine each target carefully as a potential ice-free surface suitable for use as a reference for zero draft. Between mid May and mid October, such targets are common. In winter, such targets may be “seen” by the IPS for only a few tens of seconds at intervals of days or weeks. Echo strength is not a reliable indicator of target identity because of the stochastic character of sound scattering at the surface (Melling, 1998b). The correct identification of ice-free targets is an art that demands experience and a meticulous examination of many candidates identified in this preliminary pass. Access to satellite imagery (which shows new leads), data from Doppler sonar and information on wind, air temperature and ice drift provides advantage in making these assessments.

If the preliminary draft of a verified ice-free target is not zero, adjust $\beta(t)$ at the time of observation to obtain a zero value. Re-iterate the preceding two steps until results are consistent with the ±0.05-m target for accuracy. Since calibration points for $\beta(t)$ are highly asynchronous, a reasonable interpolation between values must be achieved. It is often useful to add fictitious calibration points as ‘controls’ to constrain the interpolation to reasonable values

Determine which portions of each record were obtained during prolonged ice-free conditions. These periods are generally contaminated (from the sea-ice perspective) by variations in target range caused by waves and by sub-surface clouds of bubbles from breaking waves. The discrimination of ice from such spurious targets of non-zero draft is problematic. Remove the ice-free (less than one tenth ice concentration) periods from the data files to facilitate further processing.

Edit the ice-draft record using automated methods and then manual review. This is a complex and labour-intensive procedure that demands prior experience with such data. It must be tackled conscientiously. Some common challenges are discussed below.

COMMON CHALLENGES IN THE PROCESSING OF RANGE DATA FROM THE IPS

Identifying Ice-free Waters

Under rare calm conditions, consecutive echoes from an ice-free water surface are short-lived and consistent in range and amplitude. These properties correspond to specular reflection from a very smooth air-water interface.

More typically, the water surface is roughened by capillary and/or gravity waves. These cause the air-water interface to vary in range. They also inject clouds of air bubbles to depths of several metres. Because the clouds are effective scatterers of sound, consecutive ‘surface’ echoes fluctuate dramatically in range and amplitude, giving the impression that ice up to several metres in draft is present. Examples of IPS records under different surface conditions, including rough open water, are included in Melling and Riedel (1993).

Loss of Echoes

The IPS identifies echoes from the surface based on their amplitude. Because the scattering of sound at the surface is a stochastic process, generated by incoherent returns from a finite number of point targets within the field of view, the amplitude of the echo from a given target area fluctuates dramatically (Melling, 1998b). The detection threshold of the IPS is typically set at the fifth-percentile of amplitude for the echo from an ice target. Since 5% of echoes will not cross the threshold, the IPS records zeroes for range, amplitude and persistence at about this fraction. Such occurrences are readily identified. If the ping interval is short (a few seconds), missing ranges can be interpolated from adjacent values. If the interval is long (a few minutes), interpolation is inappropriate since adjacent values are not correlated.

Zero values result also if the echo increases through the start-echo threshold but fails to decrease below the stop-echo threshold before the maximum range is reached. This may occur with the echoes from ridge keels, whose open geometry promotes lengthy reverberation. The problem is largely eliminated if the maximum range is set at least 15 m larger than the depth of the IPS. In shallow water, this setting may also be critical in shutting out multiply scattered echoes from the seabed.

Spurious Echoes

The IPS record contains occasional echoes at short range, either because the IPS erroneously identifies a water-column target as the ice-water interface or because a value of 8192 (2^{13}) was recorded to memory (implying a defective EPROM storage location). In most instances, these ranges are so implausible that they are easily identified through application of thresholds for permissible range and ping-to-ping range change. Values can be replaced by interpolation if the ping interval is short.

Wind Waves in Leads

Rough water in leads is identified subjectively during the steps for determining $\beta(t)$, either as an atypical (for ice) ‘white-noise’ appearance, or as obvious periodic undulation of the surface (with rapidly pinging IPS). The apparent drafts within such leads are replaced by zero values. The exact boundaries of the leads, specified by ping number, are determined through detailed subjective evaluation of the draft record.

Definitive identification of rough water may be difficult if ping data have been acquired only at intervals of several minutes. Since the range to both ice and a wave-agitated sea surface are de-correlated at this interval, adjacent values provide little guidance.

ICE DISPLACEMENT FROM DOPPLER TRACKING

The steps followed in the processing of recorded time series (Doppler velocity, error variance, echo strength) to obtain ice drift are briefly summarized.

Edit the ice-motion records obtained by Doppler sonar using automated methods and then manual review. The primary challenge is the identification and 'repair' of data of poor quality obtained when pack ice is intermittently or completely absent above the instrument during the averaging interval of the sonar (typically 30 minutes). The editing of Doppler returns from pack ice is a complex and labour-intensive procedure that demands prior experience with such data. It must be tackled conscientiously. A simultaneous consideration of near-surface current (from the ADCP), of wind data and of ice drift at other observational sites where ice absence is uncorrelated may be helpful.

Where justifiable, 'repair' gaps in the ice-motion record using the best available estimates of ice drift from other sources – interpolation, ice tracking at nearby sites, near-surface current from the ADCP. The objective is an ice-velocity time series that is as nearly continuous for the duration of the ice-draft record from the same site as is practical. Continuity facilitates analysis of draft data in the spatial domain, despite some compromise of accuracy associated with 'repair'. When the time series is integrated to displacement, the 'repair' influences primarily the widths of open leads in the record, and therefore the estimate of ice concentration. Typically about 15% of the annual record, usually during the autumn and the early summer, need 'repair'. Since such repair is not always possible, there are some ice-draft data from each year that cannot be remapped to a spatial frame of reference, and exist only as time series.

Set the ice velocity identically equal to zero during intervals when the ice is stationary. Even 150 km offshore in the southern Beaufort Sea, ice is motionless for about 40% of the time in winter. If this step is by-passed, the observational 'noise' in ice speed will be integrated (see below) to create large fictitious expanses of ice during prolonged periods of no motion.

Calibrate the time series of ice drift. The narrow-band ADCP from RD Instruments Inc. stores values that are calculated with an assumed sound speed of 1536 m s^{-1}, whereas the value relevant to ice-drift speed, that at the ice-water interface, is about 1437 m s^{-1} (water at 2 db pressure, 32 salinity and -1.5°C). The conversion factor is 0.935. The ADCP determines direction relative to geomagnetic North. The magnetic declination on the Beaufort shelf changed from 39.8°E to 33.3°E between 1 January 1990 and 2004. Also, the response of the ADCP compass to change in heading typically has a non-linear component that is sinusoidal over a range of ±10°. The calibration of direction to geographic headings includes factors for declination and for non-linearity.

Integrate ice velocity to a Eulerian displacement in UTM coordinates.

$$x(t_{N+1}) = -\tau \times \sum_{i=1}^{N} u(t_i)$$

$$y(t_{N+1}) = -\tau \times \sum_{i=1}^{N} v(t_i)$$

$$s(t_{N+1}) = \tau \times \sum_{i=1}^{N} \sqrt{u^2(t_i) + v^2(t_i)}$$

Here *(u(t),v(t))* is the velocity vector in the local UTM coordinate system, *(x(t),y(t))* is the displacement, τ is the ensemble interval and *s(t)* is the curvilinear coordinate along the path. Velocity in the local UTM grid has components modified by a counter-clockwise rotation equal to the mooring longitude (east) minus the

UTM central longitude (east). UTM zones 8 and 9 are centred on the 135°W and 129°W meridians, respectively. Our standard for the displacement vector is the negative integral of ice-drift velocity. When registered to the mooring location, this vector delineates (approximately) the locus of points on the ice that have passed, or will in time pass, over the mooring. This differs from the trajectory of the ice that was over the mooring at the start of recording, commonly known in oceanography as a progressive vector. Our convention facilitates the co-registration of draft cross-sections and images from satellite-based sensors.

Note that the ADCP from RD Instruments Inc. identifies each record with the time at which the velocity-averaging period was *initiated*. The time reference for the displacement vector is the starting time of the record and position reference (0,0) is the location of the mooring. Implicit in the calculation of displacement is a presumption that the pack moves as a rigid plate. In reality, this is not so, but this interpretation is acceptable over small time intervals and small distances along the path.

Where practical, we maintain a continuously incrementing track-line coordinate. However, gaps in the time series of ice velocity that cannot be 'repaired' cause arbitrary resets of the track-line coordinate to zero.

COMMON CHALLENGES IN THE PROCESSING OF ICE-DRIFT DATA FROM THE ADCP

Signal Degradation in Ice-free Waters

Except under very calm conditions, sound is backscattered strongly from the sea surface. The velocity associated with the orbital motions of wind waves is large and incoherent among the four target areas of the ADCP. Since the calculation of Doppler velocity presumes coherence across the beams, the estimation error of sea-surface velocity is large. Moreover, since wave orbital speed usually greatly exceeds surface drift, the latter is commonly obscured by observational noise. These particular characteristics of the Doppler signal in the absence of ice are sometimes identified with ease (Belliveau *et al*. 1990) but become progressively more subtle as the sea-state declines and the ice concentration increases. An example of the change in the character of the Doppler signal during a transition from ice-covered to ice-free conditions is presented by Melling and Riedel (1993).

Signal Degradation under Stationary Smooth Ice

If sea ice is very smooth, backscatter into the inclined beams of the ADCP can be very weak, leading to poor signal-to-noise ratio, wide echo bandwidth and large uncertainty in velocity. This susceptibility introduces a data-processing problem particularly when the ice is not moving. First, the errors in velocity dominate a small ice velocity; second, with little or no movement of the ice cover, the same (poor) target stays over the sonar for prolonged periods.

Such periods are identified by the large values of error velocity computed by the ADCP, despite modest values of ice velocity. An example is presented by Melling and Riedel (1993).

Low ice velocity usually occurs when the ice is present at high concentration. At such times it responds principally to the forcing on a regional scale, so that velocity is correlated over long distances. Observations at one site can often be a valuable guide in the editing of data from another.

PREPARATION OF PSEUDO-SPATIAL SERIES OF ICE DRAFT

The outputs from the data processing described to this point are edited calibrated values of ice draft at regularly spaced (short) increments of time (a few seconds) and edited calibrated values of ice displacement at regularly spaced (longer) increments of time (tens of minutes).

The statistical summaries presented later in this report are based on the time series of ice-draft observations, sub-sampled to approximately 4-minute intervals.

The following steps create a series of ice-draft values at regularly spaced increments of distance along the path of drift.

Interpolate values of displacement to the exact time of each value within the ice-draft record. Because the measured ice velocity is an average over time, a linear interpolation of the displacement is appropriate. Trim the files to the same number of records, synchronous one to the other.

Merge the values of displacement and draft into a single file, thereby associating each value of ice draft with an irregularly incrementing spatial coordinate, $s(t)$.

Re-sample the time series of $x(t)$, $y(t)$, $D(t)$ to regular increments, typically every metre, in the curvilinear coordinate $s(t)$. A double quadratic interpolation method provides the best results for the very rough topography of pack ice. This step is necessary in order that statistical summaries of ice draft, such as probability distributions, spatial spectra and spatial auto-correlation functions, can be compared with similar statistics from moving platforms such as submarines and AUVs.

The data acquired by the WASP during 1991 were sampled at a lower rate. These data were interpolated to 3-m intervals along the path.

UNCERTAINTY IN CALIBRATION

ICE DRAFT

Both of the primary parameters measured by the IPS are surrogates for distance. The total hydrostatic pressure is related to the depth of sonar and the sound travel time to the ice-water interface is related to the range.

The pressure measured by the IPS is the total hydrostatic pressure. To determine the oceanic component of hydrostatic pressure, it is necessary to subtract the contribution made by the atmosphere. We assume that the sea-level pressure equals that measured by the Meteorological Service of Canada at a nearby coastal site. Melling and Riedel (1993) use data from the region to estimate that the error in sea level introduced by this assumption is less than 0.003 m in the mean, 0.025 m at one standard deviation and 0.1 m at worst.

The hydrostatic pressure of the ocean on the IPS, $p(t)$, is the product of the gravitational acceleration, g, and the integral of *in situ* seawater density $\rho(z, t)$ through the water column above the instrument. Depth $D(t)$ can be calculated from pressure measured by the IPS if the vertical variations of temperature and salinity are known from CTD profiles:

$$D(t) = \frac{1}{g} \int_0^{p(t)} \frac{dp}{\rho(z,t)}$$

Note that as density varies with time, the relationship between pressure and depth changes. Fortunately, the apparent depth change caused by the increase in density between summer and winter is negligible in this application where the IPS is at less than 100-m depth in Arctic waters, (Melling and Riedel, 1993).

The round-trip travel time $E(t)$ is related to the range to the reflecting surface $R(t)$ by,

$$E(t) = 2 \int_0^{R(t)} \frac{dr}{c(D - r, t)}$$

Here $c(z, t)$ is the sound-speed profile as a function of depth and time. The range to a target may be determined by evaluating this integral upward from the location of the IPS to the value R which yields the observed travel time. Note that parameters vary with depth and time.

The impact of seasonal change in the sound-speed profile on the apparent range to the surface is not negligible. Melling and Riedel (1993) demonstrate that changing sound speed introduces an error of at least 0.2 m between winter and summer. Temperature and salinity profiles by CTD are rarely available other than at deployment and recovery. The only feasible method to adjust ranges for secular change in sound speed is to use corrections derived from the apparent draft of open-water areas which pass through the sonar beam. These occasional tie points constrain the selection of a plausible curve that can be used to correct ranges at all times between deployment and recovery. Tie points must be selected with great care, since mistakes in selection introduce systematic errors (under estimates) in ice draft.

Because sound speed varies with depth, an exact range correction will vary with the draft, or range, of the target as well as on the time of year. Thus, accuracy is best for thin-ice targets near the surface and deteriorates with increasing draft. In winter in the Beaufort Sea when open areas freeze very quickly, tie points for range correction are scarce. However, the temperature and salinity of water beneath continuous ice change only slowly from week to week. In summer, ice-free targets are viewed many times each day, but the temperature and salinity of the upper ocean are much more variable. River inflow, ice melt water and solar heating are contributing factors. Our estimate for accuracy in the draft of level ice from moored sonar in this programme is ±0.05 m.

Under rough ice, the first contact of the transmitted sound pulse with the ice may not be exactly overhead, because the sonar beam has finite angular width. Thus the local draft of ice will be overestimated on average in rough ice. The magnitude of the overestimate cannot be generally specified, since it depends not only on the beam pattern of the sonar, but on its source level and sensitivity and on the geometry, scattering cross-section and range of the ice. By reducing the field-of view of the IPS to 0.8 m from a depth of 50 m (Melling, 1998b), we have reduced this systematic error to a practical minimum.

ICE DRIFT

Uncertainty in ice-velocity derived by the ADCP arises from three sources: (1) Sampling error in the estimation of mean Doppler shift, (2) Uncertainty in the sound speed used to convert Doppler shift to velocity and (3) Uncertainty in ADCP heading, pitch and roll.

The sampling error is random and a function of the acoustic frequency and pulse length used by the ADCP, the signal-to-noise ratio and the number of pings averaged. For the ADCP configuration of these deployments, the sampling error was 0.7 cm s^{-1} in each component of velocity at good signal-to-noise ratio. When an ADCP is tracking floes which have a very smooth under surface, much of the transmitted pulse, incident at 30°, is reflected onward at 30°. A weak backscattered signal may be buried in noise at the receiver. At poor signal-to-noise ratio, the sampling error, estimated from the root-mean-square value of the vertical velocity component, increases to several cm per second. Poor precision in Doppler velocity is only problematic when a weak target is stationary over the IPS.

The calculated ice velocity is linearly dependent on the speed of sound at the ice-water interface. Sound speed beneath ice varies little over the course of the year, because the temperature at the ice-water interface is always close to freezing. A systematic error of no more than 1% may be present.

The conversion of velocity components from a beam-referenced coordinate system to an Earth-referenced system is based on measurements of tilt and heading by the ADCP. The accuracy of the tilt measurement is not critical, since a (large) error of 5° in tilt generates an error of only 3% in a velocity component. Errors in the compass measurement of heading, however, translate directly into errors in the direction of ice drift. The non-linearity in the ADCP compass response can be quite large (±15°) in the Beaufort Sea because the horizontal component of the geomagnetic field is only 7000 nT. Corrections must be made.

Compasses were calibrated in a non-magnetic enclosure located near the PCSP base at Tuktoyaktuk. The output of the compass was measured at 11.25° increments in heading and corrections for the observed non-linearity were entered into a look-up table in EPROM within the ADCP. The ADCP rotation was repeated to determine the residual non-linearity. For KVH-manufactured compasses, the systematic sinusoidal component residual was about ±2° and the random component about the same magnitude. For the EG&G-manufactured compass (s/n 0179) the residual was much larger. Compass rotations were repeated at greatly different temperature and after intervals of 3-5 years, but no significant differences dependent on temperature or elapsed time were noted.

Corrections for systematic residual non-linearity in heading are applied during data processing, leaving a random error of ±2°. To permit assignment of a unique value of heading correction for each ensemble (which represents data gathered over 15-45 minutes of pinging), each ADCP mooring was equipped with a vane and a swivel. The action of current on the vane stabilizes the heading of the ADCP during acquisition of an ensemble.

ICE DRAFT TIME SERIES FOR THE WORLD DATA CENTRE A - GLACIOLOGY

In the Northern Hemisphere, moored sonar have been used for ice-draft measurement in several areas of focus around the Arctic.

Locations of all IPS deployments in the Arctic to 2003

Figure 18. Locations of all deployments of ice-profiling sonar in the Arctic to 2003.

In most studies that have used moored sonar to measure ice draft, statistical parameters have been calculated from observations spaced regularly in time, not distributed uniformly along a line. Moreover, the interval between samples has typically been much greater than the values of a few seconds used in this project. In order to facilitate comparisons between Canadian data from the Beaufort Sea and that from other countries (Norway, Germany, USA), we prepare a sub-sampled version of our time series that meets agreed archival specifications of the World Data Center A (Glaciology) in Boulder USA (*http://nsidc.org/noaa/moored_uls/index.html*)

We started with the edited, calibrated files of draft values at the original sampling interval. For convenience, these files have been truncated to eliminate observations during prolonged ice-free conditions.

New files have been created using values extracted at 4-minute intervals from the original data.

Continuous time series at 4-minute interval have been created for the years of observation at each site by concatenating the sub-sampled data files from all deployments. At times when the original full-length sonar record revealed prolonged ice-free conditions (or rough seas in which ice at low concentration cannot be detected), flag values of 0 have been inserted. Shorter periods of open water were not removed during processing and are evident as ice draft near zero (±0.05 m). At times when no observations were made, when for example there was no instrument in the sea or the IPS was non-functional, flag values of -88.88 have been inserted. There remain a few times when temporary ambiguity in the validity of echo ranges merited a judgment of ‘bad data’ and a flag value of -99.99.

We compute various statistical indicators of ice draft for nominal monthly intervals. The intervals actually alternate between 31-day and 30-day duration, based on the calendar year. In a leap year, the last ‘month’ of the year has 30 days. In other years it has 29 days. The calculated statistics are the fraction of possible data available for the period, the fractions of data with draft less than -0.05 m and greater than 40.05 m, the histogram, the mean including open water, the standard deviation, the mean excluding open water, the average concentration and the 20th, 50th and 80th percentiles. Drafts flagged as ‘missing’ are not included. The bins of the histogram are 0.1 m in width. There are 401 bins with the smallest spanning (-0.05, 0.05) and the largest (39.95, 40.05) m. The average concentration is the fraction of data with draft exceeding the upper bound of the first bin (0.05 m). The mean draft excluding open water is based on the same threshold.

Ridge keels are not resolved as features in this archive because the time required for a keel to drift over the sonar is comparable to the 4-minute interval of the time series. However, the thick ice of which keels are composed is detected in a stochastic sense via the systematic approach to sampling.

There are 10,800 draft values at 4-minute interval in a 30-day month. At an average monthly drift speed of about 0.1 m/s, lower in winter and higher in summer, the average separation of data points is about 24 m. The average de-correlation scale of ice draft is certainly no shorter than 24 m (Melling and Riedel, 1995); a value of at least 40 m may be more representative for ridge keels and a larger value for level ice. Therefore, the number of statistically independent values of draft acquired in 30 days is probably less than 6,000.

Recognizing that the standard deviation of sea-ice draft is comparable to the mean (Melling and Riedel, 1996a), we estimate the sampling uncertainty in monthly mean values to be about ±1.5% (±0.05 m for 3-m ice). However, the difference between means over time and averages over distance, caused by non-uniform ice movement, can at times reach 30% (Melling, 2000). The large and variable bias of time-series means relative to spatial averages complicates the inter-comparison of time series from moored sonar with cross-sections derived from submarines.

Because the speed of ice drift has important influence on the values of and uncertainties in the statistical parameters of ice draft, we also compile monthly statistics of this variable. The same flagging convention has been used. For reasons discussed in an earlier section of the report, no accurate measurements of ice drift are available during times when there are open-water flags in the ice-draft file.

Statistical measures of ice speed are calculated for the same nominal monthly intervals using all acceptable values recorded by the ADCP (i.e. no sub-sampling). In the months wherein one deployment ends and another begins, the statistics are computed as sums appropriately weighted to reflect any difference in sampling interval between the deployments. The measures calculated are the fraction of possible data available for the period, the fraction of data with speed greater than 100 cm s^{-1}, the histogram, the mean including zero speeds, the standard deviation, the mean excluding zero speeds, the average incidence of no ice movement and the 20th, 50th and 80th percentiles. Speeds flagged as ‘missing’ are not included. The bins of the histogram are 2 cm s^{-1} in width. There are 50 bins with the smallest spanning (0, 2) cm s^{-1} and the largest (98, 100) cm s^{-1}. The average incidence of no ice movement is the fraction of data with speed within the first bin. The mean speed excluding zero speeds is based on the same threshold.

MONTHLY SUMMARIES OF TIME-SERIES DATA (1990-1999)

All data from the 1990s (April 1990 to September 1999) are summarized via monthly values of key statistics in graphical form. There are observations from sites 1-8 during this period.

Five panels on a single page present the decade for each group of variables at each site. Each panel displays several variables using coloured bars and symbols. Bars in consecutive panels may be shaded with alternating colours for clarity in the event of occasional trespass into the panel above. Statistics have not been computed if fewer than one quarter of the observations possible are available for that month. This occurrence is indicated on the plots.

MEAN DRIFT SPEED

Four statistics are displayed: (1) The average speed of ice drift, (2) The standard deviation of drift speed, (3) The fraction of the month during which the ice was immobile and (4) The average speed of drift when the ice was mobile. Months with insufficient data are indicated.

Drift at site 1.emf

Figure 19. Monthly mean speed of ice drift at site 1.

Drift at site 2.emf

Figure 20. Monthly mean speed of ice drift at site 2.

Drift at site 3.emf

Figure 21. Monthly mean speed of ice drift at site 3.

Drift at site 4.emf

Figure 22. Monthly mean speed of ice drift at site 4.

Draft at site 5.emf

Figure 23. Monthly mean speed of ice drift at site 5.

Draft at site 6.emf

Figure 24. Monthly mean speed of ice drift at site 6.

Drift at site 7.emf

Figure 25. Monthly mean speed of ice drift at site 7.

Drift at site 8.emf

Figure 26. Monthly mean speed of ice drift at site 8.

Normalized histograms and basic statistical measures (mean, standard deviation, median, 20th and 80th percentiles, minimum and maximum) have been calculated.

MEAN ICE DRAFT

Four statistics are displayed: (1) The average draft including open water as ice of zero draft, (2) The standard deviation of ice draft, (3) The fraction of the month during which ice was present (ice concentration) and (4) The average draft of the ice that was present. Months with insufficient data are indicated.

The extent of the ice surveyed during each month depends on the average speed of drift. Approximately 130 km of ice are observed in 30 days if the average drift is 5 cm s^{-1}.

Draft at site 1.emf

Figure 27. Monthly mean ice draft at site 1.

Draft at site 2.emf

Figure 28. Monthly mean ice draft at site 2.

Draft at site 3.emf

Figure 29. Monthly mean ice draft at site 3.

Draft at site 4.emf

Figure 30. Monthly mean ice draft at site 4.

Draft at site 5.emf

Figure 31. Monthly mean ice draft at site 5.

Draft at site 6.emf

Figure 32. Monthly mean ice draft at site 6.

Draft at site 7.emf

Figure 33. Monthly mean ice draft at site 7.

Draft at site 8.emf

Figure 34. Monthly mean ice draft at site 8.

PERCENTILES OF ICE DRAFT

Normalized histograms and basic statistical measures (mean, standard deviation, median, 20th and 80th percentiles, minimum and maximum) have been calculated.
The 20th, 50th (median) and 80th percentiles of ice draft are displayed.

Draft percentiles at site 1.emf

Figure 35. Monthly percentiles of ice draft at site 1.

Draft percentiles at site 2.emf

Figure 36. Monthly percentiles of ice draft at site 2.

Draft percentiles at site 3.emf

Figure 37. Monthly percentiles of ice draft at site 3.

Draft percentiles at site 4.emf

Figure 38. Monthly percentiles of ice draft at site 4.

Draft percentiles at site 5.emf

Figure 39. Monthly percentiles of ice draft at site 5.

Draft percentiles at site 6.emf

Figure 40. Monthly percentiles of ice draft at site 6.

Draft percentiles at site 7.emf

Figure 41. Monthly percentiles of ice draft at site 7.

Draft percentiles at site 8.emf

Figure 42. Monthly percentiles of ice draft at site 8.

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