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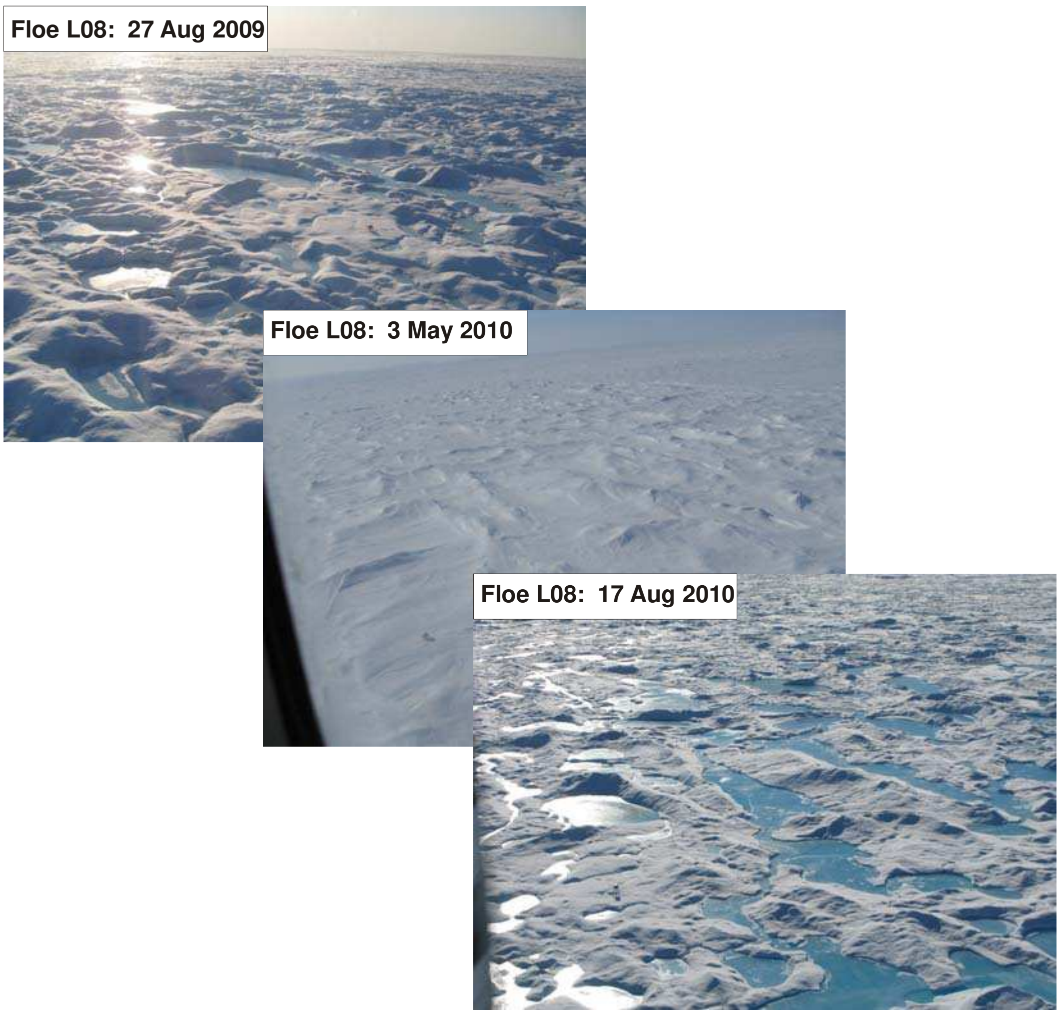

M. Johnston

Technical Report, CHC-TR-082

June 2011

National Research Council Canada
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CHC CANADIAN HYDRAULICS CENTRE

Results from Field Programs on Multi-year Ice
August 2009 and May 2010

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Abstract

Ten multi-year ice floes sampled in the high Arctic in late summer 2009 and spring 2010 are described. Ice thicknesses obtained from detailed drill hole profiles indicated average floe thicknesses from 3.4 to 14.7 m (±1.3 to 4.3 m). A maximum thickness of 21.1 m was measured, which was the limit of the two-person drill team, however the sail height of some other features on the floes suggested much thicker ice. Voids, pockets and loose blocks on the underside of the ice were sometimes noted while drilling through multi-year ice in August 2009 and in May 2010, albeit less frequently.

Thicknesses obtained from drill-hole measurements on four of the very thick multi-year ice floes were compared to thicknesses obtained over the same profile areas by a helicopter-based electromagnetic induction (HEM) system. Compared to drill-hole measurements, the HEM underestimated the average thicknesses of the four floes by 15 to 24%. Results showed that the HEM did not reproduce thicknesses larger than about 12 m and it overestimated the percentage of ice from 3 to 7 m thick. It is expected that the HEM provided no data about ice thicker than 12 m because the thickness of deformed multi-year ice within the sensor's footprint was so variable and also because of the attenuating effect that large, sea-water filled voids had upon the EM soundings.

Two deformed, multi-year ice floes were instrumented with 11 m long temperature chains in August 2009. The instrumentation extended through 12.4 m thick ice on the first floe (Floe L03, 74°N) and 13.5 m thick ice on the second floe (Floe L08, 77°N). Both floes had a 'C-shaped' temperature profile to a depth of about 7.5 m in August 2009, below which the ice was isothermal at near melting temperatures. The coldest temperature (-5°C) occurred towards the interior of the floe (4 to 5 m depth). The temperature vs. time series suggests that about 4 m of ice was lost from the bottom of the Floe L03 (12.4 m thick) as it drifted from Kane Basin to the northern part of Baffin Bay, prior to the last data transmission in September 2009. Floe L08 continued to transmit temperature data for one year. In August 2010, Floe L08 was near-isothermal throughout its full thickness, with the coldest temperature being -3°C at an ice depth of 4 to 5 m – compared to the "C-shaped" temperature profile that the floe had in August 2009. About 1 m of ice ablated from the top surface of Floe L08 during the summer of 2010 and an undetermined amount of thinning occurred on the underside of the floe.

Floe L08 was re-visited in May 2010, when cores were taken to a depth of 5 m and borehole strength tests were conducted at 30 cm depth intervals to an ice depth of 5.40 m. The uppermost 5 m of ice had an average temperature of -11.3°C and an average salinity of 1.4‰. Borehole strength tests were conducted in two boreholes on Floe L08 to a depth of 5.40 m. The maximum ice pressure attained in each borehole was 37 MPa however the peak strength at some depths could not be obtained due to the limited capacity of the borehole system. As anticipated, the strength of the ice was very dependent upon the ice temperature, which is consistent with the past four years of borehole strength tests in multi-year ice.

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Results from Field Programs on Multi-year Ice August 2009 and May 2010

1.0 Objectives

This report presents results from two field programs on multi-year ice: the summer of 2009 and the spring of 2010. Multi-year ice is the focus of the work because it has been shown to cause the highest loads on offshore structures (Timco and Johnston, 2004) and it is associated with the greatest number of ship damage events (Kubat and Timco, 2003). Despite the importance of multi-year ice, relatively little is known about its floe size, thickness, strength, and seasonal variations in its physical properties. All of these aspects influence design criteria for offshore structures and are important for promoting safe and efficient shipping in ice-covered waters.

To summarize the current state of knowledge about the thickness of multi-year ice, Johnston et al. (2009) compiled data from 34 of the most well-known, on-ice studies of multi-year ice. The authors showed that thickness measurements have been made on fewer than 200 multi-year floes over the past 40 years. Only about half of those floes provide detailed information about how the ice thickness varies along transects (profiles); none of the studies examined how ice thickness relates to surface topography. This work provides information about both of those aspects. Detailed drill hole measurements of multi-year ice were conducted to determine how the thickness of multi-year ice varies over 100 m long transects – a distance comparable to the width of a typical offshore structure. The information attained during the field program will help determine where multi-year ice is most likely to fail as it drives against a structure and it will provide a better definition of the actual contact area over which the load is applied.

Another important aspect of this work relates to determining whether some forms of multi-year ice cease to be hazardous to ships and structures in late summer and to determine some means of establishing damage criteria with which to evaluate multi-year ice. That, in turn, requires a better understanding of the thickness and strength of the myriad forms of multi-year ice, and the effect of seasonal warming on multi-year ice. This report includes information about how the temperature of multi-year ice varies over its full thickness for up to one year, which is expected to provide a first approach to estimating the strength of the ice at depths where it has not yet been measured (below an ice depth of 6 m). Documenting changes in the temperature, strength and thickness of multi-year ice in excess of 10 m thick as it drifts through the Arctic is unique – prior documentation of this kind has not been made on extremely thick multi-year ice.

Support for the work comes from the Government of Canada (Transport Canada, Program for Energy Research and Development), from the Government of Nunavut and from Industry. This work is very relevant operations in Arctic ice-covered waters because it provides the scientific understanding needed to ensure that shipping and offshore development proceed safely, with reduced risk to the environment and communities. This understanding is critical for regulatory approval – it will remove one of the impediments to future development.

1.1 Reports Issued for this Project

Two reports were issued for this project: one for Private Industry and another for the Canadian Government. This publicly available report combined data from the 2009 and 2010 field seasons. It focuses upon temperature data from the two instrumented multi-year floes, the ice thicknesses measured by drill-hole measurements on ten multi-year ice floes and the thicknesses of four of the sampled floes that were obtained from a helicopter-based EM sensor (HEM). The report for Private Industry is a *controlled* technical report that includes data from the 2009 field season. That report is proprietary because it contains data from the ice-based EM sensor study that was funded by ConocoPhillips Canada.

2.0 Study Areas for 2009 and 2010 Field Seasons

This report includes results from two field programs. Most of the report focuses upon results from the month-long field program that was conducted in August 2009. Results from the two-week long, follow-up field program that was conducted in the spring 2010 are also presented. Nine multi-year ice floes were sampled from the CCGS *Henry Larsen* in August 2009 (Figure 1). In the May 2010, one of the floes sampled from the CCGS *Henry Larsen* was revisited and an additional multi-year floe was sampled in Wellington Channel. The intention of conducting repeat measurements on Floe L08 was to assess how the thickness of the ice had changed, measure its temperature, salinity and strength and to download data from the instrumentation package that had over-wintered on the floe.

Nine multi-year ice floes were sampled from the CCGS *Henry Larsen* as the ship sailed north from Thule, Greenland to Hall Basin and then southwest to Sverdrup Basin. On-ice measurements were conducted on an opportunity basis while the ship fulfilled the objectives of Dr. H. Melling's IPY-sponsored Canadian Arctic Through-Flow (CAT) Study (http://www.dfo-mpo.gc.ca/science/publications/article/2008/12-08-2008-eng.htm). The CAT Study is the culmination of ten years of effort within the Canadian and international scientific community to measure the flow of seawater and ice through the Canadian Arctic Archipelago. One important component of the CAT Study involved using an array of moorings to measure the thickness and movement of sea ice through Nares Strait. Dr. Melling welcomed the opportunity to have on-ice thickness measurements to supplement his study.

The full contingency of scientists met in St. John's, Newfoundland on 4 August 2009, one day prior to boarding the plane that the Canadian Coast Guard had chartered to Thule Air Base, Greenland. Personnel arrived in Thule on the afternoon of 5 August. By early evening, the ship was underway to the main study area in Nares Strait because, at best, there are only a few weeks in August when multi-year ice is loose enough to allow the CCGS *Henry Larsen* to operate comfortably.

Since the oceanographic measurements and on-ice measurements made full use of the ship's Officers and Crew, it was a fine balancing act for Captain Vanthiel and Dr. Melling to determine when (and how) to support the different science programs. Generosity is a key descriptor here because often, the ship patiently waited nearby for the on-ice team to complete their measurements. Certainly, the good relationship that CCG, DFO and NRC-CHC have established working together during the two previous Nares Strait campaigns (August 2006, August 2007) allowed operations flow smoothly in August 2009.

Typically, the on-ice field team consisted of four people, which is the minimum number of people required for two teams to work on the ice independently. The team included two people from NRC-CHC (M. Johnston and R. Lanthier), one person contracted to the NRC-CHC to help with the work (C. Fillion) and one assistant from the CCGS *Henry Larsen*. Floes were selected about 15 minutes from the ship (flying time) when possible, to maintain radio communication with the ship and to maximize the field team's time on the ice.

The objective of the program was to sample a range of floe thicknesses, although there was some bias towards the more formidable multi-year floes since they pose the greatest risk to ships and offshore platforms. Experience has shown that discriminating 'thin' multi-year ice from 'thick' multi-year ice can be extremely challenging – both from the air and from the ship's bridge. Criteria were developed for quickly assessing the integrity of multi-year floes based upon features such as surface roughness, extent of decay/ponding, ice freeboard, floe size, presence of dirt on the ice and the extent of weathering.

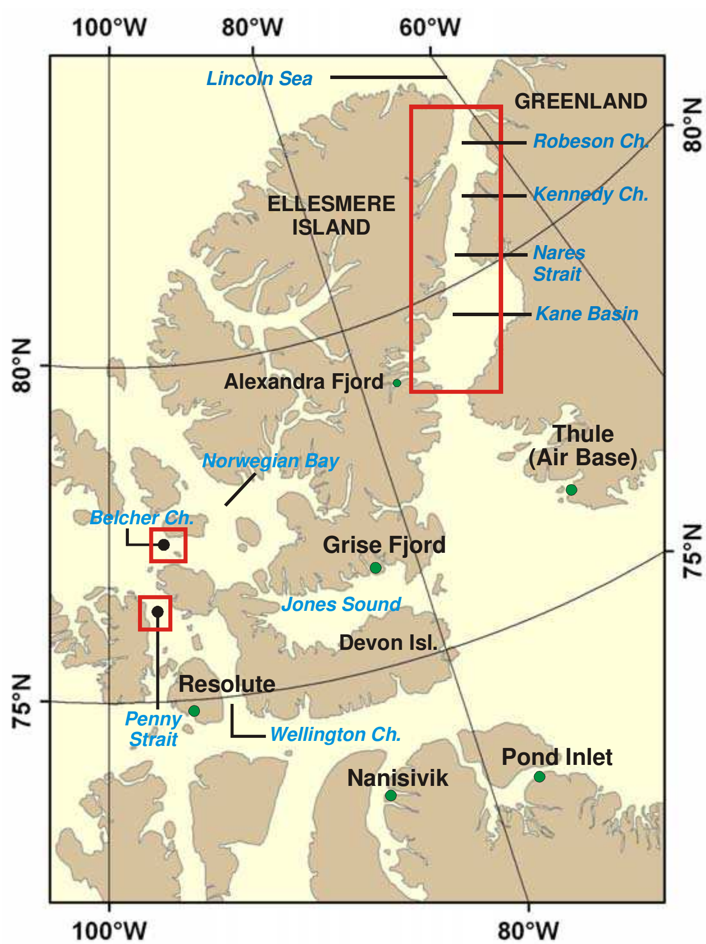

Figure 1 Multi-year ice floes sampled in summer 2009 and spring 2010
May 2010 measurements focused upon revisiting Floe L08 in Belcher Channel and sampling one floe in Wellington Channel

Upon departing Thule on the evening of 7 August, the ship sailed about 400 km north to Alexandra Fjord, to collect the 350 kg of equipment that Polar Continental Shelf Program (PCSP) had graciously delivered on a flight to support scientists camped in the Fjord (see Journal, Appendix D). The other 1300 kg of equipment had been shipped to the CCGS *Henry Larsen* in June, before the ship departed St. John's for the Arctic.

The ship arrived at the entrance of Alexandra Fjord on 9 August to find access to the fjord blocked by 7 to 8/10ths pack ice. Since the ship could advance no further, the helicopter was dispatched to gather the equipment, which required two trips to transport. The Fjord itself proved to be nearly ice-free, despite the 7 to 8/10ths concentration of ice that blocked its entrance.

3.0 Ice Conditions Encountered in August 2009

An overview of the ice conditions leading up to the trip and encountered during the trip is presented here since it provides a context for understanding the environment in which multi-year ice floes were sampled during the 2009 field program.

Typically, one or more ice bridges, or ice arches, extend from Ellesmere Island to Greenland at some point during winter and spring. Ice bridges can form across Robeson Channel, Nares Strait and/or Smith Sound (Figure 1), effectively blocking the southward drift of perennial pack ice from the Lincoln Sea. These bridges typically collapse in June or July, as areas of ice in Nares Strait and Kennedy Channel become more open, permitting multi-year ice from Lincoln Sea to drift into Kennedy Channel, Nares Strait, Kane Basin, Baffin Bay and possibly beyond. One of the multi-year floes that NRC-CHC instrumented during the 2006 Nares Strait program drifted as far south as Newfoundland over the course of just 9 months (Johnston, 2008-a)[1].

A unique set of circumstances occurred in the winter of 2008/09. Several ice bridges formed across Nares Strait that winter/spring, but since none of them persisted, the perennial pack ice was blocked only by the ice bridge that formed across Robeson Channel. As a result, the narrow passageway between Ellesmere and Greenland was characterized by unusually low ice concentrations (1 to 3/10ths ice concentration, see Figure 2) until about 20 July, which was about two weeks after the Robeson Channel ice bridge collapsed (7 July). Due to those unusual circumstances, the Greenpeace *Arctic Sunrise* was able to transit as far as the northernmost coast of Ellesmere Island – retreating south to Thule only after ice conditions worsened in late July.

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[1] The winter of 2006/07 was the only year on record that an ice bridge did not form between Ellesmere and Greenland (http://www.nasa.gov, press release from JPL), allowing the continued flow of perennial pack ice throughout winter, spring and summer. Spring 2007 also produced some of the most severe ice conditions experienced off the coast of Newfoundland – conditions partly caused by an influx of multi-year ice, fragments of which included the floe on which NRC-CHC deployed a tracking beacon in Nares Strait in August 2006.

The ice charts in Figure 2 show that the highest concentration of ice was encountered in Hall Basin (7 to 8/10ths) and Belcher Channel (9 to 10/10ths), whereas the ice concentration in Nares Strait was more variable (4 to 8/10ths concentration). Once the ice floes entered Kane Basin, the ice floes became distributed over a much larger area and so the ice concentration decreased to 1 to 3/10ths.

Traditionally, some of the thickest, oldest ice in the world passes through Nares Strait. Much of the highly deformed multi-year ice originates off the northwest coast of the Queen Elizabeth Islands, where it migrates northeast and funnels into Kennedy Channel. Surprisingly then, the CCGS *Henry Larsen* encountered mostly benign looking, level old ice floes during the transit from Thule to Nares Strait in August 2009. The aerial reconnaissance that was conducted to examine ice conditions in Nares Strait, and further north towards Hans Island and Hall Basin, suggested that a different crop of ice populated the region in 2009 than in previous years. Several thick, deformed multi-year floes were observed but, overall, the floes were considerably more level than floes encountered in 2006 and 2007. Quite possibly, the ice conditions were different in August 2009 because old ice originated from a different part of the Arctic Basin (A. Muenchow, personal communication) than the ice encountered during the two previous field seasons in Nares Strait. This is illustrated, to some extent, by the MODIS imagery in Figure 3. The yellow line indicates the origin of the highly deformed ice that is swept into Kennedy Channel from the northwest coast of Ellesmere Island and the white line shows ice being drawn into Kennedy Channel from the eastern Lincoln Sea, where the ice is expected to be more level.

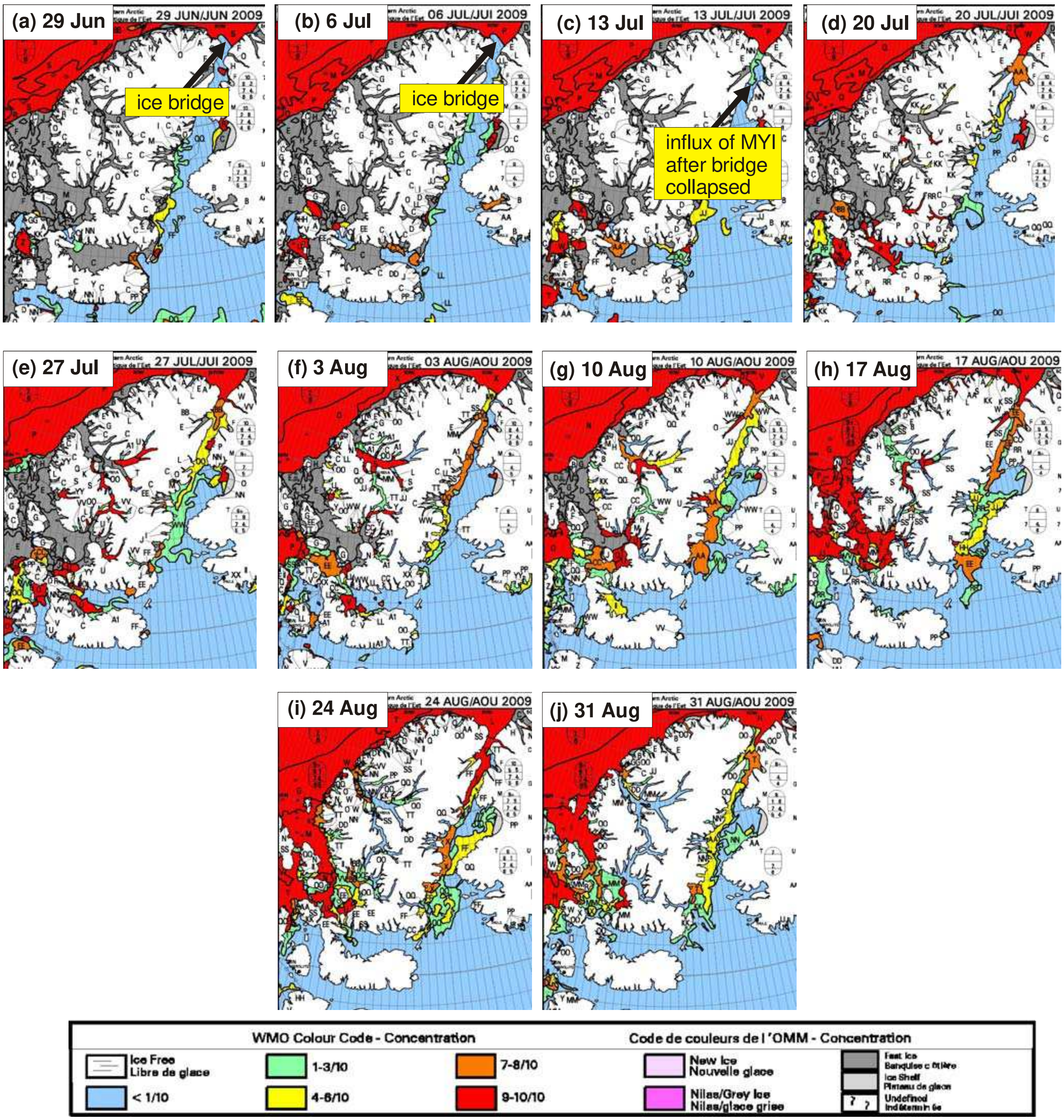


Figure 2 Regional Ice Charts showing ice concentration in the eastern High Arctic (courtesy of Canadian Ice Service)

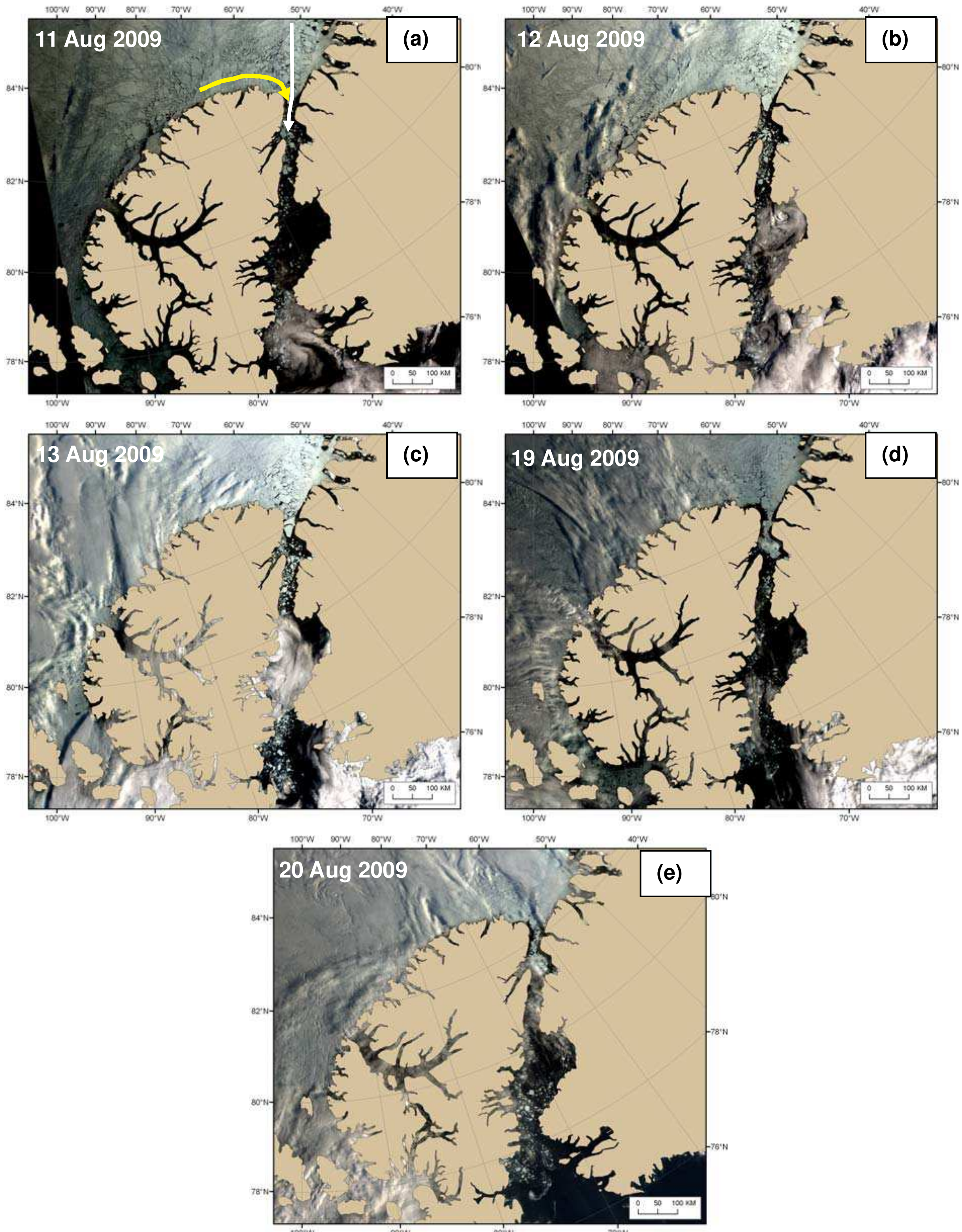


Figure 3 MODIS imagery of ice entering Robeson Channel from the Lincoln Sea (images courtesy of CIS). Yellow arrow in (a) shows ice entering from the Ellesmere coast and the white arrow shows ice entering from the eastern Lincoln Sea

3.1 Floes Sampled in August 2009 and May 2010

Figure 4 shows the location of the floes that were sampled in August 2009 and May 2010. Seven of the floes sampled in August 2009 were located in the eastern high Arctic (Kane Basin, Nares Strait and Kennedy Channel) and two of the floes were in Sverdrup Basin (Belcher Channel and Penny Strait). In May 2010, one of the floes that had been sampled in Belcher Channel was revisited and an additional multi-year floe was sampled in Wellington Channel (Floe W01).

The sampled floes ranged from about 500 metres in diameter to several kilometers across, as noted in Table 1. Typically, the multi-year floes were aggregates of small, thick multi-year sub-floes bound together by first-year, second-year ice or thinner multi-year ice. The multi-year sub-floes were often surrounded by rubbled ice created when thinner ice failed against the thicker, multi-year ice. The multi-year ice was usually devoid of snow, with the exception of some ridged and rubbled areas. All of the multi-year floes sampled in August had a various extents of surface ponding.

All of the floes sampled in August drifted during the 5 to 9 hours of on-ice sampling, depending upon environmental conditions such as wind, tide, current (Figure 5). Two of the three floes in Hall Basin drifted towards the coast of Greenland (Floes L04, L05), whereas the other floe drifted towards the Ellesmere coast (Floe L06). Floes L02, L03 and L07 in Nares Strait drifted roughly parallel to the coastline, as might be expected. When Floe L03 was visited in Kane Basin on 13 August, it drifted east towards the coast of Greenland at a faster rate than any other floe sampled during the field program (2.0 km/hr) – in fact, Floe L03 traveled almost 19 km during the 9 hour sampling period (Table 1).

The two floes sampled in May were locked in place by landfast ice. It should also be noted that when Floe L08 (Belcher Channel) was visited in May 2010, it was just 13 km west of where it had been when it was sampled in August 2009. Evidently, floes in Sverdrup Basin do not migrate though the Arctic as quickly as floes in Nares Strait and Kane Basin.

Table 1 Multi-year floes sampled during 2009 and 2010 field programs

Floe ID	avg. floe size (m)[a]	date sampled	initial position (N, W)	final position (N, W)	arrival - departure time[b]	sampling duration (hrs)	total drift (km)[c]	avg. drift speed (km/hr)
August 2009 Field Program								
L01 Kane Basin	2200	10-Aug	79.1045 71.1789	79.08755 70.84951	09:36 - 17:43(EDT)	8.1	7.8	0.9
L02 Nares Str.	2000	11-Aug	80.6010 67.9588	80.5280 68.4864	9:49 – 16:48EDT	7.0	13.2	1.8
L03 Kane Basin	1500	13-Aug	80.6624 67.5305	80.5240 68.0346	09:03 – 18:05EDT	9.0	18.8	2.0
L04 Hall Basin	3500	16-Aug	81.3278 63.8547	81.2596 63.8947	13:34 - 19:16EDT	5.7	8.0	1.4
L05 Hall Basin	2400	17-Aug	81.3338 63.5820	81.2986 63.5240	09:26 – 15:49EDT	6.4	4.3	0.7
L06 Hall Basin	1000	18-Aug	81.3741 63.1044	81.3984 63.1412	11:14 – 18:19EDT	7.1	3.1	0.4
L07 Nares Str.	500	19-Aug	80.8574 66.3659	80.8260 66.6239	09:48 – 17:52EDT	8.1	6.1	0.8
L03 Kane Basin (re-visit)	1500	23-Aug	79.0961 71.6215	79.1044 71.4769	18:00 – 22:39EDT	4.7	3.3	1.2
L08 Belcher Ch. (visit #1)	2000	27-Aug	77.3102 95.4483	77.3199 95.5127	11:09 – 19:43EDT	8.6	4.1	0.6
L09 Penny Str.	1500	30-Aug	76.5068 97.5984	76.5472 97.5538	09:28 – 18:22EDT	9.0	7.9	0.9
May 2010 Field Program								
Floe L08 Belcher Ch. (visit #2)	2000	3 May	77.2895 96.0471	77.2895 96.0471	12:00 – 20:00CDT	8.0	0	0
Floe L08 Belcher Ch. (visit #3)	2000	8 May	77.2895 96.0471	77.2895 96.0471	12:00 – 21:00CDT	9.0	0	0
Floe W01 Wellington Ch.	3200	9 May	75.2787 93.2907	75.2787 93.2907	14:30 – 19:30CDT	5.0	0	0

[a]floe size estimated from aerial photography or obtained by GPS as the helicopter flew along the floe's major axis

[b]add 4 hours to EDT to obtain UTC and 5 hours to CDT to obtain UTC

[c]total drift of floes while being sampled., as obtained from the floe trajectory logged by GPS

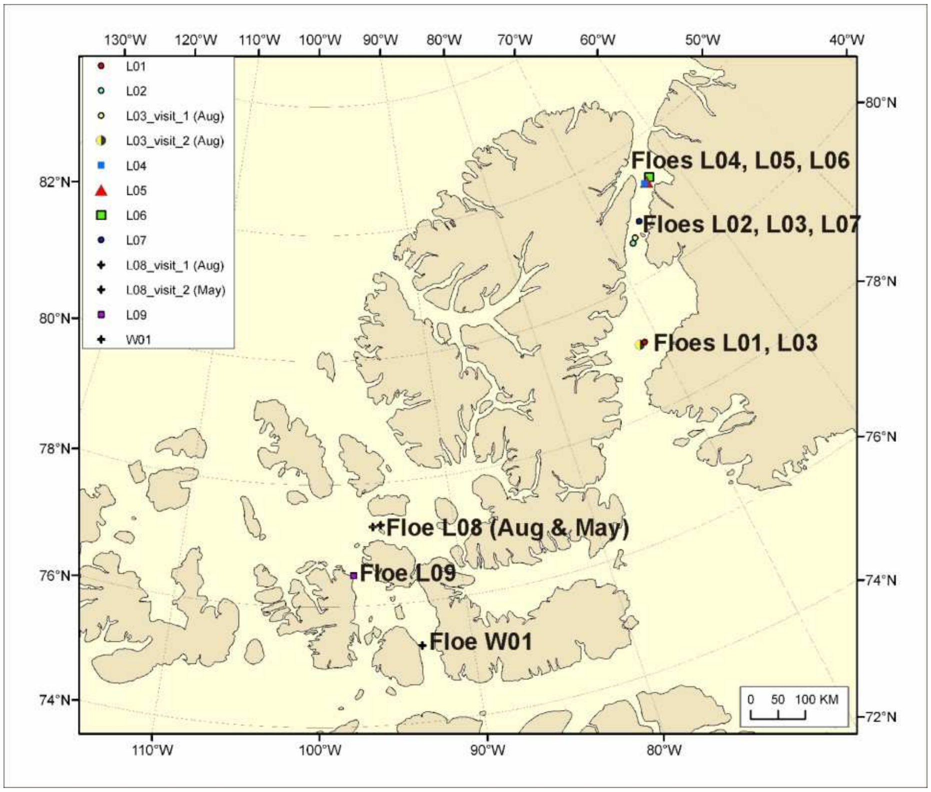


Figure 4 Location of multi-year floes sampled in Aug 2009 (9 floes) and May 2010 (2 floes)

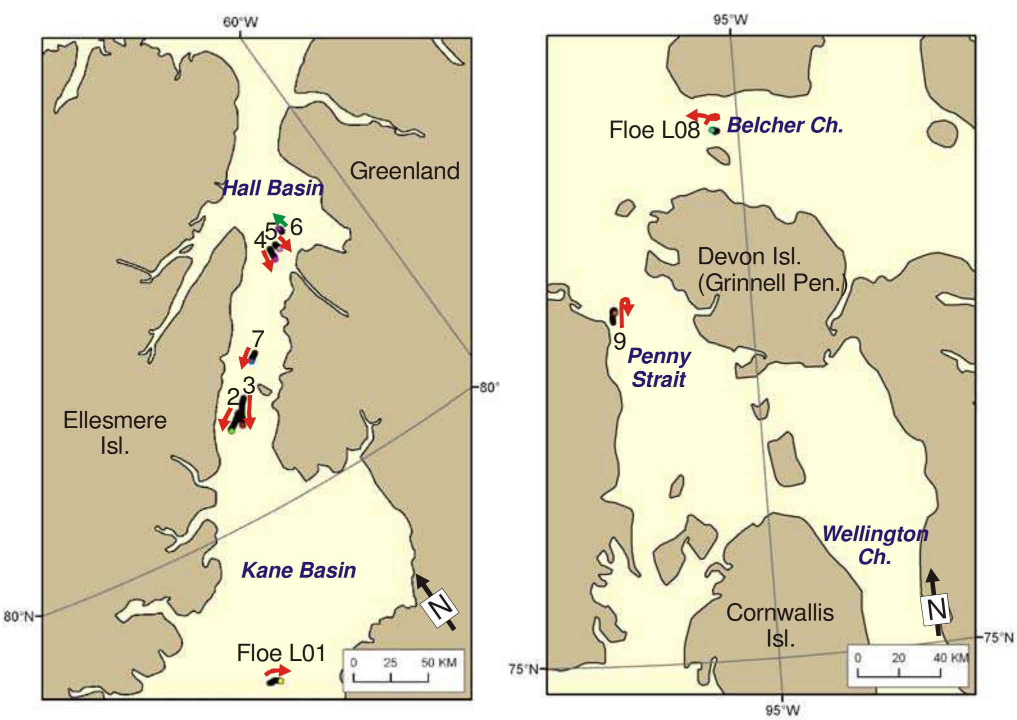


Figure 5 Location and drift of nine sampled floes

(a) Floes L01 to L07, eastern High Arctic and (b) Floes L08 and L09, central Arctic Archipelago

4.0 Methodology

A brief description of the sampling methodology is given here, followed by results from the field study.

4.1 Drill Hole Technique

The first order of business upon arriving on a floe was to map out several transects to obtain thickness information about the level and rough areas of the floe. Ice thickness “stations” were made by placing flags at 10 m intervals along a transect that was about 100 m long. Thicknesses at those stations were measured using the so-called ‘drill-hole technique’ which involved using a ¾” gas powered drill to bore up to 22 lengths (1 m each) of 2” diameter, stainless steel flighting through the full thickness of ice. Once the bottom of the ice had been reached, the auger flights were retrieved, disconnected one by one and the number of flights in each hole was noted as a rough indication of thickness. A more accurate measure of ice thickness was obtained by lowering a weighted tape into the hole until it hooked on the underside of the ice. The ice freeboard at each hole was measured by slowly raising the ice thickness tape until it cleared the waterline (or residual drill cuttings in the hole) and measuring the distance to the (snow-free) top ice surface. In a few holes, the freeboard could not be measured in this fashion because the waterline was so far below the ice surface that it could not be seen.

The drill hole technique was used to measure the ice thickness at up to 60 holes on each floe. The number of holes drilled depended on the ice thickness – drilling 20 holes in extremely thick ice was much more onerous than drilling 60 holes through mostly thin, multi-year ice. This conventional approach to measuring the ice thickness was labor intensive, but it provided one of the most accurate means of obtaining thickness data.

The drill hole technique also provided valuable information about the quality (or competency) of the ice, which is particularly important when drilling through multi-year ice in late summer since the ice can be porous. Although pockets and/or soft ice were encountered in many drill holes in August and sometimes in May, there was a substantial amount of solid ice in each drill hole. When the drill bit came upon a hard spot within a soft ice matrix, the ice had an entirely different ‘feel’. It should be noted that the bottom ice was not always soft – hard ice was observed at depths of 12 m, or more. Ideally, the strength of the multi-year floes would have been measured with the borehole indentor (see below under “ice property measurements” for spring 2010), but that would have required considerably more equipment and a much greater level of effort than could be supported during the 2009 mission.

A distinction should be made between drilling through hard ice, and difficult drilling. Drilling through soft, water-logged ice was usually much more challenging than drilling through hard, dry ice. That is because the drill team must be careful to hold back the weight of the 15 to 25 m of rods while drilling, lest the weight of the rods cause soft ice to pack into the drill bit to obstruct cutting. This happened several times when drilling deep into late-season multi-year ice. It required removing the drill rods from the hole, one by one, chipping the ice off the cutting bit and sending the rods back down the hole.

4.2 Ice Property Measurements

In May 2010, ice property measurements were made on cores to an ice depth of 6 m. Cores were extracted, in 1 m long segments, with a gas powered, fibreglass corer. The corer was used to make a 15 cm diameter borehole in the ice to a depth of about 6 m. Ice cores were retrieved, and processed, one metre at a time immediately after being emptied from the barrel. Temperatures were measured by inserting a calibrated, digital temperature probe into small holes that had been hand-drilled in the core at 20 cm depth intervals. The time that was required for the probe to reach an equilibrium temperature at the different depths was used to cut 2 cm thick, semi-circular pucks from the core at a depth intervals of 20 cm. The pucks were bagged as quickly as possible to minimize brine drainage and transported to base camp, where they were double bagged and brought to room temperature. After the bagged samples had reached room temperature, the salinity of the melt water was measured with an Orion model 105A portable conductivity meter.

The ice strength in the 15 cm diameter borehole was measured at depth intervals of 30 cm, to a maximum depth of 5.40 m. The hydraulically activated borehole indentor, designed and fabricated at the National Research Council Canada (NRC), was used to measure the *in situ* confined compressive strength (borehole strength) of the ice at each test depth. The NRC borehole indenter consists of a high-strength stainless steel hydraulic cylinder with a laterally acting piston and two indenter plates that are curved to match the wall of the borehole, as shown in Figure 6. A 10,000 psi electro-hydraulic pump, with an average flow rate of 20 in^3/min, was used to push each of the two indenters into the ice by a maximum distance of 2.5 cm. An external digital data acquisition system was used to record the displacement of each indentor plate and the oil pressure during each test.

The pressure and indenter displacement were also monitored throughout the test with a handheld keypad to ensure that the 10,000 psi capacity of the system and the 5 cm total diametrical displacement (the limit of the stroke ram) were not exceeded. After each test, the indenter plates were retracted, the borehole indenter was rotated 90° (to minimize the effect of cracking on subsequent tests) and the test unit was lowered to the next depth. In this report, the ice strength is reported as the maximum ice pressure attained during individual tests.

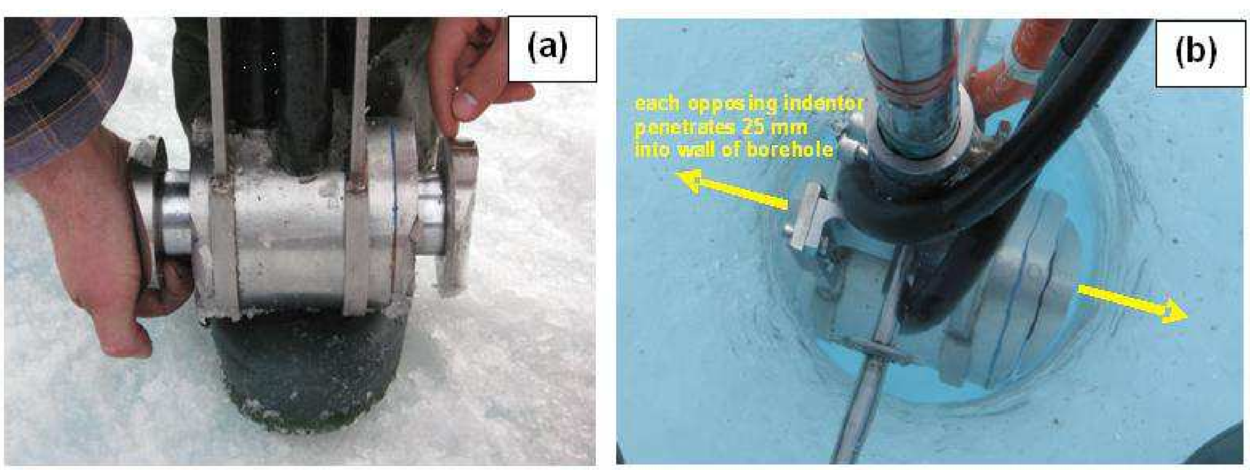


Figure 6 NRC dual acting borehole indentor
(a) two indentor plates at their full extension of 2.5 cm each and (b) borehole indentor positioned just below top ice surface, for demonstration purposes

4.2.1 Airborne EM Measurements

There are a number of airborne EM systems currently in use today, each one operates at different frequencies and uses different data processing systems. Airborne EM sensors function on the principle of *frequency* sounding, rather than *geometric* sounding. Frequency sounding uses special electronics to permit a wide range of operating frequencies to be used, without requiring the distance between the transmitter and receiver coils be changed. Airborne EM systems have the distinct advantage that they can be used to collect ice thickness information over a much larger area than is possible from on-ice measurements – but it also makes validating the results from the airborne system very challenging.

HEMs are commonly used to obtain the thickness of the polar pack (including multi-year ice), even though virtually no validation work has been done on ice more than 6 m thick – the rationale being that sea ice more than 6 m thick is relatively uncommon. In this report, drill hole measurements from four multi-year floes more than 6 m thick (Floe L04, L06, L07, L08) are compared to results from the HEM. No other study has provided this kind of comparison for thick multi-year ice.

Since the floes were drifting, the lat/long and time from the GPS that was used for the on-ice measurements was compared to the GPS that was used for the HEM in order to determine which flight segments passed along specific drill-hole transects. Additional checks were made by (1) inserting a file identifier into HEM data records to indicate when the helicopter passed over the ice floe team and (2) examining the timestamp of photographs of the HEM passing overhead. A point-by-point comparison of the EM data and drill hole data is not possible because the EM sensor measures the apparent conductivity over a region, rather than a single point. Nevertheless, the data comparison is quite illuminating, as shown later.

4.2.1.1 HEM bird used during 2009 field program

Following is a short description of the AWI helicopter-borne EM system (HEM) which is similar to the HEM used during the 2009 Nares Strait field program (C. Haas, personal communication). The description of the AWI airborne EM system (after Haas et al., 2009) is meant to give the reader an appreciation of the complexity of HEM. The AWI airborne EM sensor is 3.5 m long, has a diameter of 0.35 m, and weighs 105 kg. Generally, the HEM is towed 10 to 20 m above the ice surface (Figure 7). All components are mounted on a rigid plate inside a cylindrical kevlar shell. The AWI HEM operates at a frequency of 4 kHz and has a total of four coils: the transmitter and receiver coils, plus a bucking coil (for compensation of the primary EM field at the receiving coil) and a calibration coil (to generate very accurate signals of known phase and amplitude). The inboard computer processes Inphase and Quadrature components of the continuous harmonic signal at a sampling interval of 0.1 s which corresponds to a point spacing of approximately 4 m at a typical flight speed of 80 kt. For sea ice over typical seawater, the Inphase component of the 4 kHz frequency is used for ice thickness retrieval because it has the strongest signal, the least noise and smallest drift.

The 4 m sample spacing of the HEM should not be confused with its "footprint", which is considerably larger. Because the low frequency EM field is diffusive, its strength represents the average ice thickness of an area that is roughly 3.7 times the instrument's height above the seawater interface (after Kovacs et al., 1995). In this study, the EM bird was towed from 10 to

20 m above the top ice surface (15 m on average), which corresponds to a footprint of roughly 75 m for 5 m thick ice, 90 m for 10 m thick ice and 130 m for 20 m thick ice.

Haas et al. (2009) focus upon EM measurements over level ice, recognizing that the HEM usually underestimates the maximum thickness of deformed ice by as much as 50% or more. This is partly due to the large footprint of the HEM, but the authors state that seawater-filled cavities between loosely consolidated ice blocks may channel electrical currents, preventing any deeper penetration of the EM field. That effect exacerbates the tendency of the HEM to underestimate the thickness of deformed sea ice.

Figure 7 Towing the HEM (circled in yellow) over Floe L08, August 2009

4.2.2 *In situ* Temperature Chains

In August, two multi-year ice floes were selected to install 11 m long temperature chains in order to document the ice temperature profile of the full thickness of ice, for up to one year. The temperature chain, its data acquisition system and the Iridium telemetry were housed in a buoy (“ice buoy”) that was slung from the CCGS *Henry Larsen* to the floe by helicopter. Since the Screening Decision Report issued by the Nunavut Impact Review Board (NIRB) recommended that the ice buoy be fully recoverable (see Appendix B)[2], a great deal of effort was spent designing, fabricating and testing the ice buoy. The ice buoy was designed and constructed at the National Research Council’s Design and Fabrication Services (DFS) in Ottawa. It was designed to protect the sensitive telemetry and data acquisition system from the elements, bear attacks and water intrusion should the ice buoy melt free of the ice. The body of the buoy was constructed of stainless steel to prevent corrosion (20” high by 4.5 ft diameter, at 150 kg). The top of the buoy was covered with a high impact, stabilized acrylic dome (42” diameter, 25 kg) to permit unimpeded transmission from the Iridium and GPS antennas, and to protect the six solar panels needed to charge the batteries. The buoy carried a payload of about 125 kg (two gel cel batteries, data acquisition system, heater for Iridium modem, solar panels). The ice buoy was fully assembled and tested in the wave basin at NRC-CHC prior to shipping, in order to ensure that it floated and remained watertight.

The two 11 m long temperature chains used a total of 41 BetaTherm 100K6A thermistors. The thermistors were spaced evenly (at 25 cm intervals) to a depth of 10 m, below which a final sensor was placed (at the 11 m depth) to measure the seawater temperature. Two cables were used for each temperature chain. The first cable (7 m long) incorporated sensors from ice depths 0 to 5 m, allowing for the 2 m lead length. The second cable (13 m long) contained sensors from ice depths 5.25 to 11 m. The ready-made cables were purchased from Campbell Scientific Canada, were said to be flexible at cold temperatures, provided a durable, watertight enclosure around each thermistor (see the photograph in Appendix B) and had been field tested – although not in an application exactly like this one.

An automated two-way Iridium telemetry system was used to phone the floe’s data acquisition system each day, download daily temperature measurements (measured at 15 minute intervals, throughout the day), and permit changes to be made to the program as required. The two issues that were believed to have caused problems for the telemetry system in 2008 were remedied during the 2009 field season by (1) using an acrylic dome to prevent snow from accumulating over the antenna and impeding reception and (2) using a heater to periodically warm the Iridium modem when temperatures dropped below -5°C. Despite those changes, the telemetry system failed after two months of operation, most likely because of an incompatibility between the Iridium modem and the Campbell Scientific data logger (see Appendix B).

[2] *“Proponent should consider designing the equipment for more accurate recovery (i.e. bear proofing containers to reduce potential for equipment to be damaged, and floatation containers to keep units accessible if ice melts), and working with local community HTO’s for quicker recovery when signals are lost for best chance of recovering equipment.”*

5.0 Results from Field Studies

5.1 Floe L01: Kane Basin, Aug 10

The first multi-year ice floe of the season was sampled on 10 August, as the ship transited east towards the Greenland coast. Ice conditions in the eastern part of Kane Basin (Greenland side) were considerably lighter than in the west (Ellesmere side). Most of the floes on the Greenland side were widely dispersed and drifted in open water, whereas floes on the Ellesmere side were more closely-spaced. Floe L01 was about 2.2 km across, as measured by flying across the floe's long axis. The region of ice that was selected for sampling had a fresh looking ridge, about 3 to 4 m high (Figure 8). Apart from the sinuous ridge that extended across Floe L01 (Figure 9), the surface of the floe was relatively level, with extensive ponding. The field team landed on Floe L01 at 09:36hrs and departed the floe at 17:43hrs. During that time, the floe drifted 7.8 km northeast at an average rate of 0.9 km/hr.

Figure 8 Three metre high ridge on Floe L01

5.1.1 <u>Surface and bottom topography</u>

Figure 9 shows the locations of some of the drill holes that were made along five transects on Floe L01. Transect 1 was perpendicular to the ridge that wound its way across the floe, transects 2, 3 and 4 were made on the thicker of the two floes, and transect 5 passed along the ridge crest. A total of 42 holes was drilled along the five transects, resulting in an average thickness of 4.2 m (± 3.0 m).

Figure 10 shows the surface and bottom topography of Floe L01 along the five transects. A maximum freeboard of 0.8 m was measured on the level portions of the sampling area. The ridge had freeboards ranging from 1.4 to 3.0 m. The maximum ice thickness (12.9 m) was measured on the ridge, where the sail was 3.0 m high (hole RC1) and the minimum thickness (0.9 m) was measured near a drainage feature (hole B15). Most regions of Floe L01 had minimal surface roughness and a smooth bottom topography.

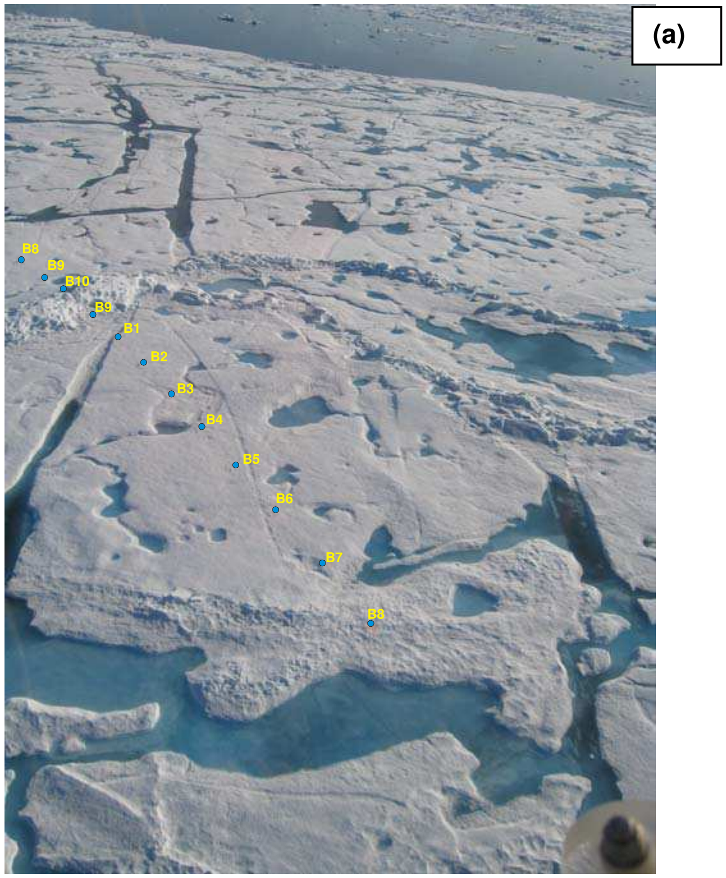
Some of the drill holes on Floe L01 revealed the presence of loose blocks of ice on the underside of the floe, as noted in Table 2. The loose blocks made obtaining accurate ice thickness measurements difficult. The blocks were dislodged while drilling, only to shift back into position after the drill rods were removed from the hole, which prevented the ice thickness tape from reaching the bottom of the hole. Each time that happened, the 1 m long drill rods were reconnected and passed back down the hole to push the blocks out of the way. Sometimes the blocks stayed out of the way, but in many cases, it simply was not possible to use the tape to accurately measure the ice thickness. In those cases, the ice thickness was estimated from the number of drill rods required to penetrate through the full thickness of ice. The absence of decimals in Table 2 indicates when the ice thickness was estimated from the number of drill rods.

Drilling through Floe L01 revealed that the ice in a number of holes was not solid throughout its full thickness, but contained pockets (voids) and/or soft layers of ice at various depths (Table 2). For example, in hole B9, drilling indicated solid ice to a depth of about 6 m, then a soft spot was encountered, beneath which the ice was solid to a depth of approximately 10 m. Loose blocks were noted below a depth of 10 m.

Table 2 Drill holes on Floe L01 in which pockets or loose blocks were noted

Hole	**thickness (m)***	**loose blocks noted**	**notes**
B1	3.6	Yes	--
B9	10	Yes	solid ice to 6 m depth, soft spot, solid ice to 10 m. Since thickness tape will not pass below 7.2 m (due to misalignment caused by a void), the ice thickness was estimated from number of rods used.
B10	7.8	Yes	--
B12	9.3	Yes	--
B17	6.9	No	pocket at 4.0 m depth
B18	4.8	No	pocket at 4.0 m depth
B19	4	No	pocket at 2.7 m depth
B20	5	No	pocket at 3.9 m depth

* thicknesses with one significant figure were estimated from number of drill rods used in hole



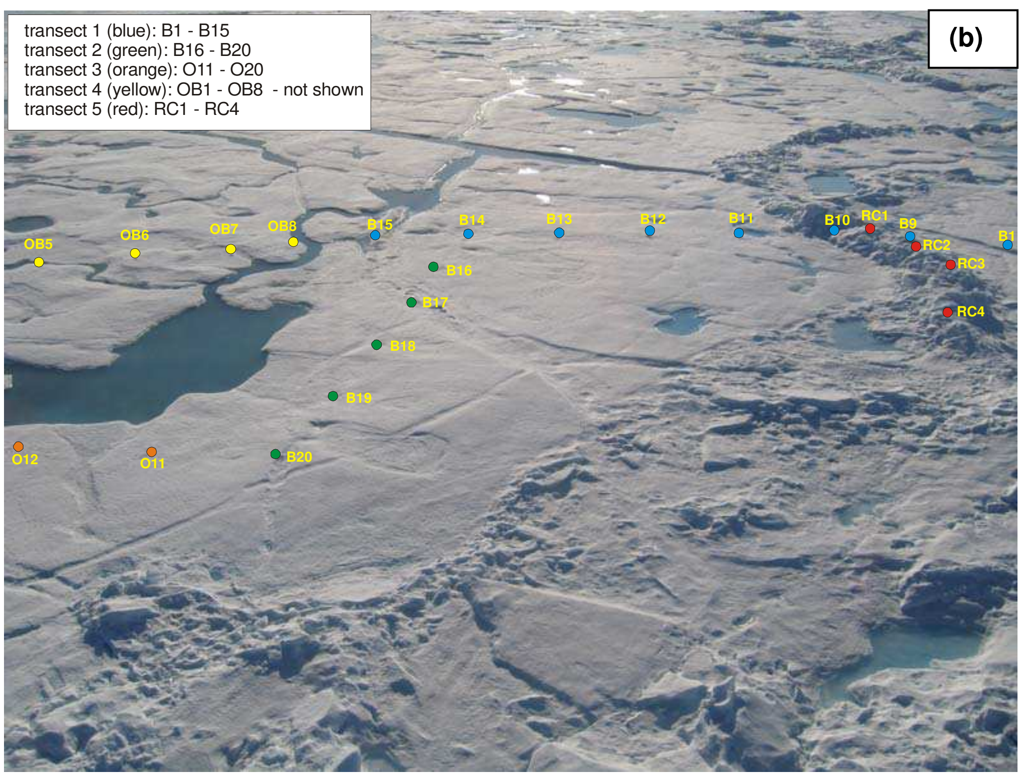


Figure 9 Aerial views of Floe L01
(a) a portion of transect 1 and (b) portions of transects 1, 2, 4 and 5 where drill holes were made

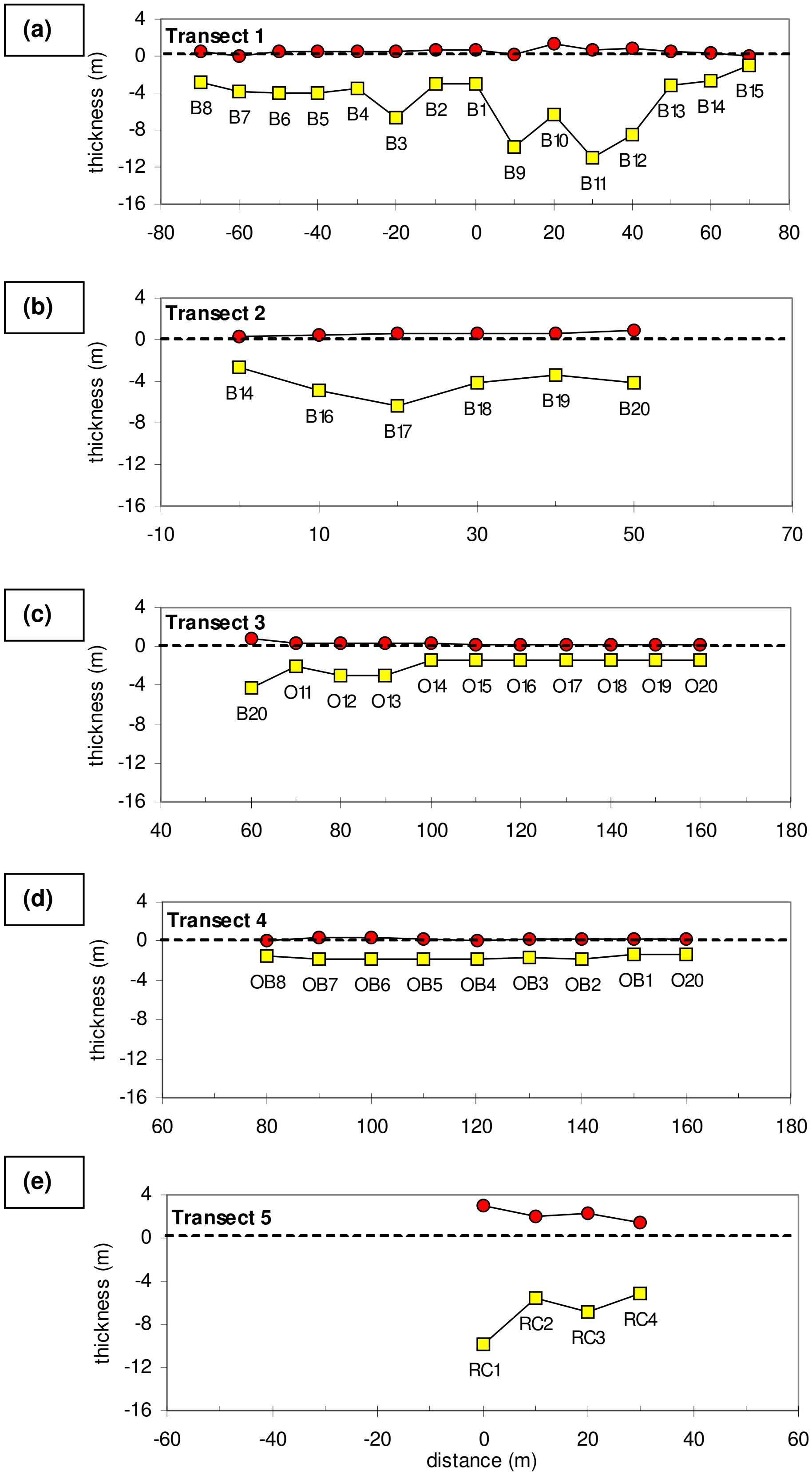


Figure 10 Floe L01: Surface and bottom topography from drill hole measurements

5.2 Floe L02: Nares Strait, Aug 11

Since most of the ice in the vicinity of the ship on 11 August qualified as isolated, level multi-year ice floes drifting in open water, an aerial reconnaissance was conducted to investigate ice conditions further north, where it was hoped more formidable floes could be found. The field team flew 60 km north to examine the ice lodged against Franklin Island, which satellite imagery suggested might be a good region for conducting on-ice measurements. The satellite imagery was deceptive however; ice conditions to the north proved similar to conditions around the ship. Having determined that the ice further north offered no real advantage, it was decided to return south to select a floe in closer proximity to the ship.

Floe L02 (Figure 11) was selected because it was representative of ice in the area, most of which seemed to be fairly young multi-year ice. The first drill hole on Floe L02 returned a thickness of 5.8 m – information that was directly relayed to the pilot, who had said that 'floes in the area were paper thin'. Letting the ship (and the pilot) know that the ice was almost 6 m thick, despite its appearance, was meant to allay any concerns about the safety of field team – it also confirms that visual observations commonly underestimate the ice thickness. Measurements were conducted on Floe L02 for about 7 hours, during which time the floe drifted 13.2 km south at an average speed of 1.8 km/hr.

5.2.1 Surface and bottom topography

A total of 61 holes was drilled along three, 100 to 200 m long transects (Figure 11) resulting in an average thickness of 3.4 m (±1.3 m). The thickness profiles in Figure 12 show that, oddly enough, the very first drill hole returned the thickest ice (5.8 m, hole OB3), whereas the ridged area of ice was just 5.3 m thick (hole OB4). The thinnest ice (1.2 m) was measured near what appeared to be a healed fracture in the ice (hole O3) but the ice was 4 to 5 m thick just 10 m away (holes O2 and O4, Figure 12-b). The freeboard of Floe L02 ranged from zero near melt ponds or drainage features, to a maximum of 1.0 m. Pockets and/or soft areas of ice were encountered in 7 of the 61 drill holes (Table 3).

Table 3 Drill holes on Floe L02 in which pockets or loose blocks were noted

Hole	**thickness (m)**	**loose blocks noted**	**notes**
B17	1.8	No	pocket, depth not specified
O2	3.5	No	pocket, depth not specified
O3	1.3	No	pocket, depth not specified
O6	4.2	No	soft at approx. 3 m depth
O8	1.5	No	pocket, depth not specified
OB7	4.1	No	pocket at approx 1 m depth
OB5	3.7	No	pocket, depth not specified

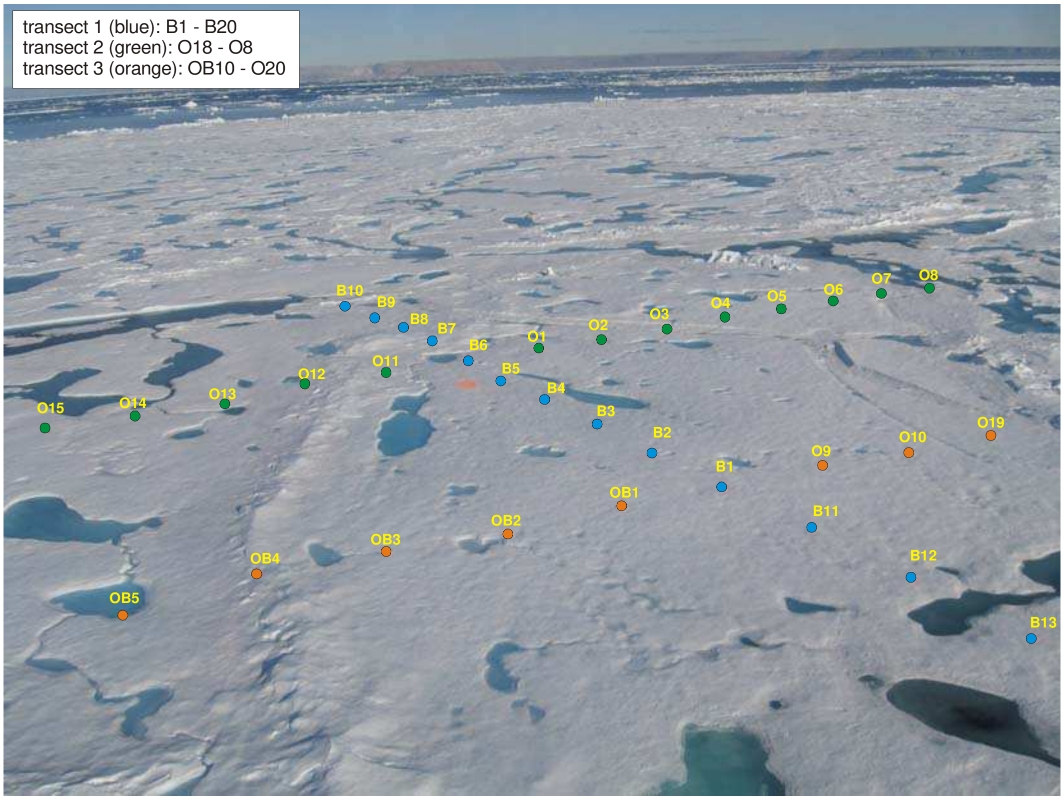


Figure 11 Aerial view of Floe L02 showing Transects 1, 2 and 3

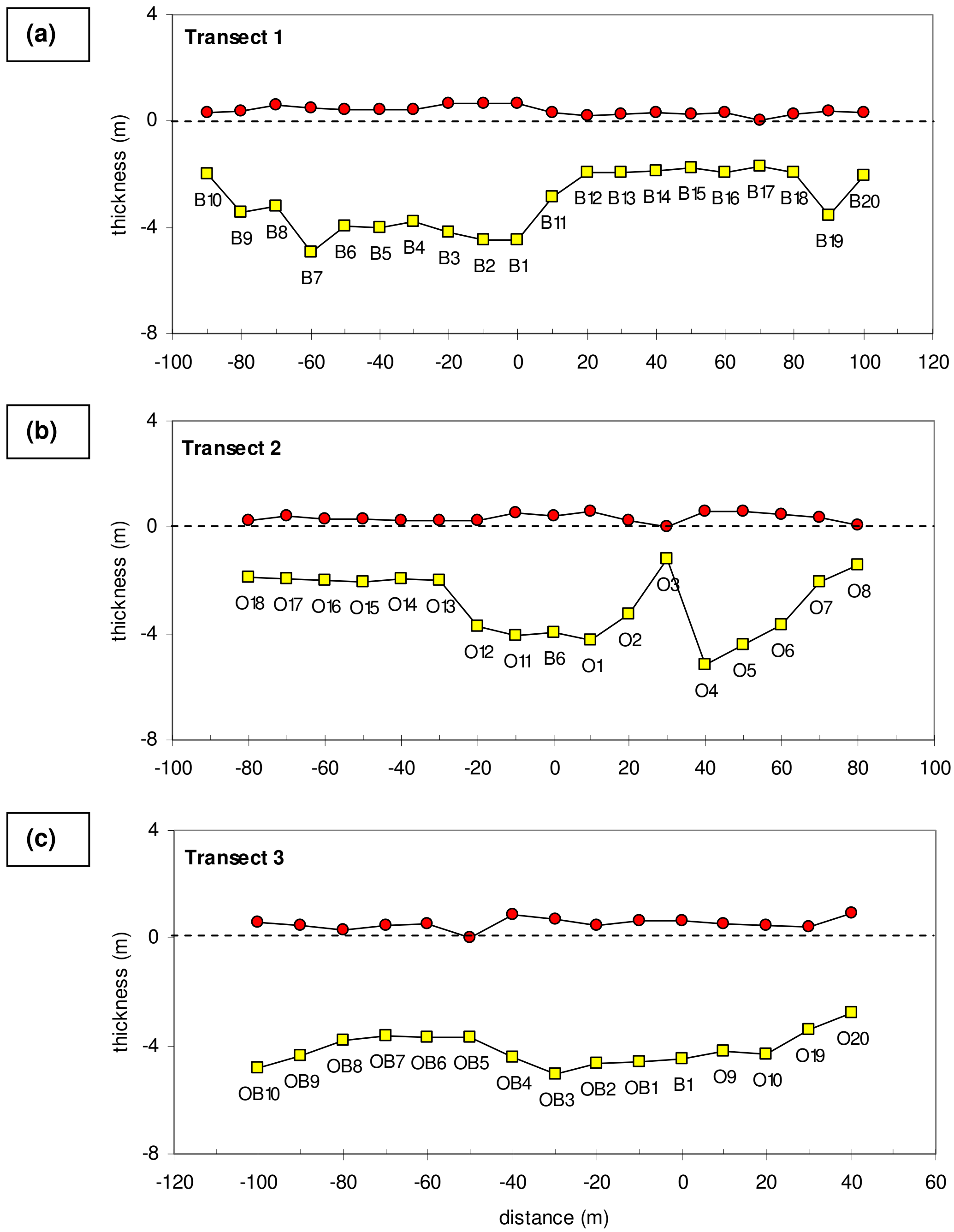


Figure 12 Floe L02: Surface and bottom topography from drill hole measurements

5.3 Floe L03: Nares Strait (Aug 13, 14) and Kane Basin (Aug, 23)

Floe L03 (2.0 km diameter) was identified as a potential candidate for sampling during the 13 August aerial reconnaissance of Nares Strait. The floe drifted next to a large fragment of glacial ice that had recently calved from the floating tongue of Petermann Glacier. The floating tongue of the glacier is 70 km long and about 20 km wide, thinning from 600 m at its grounding line to 60 m at its front (as noted in Peterson et al., 2009). Figure 13 shows the fragmented piece of glacial ice (a) from the air and (b) as it was seen from Floe L03. The glacial fragment was more than 1 km long and had up to 20 m of freeboard. In July 2008, another large fragment of glacial ice (3.5 km by 10 km) had fractured from Petermann glacier, and subsequently drifted towards Jones Sound (Peterson et al., 2009). Measurements from an ice profiling sonar in Nares Strait captured the drifting tabular iceberg in 2008, revealing a mean thickness of about 63 m (H. Melling, personal communication).

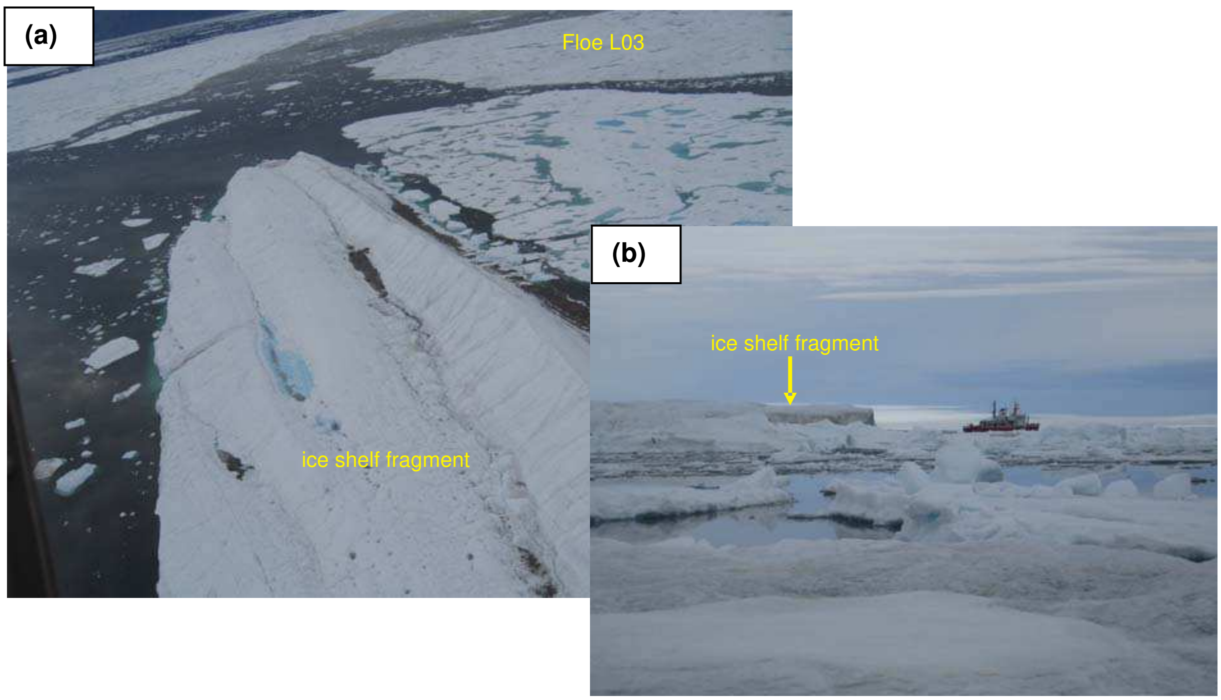


Figure 13 Floe L03 (1.5 km diameter) and neighboring ice fragment from Petermann Glacier

Figure 14-a shows that Floe L03 was actually a composite of two different multi-year floes: the part of the floe in the foreground of the image was very deformed and had a dirty surface, whereas the ice towards the background of the image was more level, some areas having melted through the full thickness of ice (dark green/black areas within the ponds). On-ice measurements were made in the extensively hummocked area of ice that was similar to several of the floes sampled in the region in 2007 (Johnston, 2008-b). The 3 m high hummock in Figure 14-b was one of the largest hummocks in the sampling area.

Although not planned as such, Floe L03 was visited on four separate occasions during the Nares Strait program. The first visit was made to conduct detailed thickness measurements (13 August), a second visit was made to install a CALIB tracking beacon (14 August), a third visit was made to assess whether the Floe L03 was still suitable for installing one of the ice buoys (morning of 23 August) and then finally to deploy the ice buoy (late afternoon 23 August).

5.3.1 Surface and bottom topography

Floe L03 (13 August) drifted 18.8 km south at an average speed of 2.0 km/hr during the 9 hours that were spent on the ice. A total of 32 holes were drilled at 50 flags along two transects. Drilling those 32 holes was no small feat because both transects extended through areas of extensively hummocked ice. Most of the holes were drilled along Transect 1, which extended from the floe edge (hole B1) into a severely hummocked area of ice (hole B30). Four additional holes were drilled along Transect 2, where it intersected Transect 1 (Figure 14-a). The average thickness of Floe L03 was 8.6 m (±4.3 m).

The top surface of Floe L03 appeared daunting from the air, but drill-hole measurements showed that the roughness of the floe's top surface paled in comparison to its bottom surface (Figure 15). Several of the floes that had been sampled during the 2007 Nares Strait program had the same characteristics (Johnston, 2008-b). The hummock in Figure 14-b, which was about 3 m high, was the most substantial feature in the sampling area. This hummock was probably about 30 m thick, based upon the 12 to 14% ratio of freeboard to total ice thickness from nearby holes. The hummock in Figure 14-b marked the beginning of the most severely deformed area of ice – all of the drill-holes beyond that point returned thicknesses of more than 12 m (B27, B28, B29 and B30). The area of hummocked ice extended about 100 m on either side of Transect 1, terminating in a dramatic shear feature, about 40 m past the end of Transect 1 (Figure 14-a).

The maximum thickness of Floe L03 (19.9 m) was measured at hole B27, near the 3 m high hummock. The minimum thickness (2.7 m) was measured near a melt pond (hole B16). The freeboard of Floe L03 ranged from 0.1 to 2.45 m. Pockets were encountered in only four of the 32 drill holes (holes B6, B9, B10 and B29 see Table 4). Hard or very solid ice was met near the bottom of two holes. Loose blocks were felt on the underside of the floe at only one hole (B22), but they may also have been present at holes B26 and B27 because three more metres of drill rod were needed to penetrate the ice at both those holes than measured from the thickness tape (16.6 m vs. 19 rods; 19.9 m vs. 23 rods).

Table 4 Drill holes on Floe L03 in which pockets or loose blocks were noted

Hole	thickness (m)	loose blocks noted	notes
B6	8	No	pocket at 5.8 m; soft at approx 7 m depth
B9	13	No	pocket at approx. 9 m
B10	12	No	hard ice at approx. 11 m
B14	3.8	No	hard ice towards bottom of hole
B22	9.2	Yes	felt loose piece of ice at bottom of hole
B26	16.6	No	thickness tape gave 16.6 m, but used 19 rods to drill hole
B27	19.9	No	thickness tape gave 19.9 m, but used 23 rods to drill hole
B29	14	No	pocket at approx 11 m

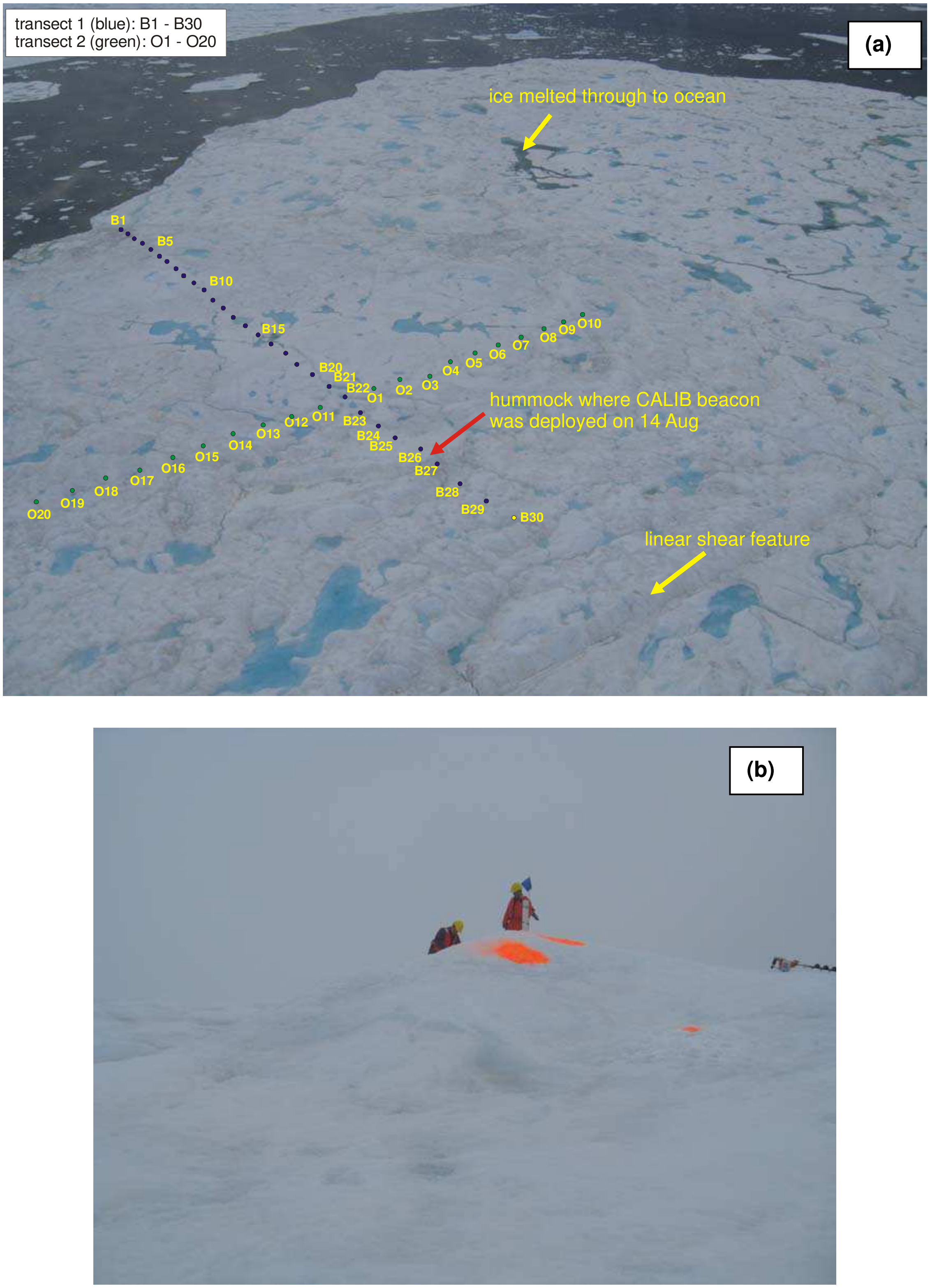


Figure 14 Aerial view of Floe L03
(a) 13 Aug, when drill hole measurements were made and (b) 14 Aug, when the CALIB beacon was installed on the 3 m high hummock between holes B26 and B27. The hummock was not drilled through its full thickness.

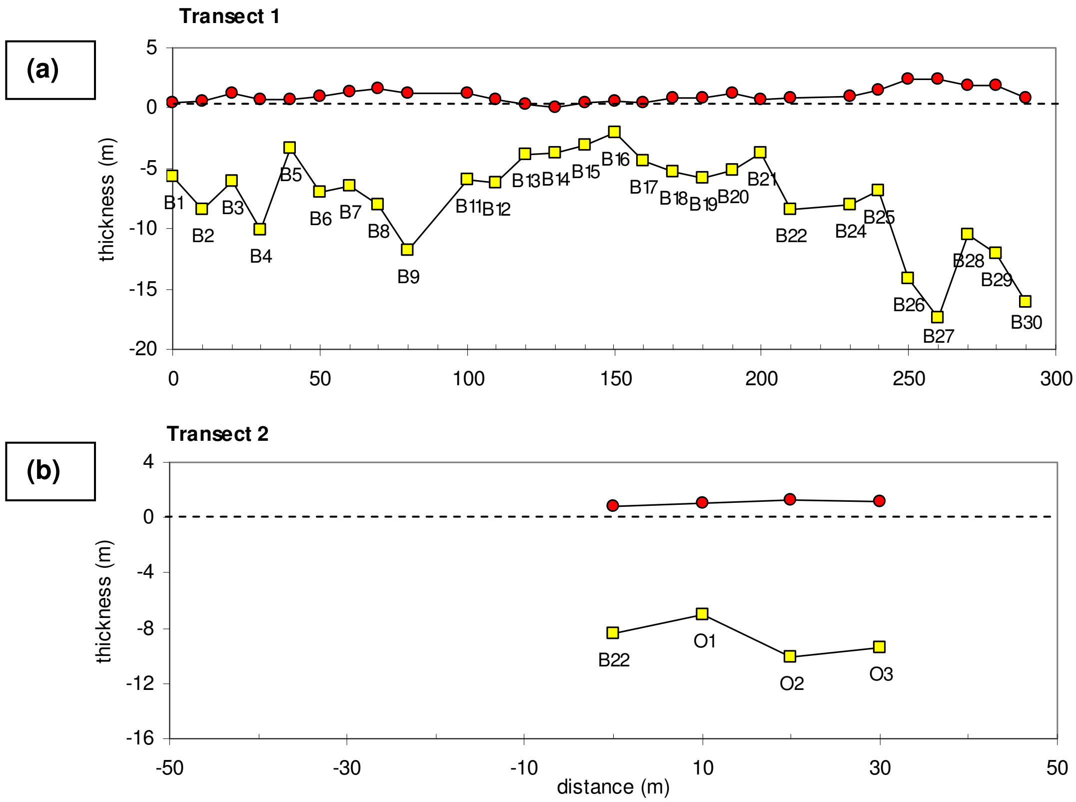


Figure 15 Floe L03: Surface and bottom topography from drill hole measurements

5.3.2 <u>Tracking the position of Floe L03 with a CALIB beacon</u>

The field team departed Floe L03 at 18:00 hrs on 13 August, after a long day of measurements. Although Floe L03 was only the third floe sampled, it certainly qualified as a potential candidate for one of the two ice buoys to be deployed during the program. Upon returning to the ship that evening, and hearing that the ship would be leaving the area, it was thought prudent to install a beacon on Floe L03 the following morning, so that the floe could be re-visited when the ship transited south, one week later.

The morning of 14 August brought dense fog, but also good luck. At first glance, it seemed that the ship had sidled up to a floe very similar to Floe L03. Had the ship and the floe drifted together during the night? All eyes on the bridge scanned the horizon for the orange marking paint from the previous day's drill hole measurements. Soon, the Chief Officer announced "I see it ... over there!". Word was given to ready the crane and the over-the-side basket so that a field team of three could be deposited on the ice to install the beacon. The 3 m high hummock in Figure 14-b was selected as a home for the beacon. A hole was drilled in the hummock (20 cm deep, 15 cm diameter), into which the 10 cm diameter beacon was deposited. Large orange circles were painted on all sides of the hummock to help locate the floe should it be able to re-visit it the following week, during the transit south.

5.3.3 Installing Ice Buoy No. 1

Ten days later, on 23 August, the ship passed south of where Floe L03 had been visited on 13/14 August, expecting to find the floe nearby. It was surprising to learn that the coordinates of the CALIB beacon on the floe put it about 26 n.mi. (48 km) northeast of the ship. That meant the floe was north of where the ship was now stationed, at the entrance of Alexandra Fjord. The science team and Captain Vanthiel fully expected that the floe would have drifted south, not northeast.

The position of the floe presented a problem: the ship was too far away to allow people to work on the floe for any length of time (in case the floe needed to be evacuated should something go wrong). It was also deemed too far to sling the 250 kg ice buoy to the floe. The only solution was to conduct an aerial reconnaissance to see whether Floe L03 was still suitable for installing the ice buoy and, if it was, to steam towards the floe. If the floe had severely deteriorated since being visited ten days ago, the tracking beacon would be recovered (for later use) and no additional instrumentation would be installed. If the floe was still a suitable candidate for installing the ice buoy, the ship would steam the distance (26 n.mi or about 4 hours) to the floe. Captain Vanthiel and H. Melling were prepared to do this, even though it would delay the oceanographic program (which required heading south, not north).

Since the objective of the first aerial reconnaissance was merely to determine whether the floe was still a suitable candidate for the ice buoy, no field equipment was taken. The helicopter landed on Floe L03 at 12:40 hrs to find the floe still very much intact (Figure 16-a) – although the ice surface appeared to be slightly more ponded than the last visit. The tracking beacon was not at the crest of the hummock, where it had been installed on 14 August, instead it laid on the (dry) ice at the foot of the hummock. Evidently, ice around the beacon had melted enough to allow it to tip over and roll down the hummock. After that quick check, the field team returned to the ship.

Having determined that the floe was still suitable for installing the instrumentation, the ship changed direction to head northeast to the floe. By about 18:00 hrs the ship was within range of Floe L03 and a field team of four was dispatched to locate a place for installing the ice buoy. Two holes were drilled in the hummocked ice at the end of Transect 1. Drilling a 2” hole for the temperature chain proved difficult, as did locating the (soft) bottom of the ice sheet with the ice thickness tool. The ice at the first hole was more than 14 m thick. A second hole was drilled about 5 m away from the first, returning a thickness of 12.4 m thick. Although that was still too thick for the 11 m long temperature chain, it would have to suffice in the interest of time.

The second group of recruits arrived at 20:45 to help with the installation, followed shortly after by the ice buoy, dangling from the helicopter by a 45 m long cable (Figure 17-a). By 21:30 hrs, the temperature chain had been installed in the 12.4 m thick ice (Figure 17-b), roughly 300 m from the floe edge (Figure 16-a, b). The uppermost temperature sensor was flush with the top ice surface, below which the sensors extended to a depth of 11 m (the bottommost sensor had been intended to measure the seawater temperature, but instead measured the temperature of the ice at a depth of 11 m).

Having installed the ice buoy, a few repeat holes were drilled at several of the drill-hole stations to provide an indication of the thinning that had taken place over the past 10 days. The repeat holes were drilled about 15 cm from the hole that had been made during the first visit to the floe, ten days prior. The repeat drill holes indicated that the ice at holes B17 and B26 underwent 20 cm and 60 cm of ablation respectively (see Table 5), whereas the ice at hole B24 thinned by 3.9 m over ten days. That seems unlikely, if melting alone is taken into account, but it may be that the radical decrease in thickness was caused by loosely consolidated blocks on the underside of the ice dislodging as the floe drifted 48 km through the relatively warm surface waters of Kane Basin. It is also possible that the ice thickness 15 cm away from the initial drill hole would have been quite different than the adjacent hole, since radical differences in thickness have been observed over small scales on the underside of shear ridges (B. Gorman, personal communication).

Table 5 Comparison of drill hole thicknesses for 13 August and 23 August

Drill hole	**thickness on 13 Aug**	**thickness on 23 Aug**	**difference***
B17	4.8 m	4.6 m	-0.2 m
B24	8.9 m	5.0 m	-3.9 m
B26	16.6 m	16.0 m	-0.6 m

*Drilling adjacent holes to determine the decrease in thickness of deformed multi-year ice is subject to considerable error, as discussed in the text. As such, it is not a suitable means of measuring ablation.

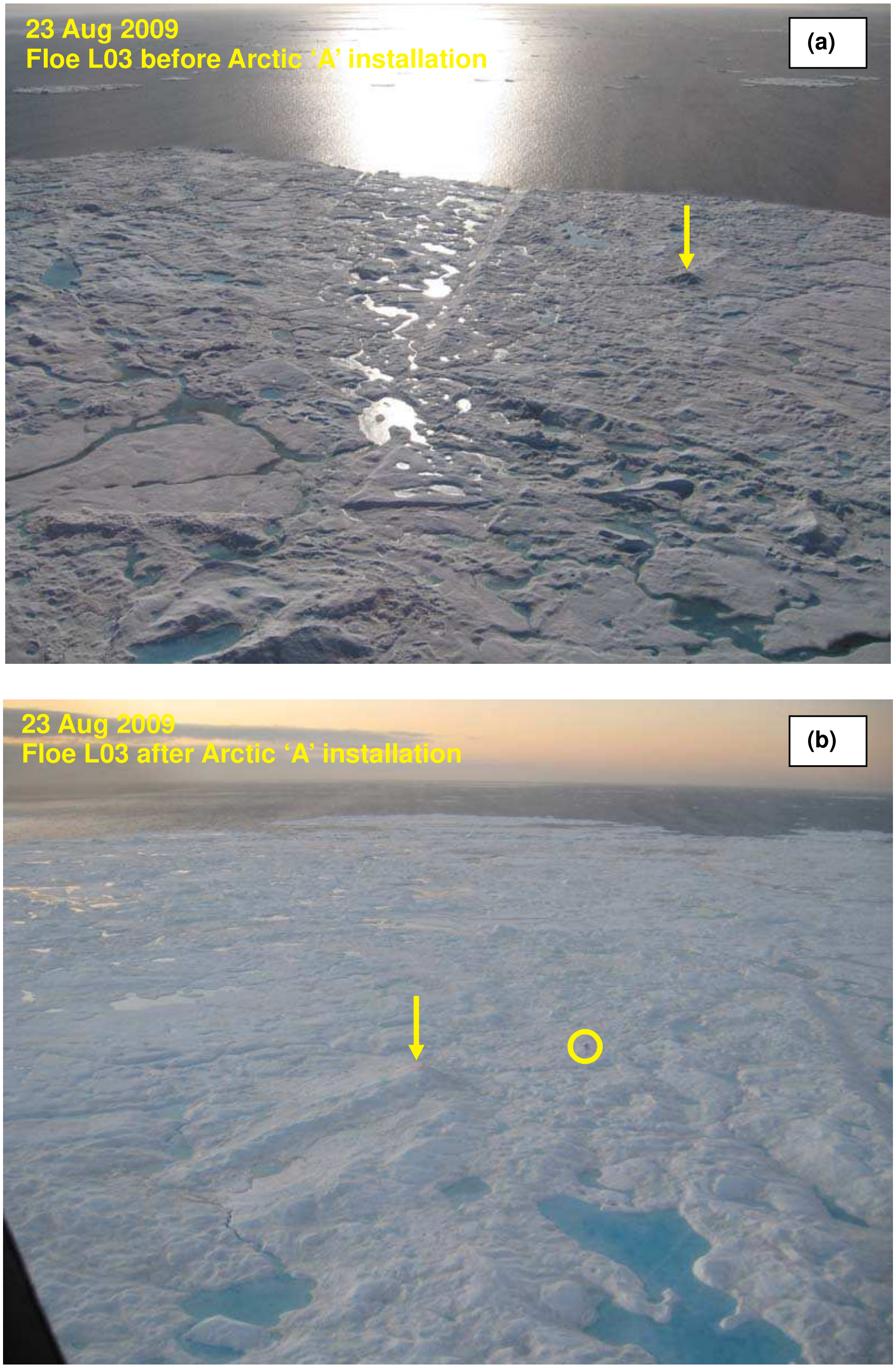


Figure 16 Aerial views of Floe L03 on 23 August
(a) before and (b) after the ice buoy was installed (circled area). The arrow shows the hummock on which the CALIB was installed/removed.

Figure 17 Installing the ice buoy on Floe L03
(a) using a helicopter to sling the ice buoy into position and (b) ice buoy as it was left late in the late evening of 23 August. The temperature chain was installed in 12.4 m thick ice. The black protective metal conduit extending in front of the ice buoy houses the portion of temperature cable above the ice surface.

5.3.4 Changes in Temperature and Thickness of Floe L03

From 14 to 23 August, the tracking beacon reported Floe L03's position every 15 minutes. Once the CALIB tracking beacon had been retrieved and the ice buoy installed (23 August), the floe's coordinates were obtained from the ice buoy itself, which logged the floe's position only twice per day, to conserve battery power. Figure 18 shows the floe's drift from 14 August until the last measurements were obtained from the ice buoy on 16 September. The map clearly shows which portion of the record was obtained from the CALIB tracking beacon (closely spaced data points) and which portion was obtained from the ice buoy's GPS (widely spaced data points).

From 14 to 18 August, Floe L03 drifted south along the coast of Ellesmere Island, until strong winds forced the floe northeast, where the ship caught up with it heading towards the Greenland coast on 23 August. Floe L03 followed the Greenland coast until it drifted back towards Ellesmere Island, and then flushed through Smith Sound on 2 September. The floe then entered the northern part of Baffin Bay and drifted south until 16 September, where it last reported east of Devon Island. There, the floe may have deteriorated to such an extent that it could not withstand the open water swell in northern Baffin Bay. If that was the case, Floe L03 would have joined the ranks of many other fragmented multi-year floes in an area. Given the extreme thickness and topography of Floe L03, it is also quite possible that the floe continued to drift south, but no data were transmitted because of a communication failure, since it was later learned that the modem and the logger were incompatible (see Appendix B). Attempts to re-establish communication with the Floe L03 were made for many months, unsuccessfully.

Although temperatures from Floe L03 transmitted for about only one month, the floe relayed extremely valuable information about how quickly the properties of drifting multi-year ice floes can change. First, select temperature profiles from 23 August to 16 September (Figure 19) show that all sensors in the temperature chain had come to equilibrium with the surrounding ice (-1.5°C or colder) by 25 August, two days after the chain was installed. That information can be used to infer that the full length of temperature chain had completely frozen into the ice – an important assumption when calculating the amount of thinning that occurred on the underside of the ice. In late August, Floe L03 had the characteristic "C-shaped" temperature profile of late-summer multi-year ice to a depth of 8 m, with the coldest temperature (-5°C) occurring towards the interior of the ice. Below a depth of 8 m, the ice was isothermal (near 0°C) and remained so until the last data were transmitted on 16 September.

Beginning on 8 September, the ice at a depth of 11 m began to steadily warm (not shown). Recall that 1.4 m of ice extended below the 11 m temperature sensor when it was installed on 23 August. The warming trend began at the 11 m sensor and moved progressively further up the chain until 16 September, when the 12 sensors between the 7.5 and 11 m depths all registered temperatures of +0.3°C to +0.4°C – indicating that the sensors were now in seawater. Warming of the bottom ice slowed as Floe L03 drifted towards the colder Canadian waters. Preliminary results suggest that the systematic manner in which the bottom ice warmed, and the rate at which those changes occurred, can be interpreted as a thinning of almost 5 m (to a thickness of 7.25 m, from 12.4 m). Most of that thinning occurred between 8 and 13 September, as the floe crossed Baffin Bay from the warmer Greenland waters to colder Canadian waters (Figure 18). The 5 m decrease in thickness is phenomenal, but it also must be remembered that the ice below a depth of 8 m was isothermal in late August and that the ice may have been loosely consolidated – factors that would have contributed to the rapid deterioration of the bottom ice.

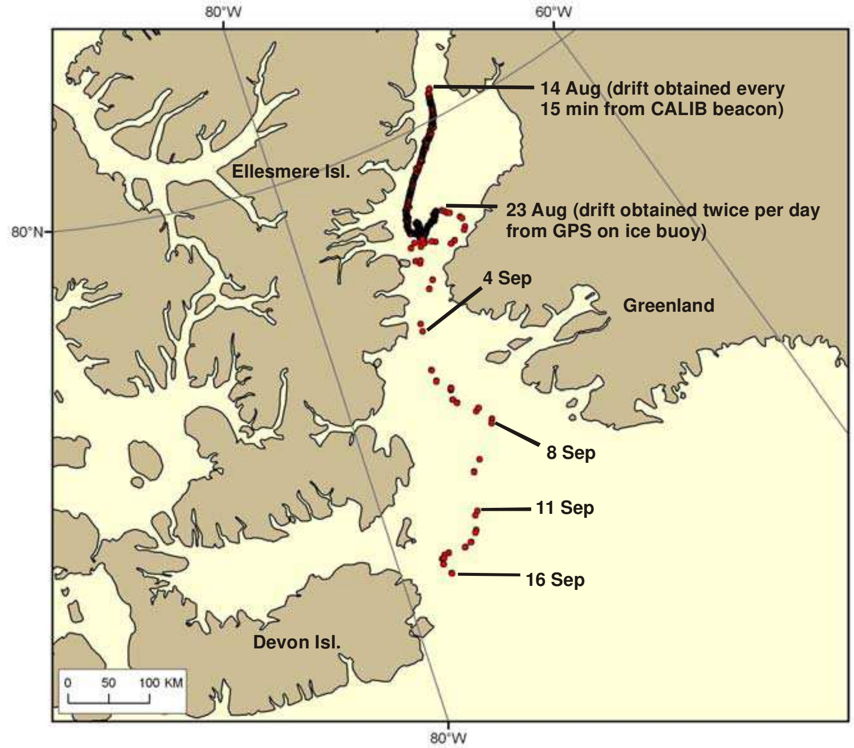


Figure 18 Drift of Floe L03 from 14 August to 16 September

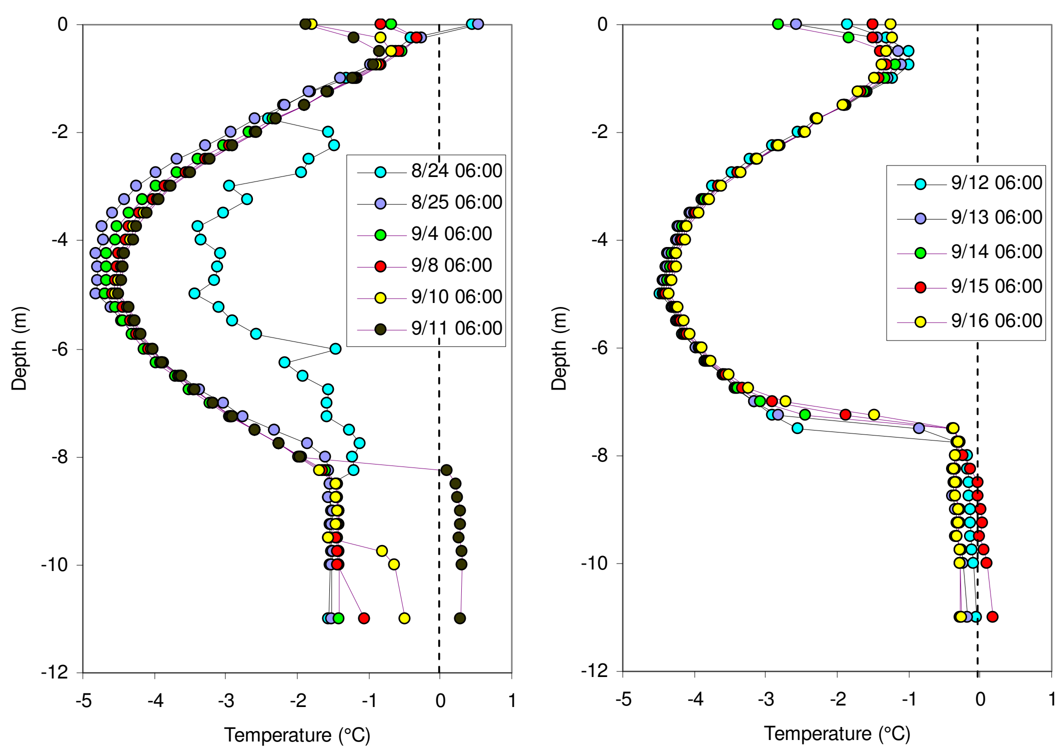


Figure 19 Select temperature profiles for Floe L03
Radical changes in temperature occurred from 8 to 11 September, as the floe drifted from Greenland towards the coast of Devon Island

5.4 Floe L04: Hall Basin, Aug 16

On 16 August, the ship headed 150 km north to Hall Basin to complete oceanographic measurements in Petermann Fjord, download data from cameras overlooking Petermann Glacier and maintain a weather station in the area. The decision to move north was a spontaneous one that came about only because satellite imagery indicated the transit from Nares Strait to Hall Basin would be relatively easy for the CCGS *Henry Larsen.*

The opportunity to sample a fourth floe presented itself that afternoon. A floe close to the ship was selected for sampling, in order to minimize time in the air and maximum time on the ice. Floe L04 was a large multi-year floe (3.5 km diameter) with some ridging and extensive ponding. An elliptical sub-floe, about 70 m across by 130 m long, with a clearly defined rubbled/ridged perimeter was selected for the sampling area (Figure 20). The field team landed on Floe L04 at 13:34 hrs and departed at 19:16 hrs, during which time the floe drifted 8.0 km southeast at an average speed of 1.4 km/hr.

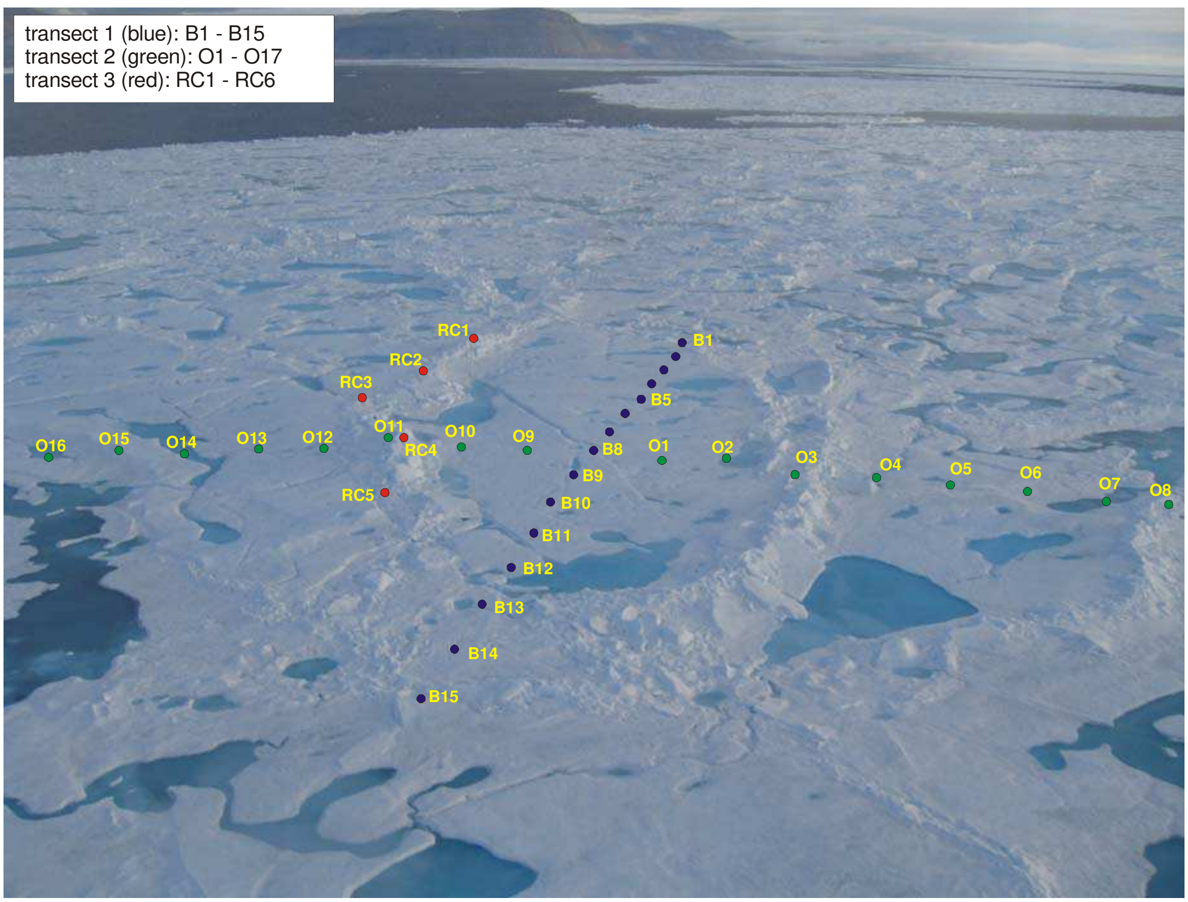


Figure 20 Aerial view of Floe L04 showing the two drill hole transects

5.4.1 Surface and bottom topography

Three transects were made on the floe: Transect 1 extended along the long axis of the sub-floe, Transect 2 spanned the minor axis of the sub-floe and over the surrounding ice, and Transect 3 was made along a portion of the floe's ridged perimeter (Figure 20). A total of 23 holes was drilled along the three transects, resulting in an average floe thickness of 8.3 m (±3.6 m). Given the sub-floe's relatively level surface, it was surprising that the thickness of adjacent drill holes varied as much as it did. In fact, the thickest ice was encountered at the centre of the floe, at hole B8 (see Figure 21, Figure 22). The ice at hole B8 was 14.6 m thick, but just 10 m away, at hole B7, the ice was 4.4 m thick. The freeboard along Transects 1 and 2 ranged from -0.3 m (at the edge of melt pond) to 1.8 m (hole B3). This particular floe, and others like it, demonstrate that the surface of some floes can be very deceptive. In fact, at least once during operations in Hall Basin, Captain Vanthiel had been surprised by how the CCGS *Henry Larsen* responded to what appeared to relatively level multi-year ice.

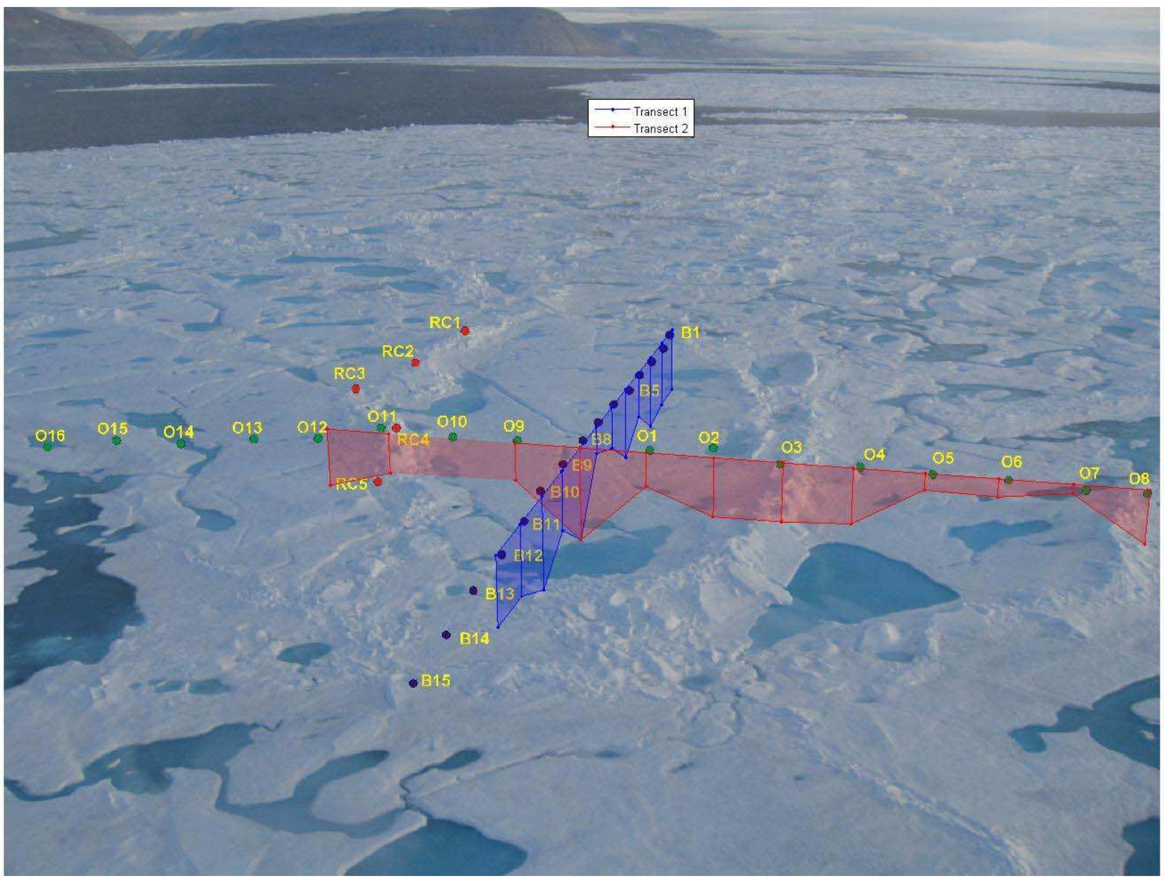


Figure 21 Three dimensional representation of total ice thickness on Floe L04
Transect 1 (red line) and Transect 2 (blue line). 3D representation courtesy of D. Sudom

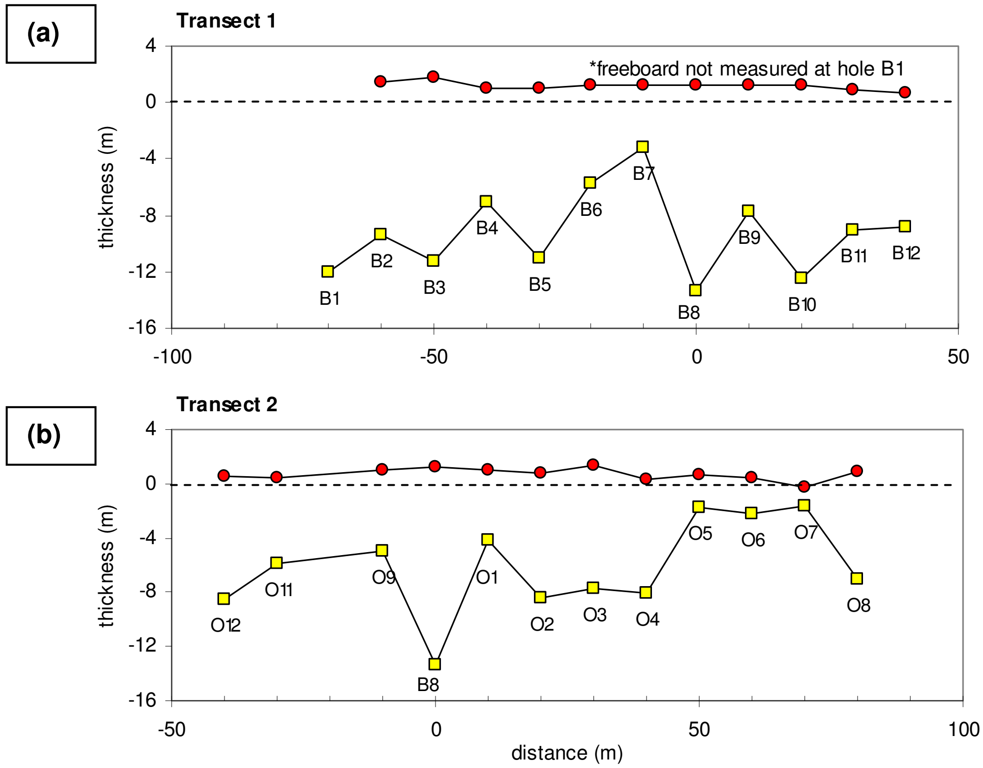


Figure 22 Floe L04: Surface and bottom topography from drill hole measurements

Floe L04 was the most challenging floe of the program in terms of accurately measuring the ice thickness – primarily because of the loose blocks that were encountered on the underside of the floe. The drill team spent so much time at the first hole, B1, that it prompted the author to question them as to the problem: the drill-hole team replied that the loose blocks were pushed out of the way then, as the drill rods were removed from the hole, the blocks floated back into position to prevent the thickness tape from reaching the bottom of the hole. When it was suggested that, in the interest of time, the ice thickness be estimated from the number of drill rods used in the hole, the drill-team replied that it was difficult to determine when the bottom of the ice had been penetrated because the ice "felt like grapefruit". Table 6 describes the drilling experience at a number of "problem holes" on Floe L04.

Table 6 Drill holes on Floe L04 in which pockets or loose blocks were noted

Hole	thickness (m)	loose blocks noted	notes
B1	12	Yes	pocket at approx 5 m and 9 m; auger gets stuck in hole
B2	10.8		pocket at approx 2 m
B3	13	Yes	pocket at approx 3 m, 6 m and 11 m
B4	8	Yes	
B5	12	Yes	pocket at 5.8 m and approx 9 m, 10 m and 11 m
B6	7.0	Yes	
B7	4.4	Yes	
B8	14.6	No	pocket at 4.4 m, 10.3 m, 12.5 m and at approx 6 m and 8 m
B9	9	Yes	
B11	10	No	pocket at 5 m
O3	9	Yes	pocket at 5.6 m, 8.0 m

5.4.2 Average thicknesses from the HEM

Floe L04 was the first floe on which it was possible to compare thicknesses from the drill-hole measurements to results from the airborne EM sensor (HEM). The helicopter made five passes over Floe L04 (Figure 23) as it towed the EM sensor 15 to 20 m above the surface of the drifting floe. A schematic representation of the approximate location of the two main drill hole transects is also included, to illustrate how short the 100 to 200 m long drill hole transects were, compared to the flight segments.

About 100 HEM data points were obtained from the 200 m long flight segment which centered upon the point where the flight line and the floe's drift trajectory intersected. The 100 HEM data points were obtained at a sampling interval of about 4 m for the 80 kt aircraft speed. The 4 m sampling interval should not be confused with the HEM's "footprint" of over thick multi-year ice – which would have been about 75 m, or more – and would have covered a substantial portion of the drill hole transect. That is why a point-by-point comparison of thicknesses from the drill-hole measurements and HEM is not possible.

The HEM measured a maximum thickness of 8.3 m over the sampling area (Figure 24) compared to the maximum drill-hole thickness of 14.6 m. The average thicknesses obtained for the five HEM flight segments ranged from 4.8 to 6.9 m, compared to average thicknesses of 6.9 and 10.3 m for the drill-hole transects (Table 7).

Table 7 Floe L04: Thickness from Drill Hole vs. HEM

	Ice thickness	**Drill hole**	**HEM**
Transect 1	avg ± st dev (m)	10.3 ± 3.0	
	max (m)	14.6	
	min (m)	4.4	
Transect 2	avg ± st dev (m)	6.9 ± 3.7	
	max (m)	14.6	
	min (m)	1.4	
Flight 1, line 1	avg ± st dev (m)	--	4.8 ± 2.2
	max (m)		7.5
	min (m)		1.7
Flight 1, line 2	avg ± st dev (m)	--	6.8 ± 0.5
	max (m)		8.3
	min (m)		6.2
Flight 1, line 3	avg ± st dev (m)	--	6.6 ± 1.1
	max (m)		8.2
	min (m)		5.0
Flight 2, line 1	avg ± st dev (m)	--	6.9 ± 0.8
	max (m)		7.8
	min (m)		4.7
Flight 2, line 2	avg ± st dev (m)	--	6.9 ± 1.6
	max (m)		8.7
	min (m)		4.0

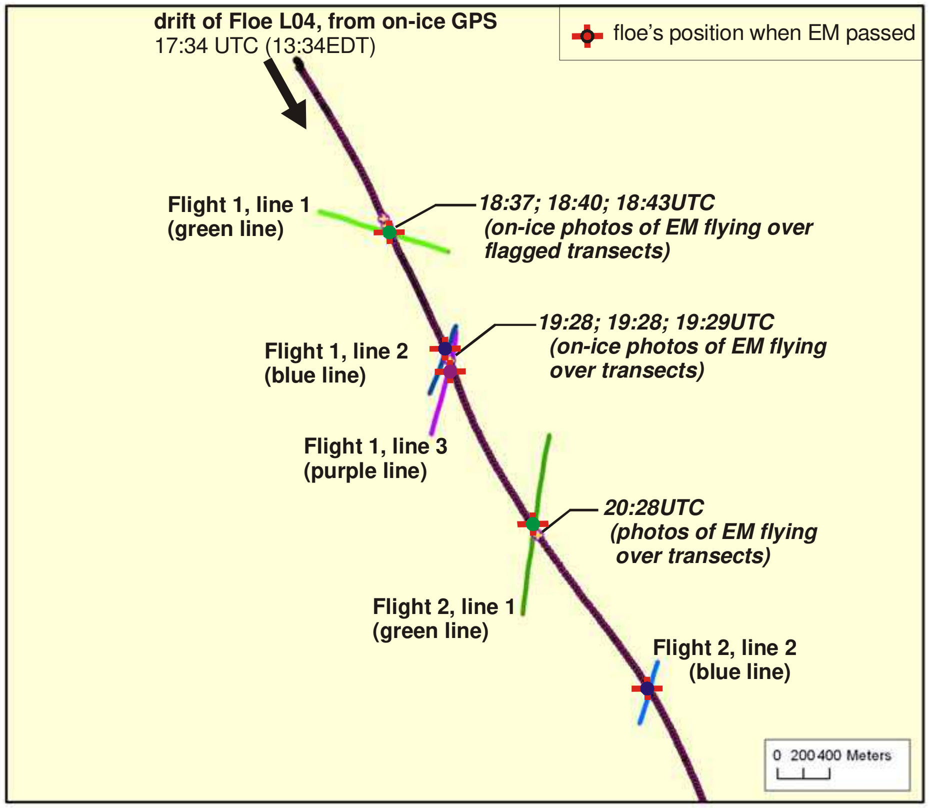


Figure 23 Floe L04: HEM flight segments coinciding with on-ice measurements
(HEM data courtesy of C. Haas)

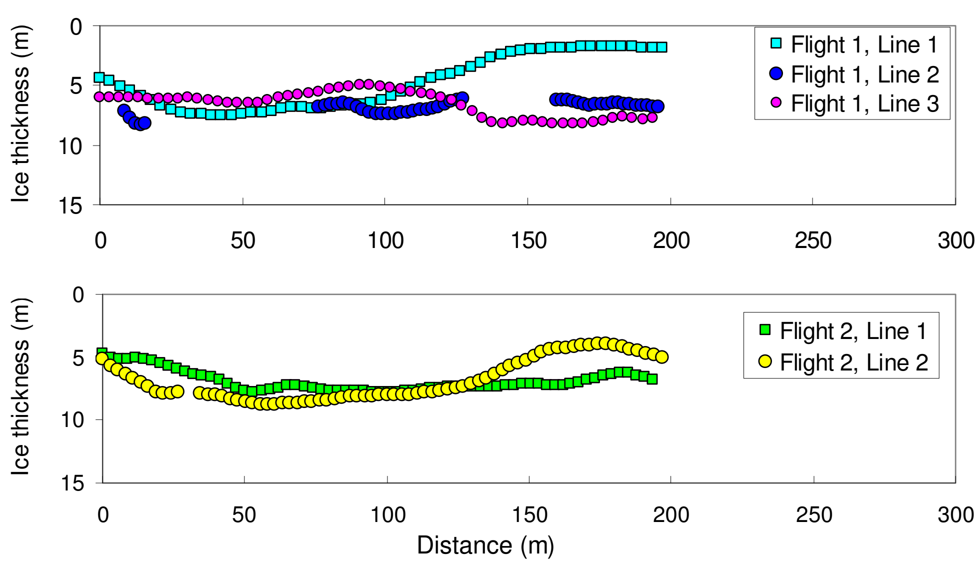


Figure 24 Floe L04: Results from the HEM where floe trajectory and flight segment overlapped
(HEM data courtesy of C. Haas)

5.5 Floe L05: Hall Basin, Aug 17

August 17 was a very foggy day in Hall Basin. Conducting on-ice measurements would not have been possible had it not been for the flexibility of Captain Vanthiel in permitting the field team to sample a floe. This was allowed, provided that (1) the helicopter did not travel more than about 300 m from the ship and (2) the field team was visible to the ship's bridge at all times. With that agreement, the field team of five embarked to sample a floe alongside the ship, Floe L05. The floe's dirty, dimpled surface, and extensively connected drainage features suggested that it was an old multi-year floe (Figure 25). The helicopter transported the field team to the floe at 09:26 hrs, and returned at 15:49 hrs. During that time, Floe L05 drifted 4.3 km southeast, at an average speed of 0.7 km/hr. Thankfully, the fog had lifted enough by the end of the day to measure the width of the floe (2.4 km) from the helicopter.

5.5.1 Surface and bottom topography

Four transects were made on Floe L05. The floe's extensive drainage features made making linear transects challenging; melt ponds are generally avoided, for safety reasons and also because they can cause severe problems for the drilling operator and equipment. Ice thicknesses were measured at a total of 40 drill holes on Floe L05, resulting in an average thickness of 4.7 m (±1.5 m). The freeboard of Floe L05 ranged from 0.2 to 1.0 m.

Figure 27 shows the surface and bottom topography of the floe along the four transects. As with the previously sampled multi-year floes, the bottom surface had considerably more topography than the top surface. The thickest ice was measured at hole OB4 (8 m) and the thinnest ice at hole O15 (2.4 m). Pockets/cavities were encountered at five drill holes but loose blocks were noted on the floe's underside at only one hole (O13, see Table 8). Floe L05 was unique in that the 4.5 m thick ice at the end of Transect 3 (hole O18) supported two, massive boulders of ice, each about 2 m on a side. Circumferential (surface) cracks were noted in the ice supporting the boulders. Seeing such massive pieces of ice sitting at the edge of the floe was a spectacle to behold. One could speculate that deformed multi-year ice forms when boulders like these are incorporated into the top or bottom of a floe, and then consolidate – as shown later in this report by photographs of Floe L09.

Table 8 Drill holes on Floe L05 in which pockets or loose blocks were noted

Hole	thickness (m)	loose blocks noted	notes
B2	7.8	No	pocket at 3.9 m
O11	6.4	No	pocket at approx 3 m
O13	7.7	Yes	
OB2	8	No	pocket at 6.4 m
OB4	8	No	pocket at 2.9 m, approx 6 m and approx 7 m
OB6	5.3	No	pocket at approx 3 m

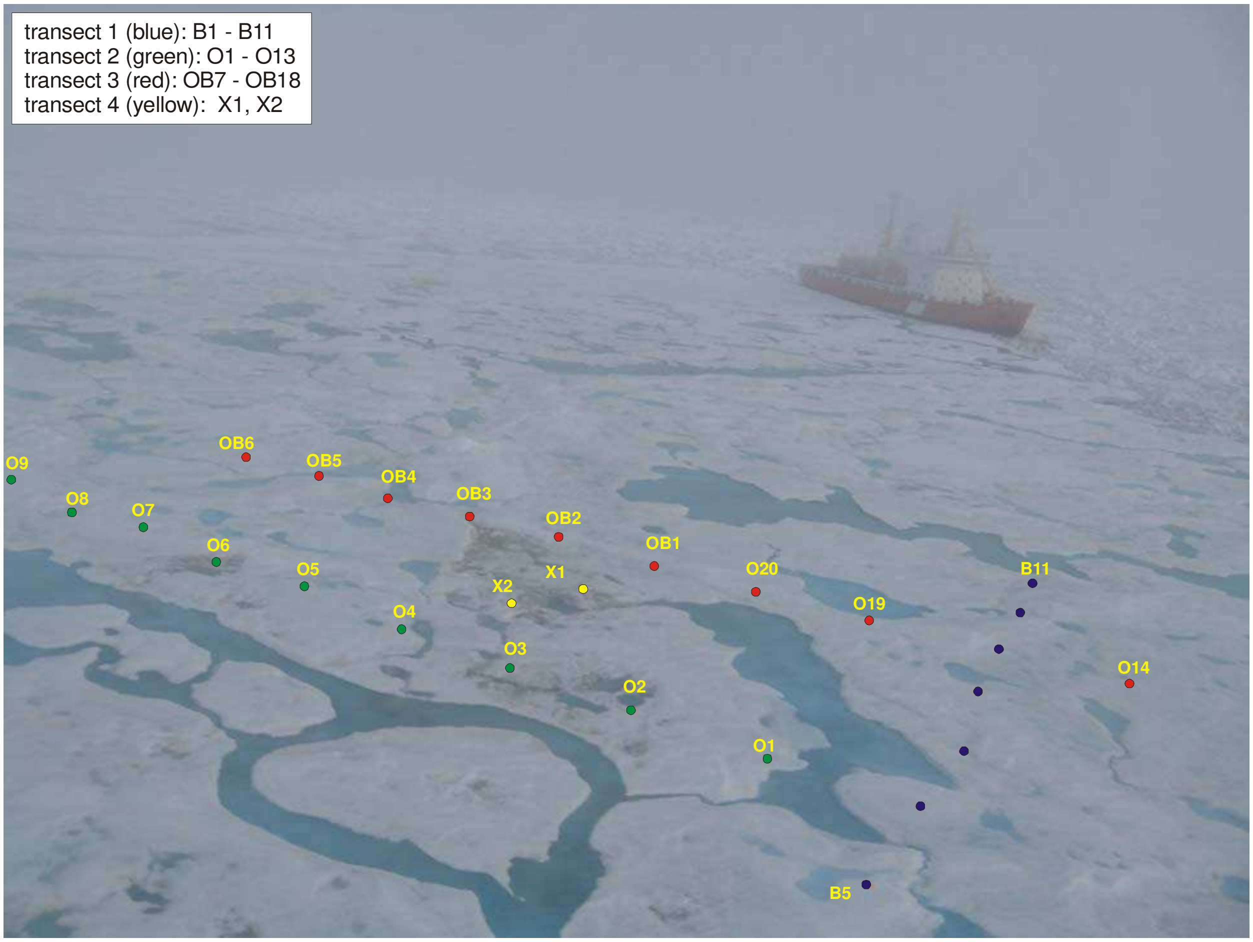


Figure 25 Aerial view of transects made on Floe L05

Figure 26 Two ice boulders supported by 4.5 m thick ice at the end of Transect 3

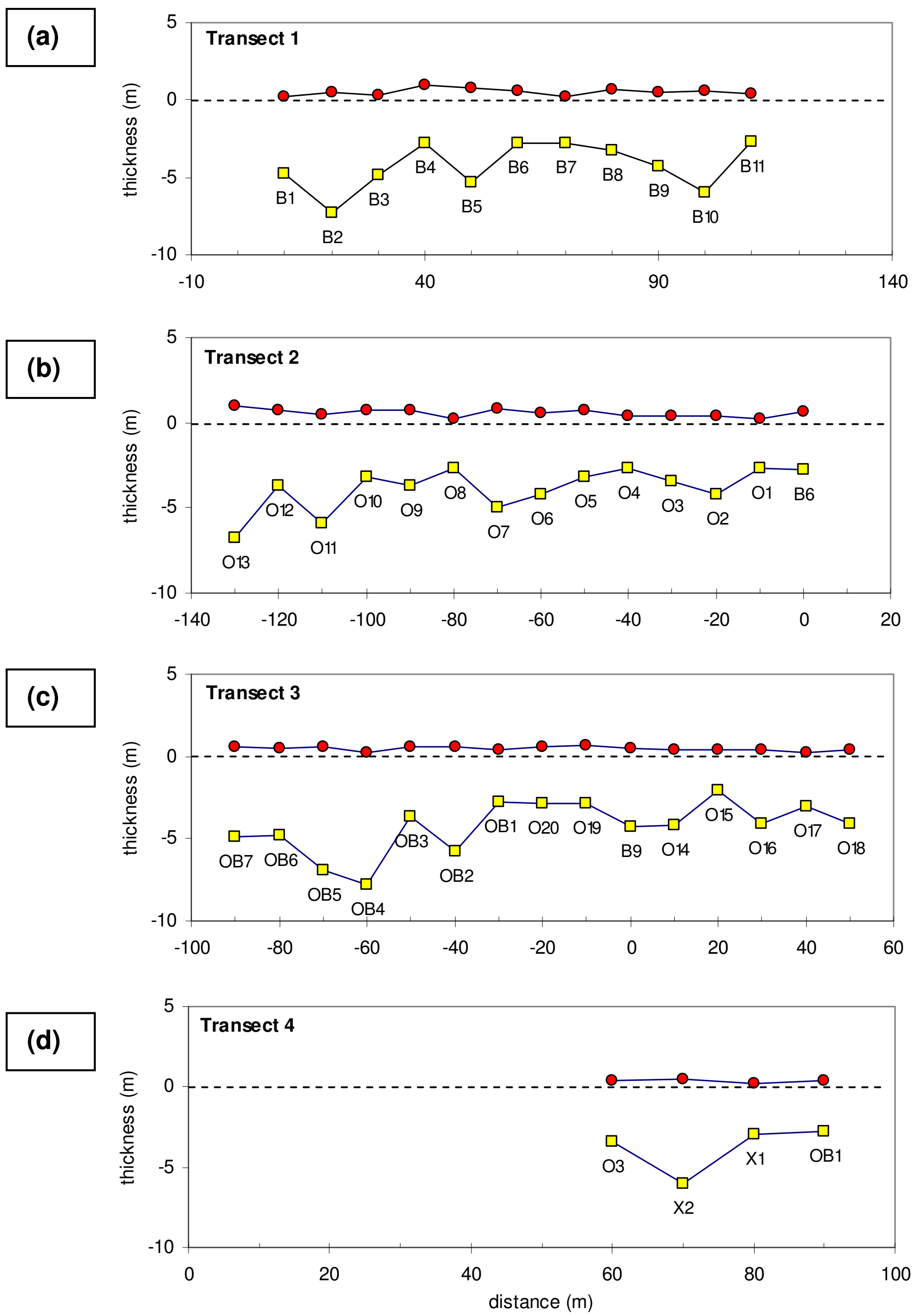


Figure 27 Floe L05: Surface and bottom topography from drill hole measurements

5.6 Floe L06: Hall Basin, Aug 18

The field team departed to sample a sixth floe on 18 August. A short aerial reconnaissance of the sea ice in Petermann Fjord was made before deciding that the most suitable (and convenient) floe floated right next to the ship. The field team landed on Floe L06 at 11:14 hrs and worked for seven hours, during which time the 1.0 km diameter floe drifted 3.1 km to the northwest at an average speed of 0.4 km/hr.

5.6.1 Surface and bottom topography

A total of 38 holes was drilled along five of the six transects on Floe L06. Due to time constraints, holes were not drilled along the ridge crest (Transect 6) and only a portion of Transect 2 was drilled (holes O1 to O8). The average thickness of the 38 drill holes was 6.5 m (±2.3 m). The thickest ice occurred at hole OB1 (11.8 m) and the thinnest ice was noted just 30 m away at hole OB4 (2.8 m). The freeboard of Floe L06 ranged from 0.1 to 1.3 m.

A number of holes along Transects 3 and 4 had soft ice at the bottom, which made measuring the ice thickness challenging (see Table 9) and caused the drill team to ask "why is the ice like this?" – no one recalled ice during the 2007 field program being so problematic.

Table 9 Drill holes on Floe L06 in which pockets or loose blocks were noted

Hole	thickness (m)	loose blocks noted	notes
B2	7.7	No	pocket at approx 4 m
O2	10.4	No	pocket at 6.3 m, approx 8 m and approx 9 m
O3	9.0	No	pocket at approx 7 m, 8 m
O4	8	No	pocket at 4.4 m, approx 6 m; have difficulty finding bottom because of soft ice
O5	7	No	pocket at 3.2 m; have difficulty finding bottom because of soft ice
O15	3.0	No	thickness tape caught at 3.0 m but 5 drill rods used in hole
O16	5.6	No	thickness tape caught on at 5.6 m but 8 drill rods were used in hole
O17	4.6	No	thickness tape caught on at 4.6 m but 7 drill rods used in hole
O18	4.4	No	thickness tape caught on at 4.4 m but 6 drill rods used in hole

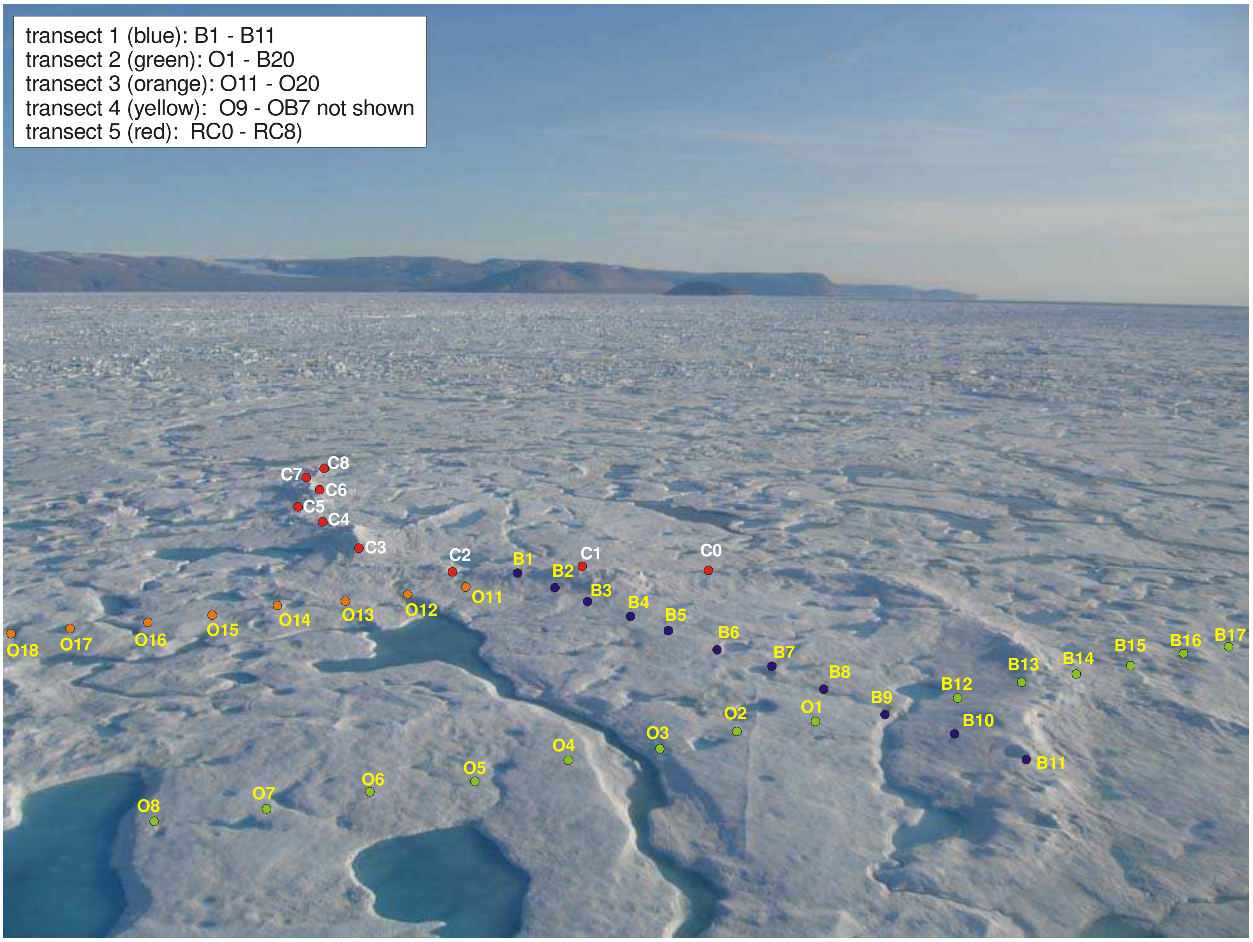


Figure 28 Aerial view of transects made on Floe L06

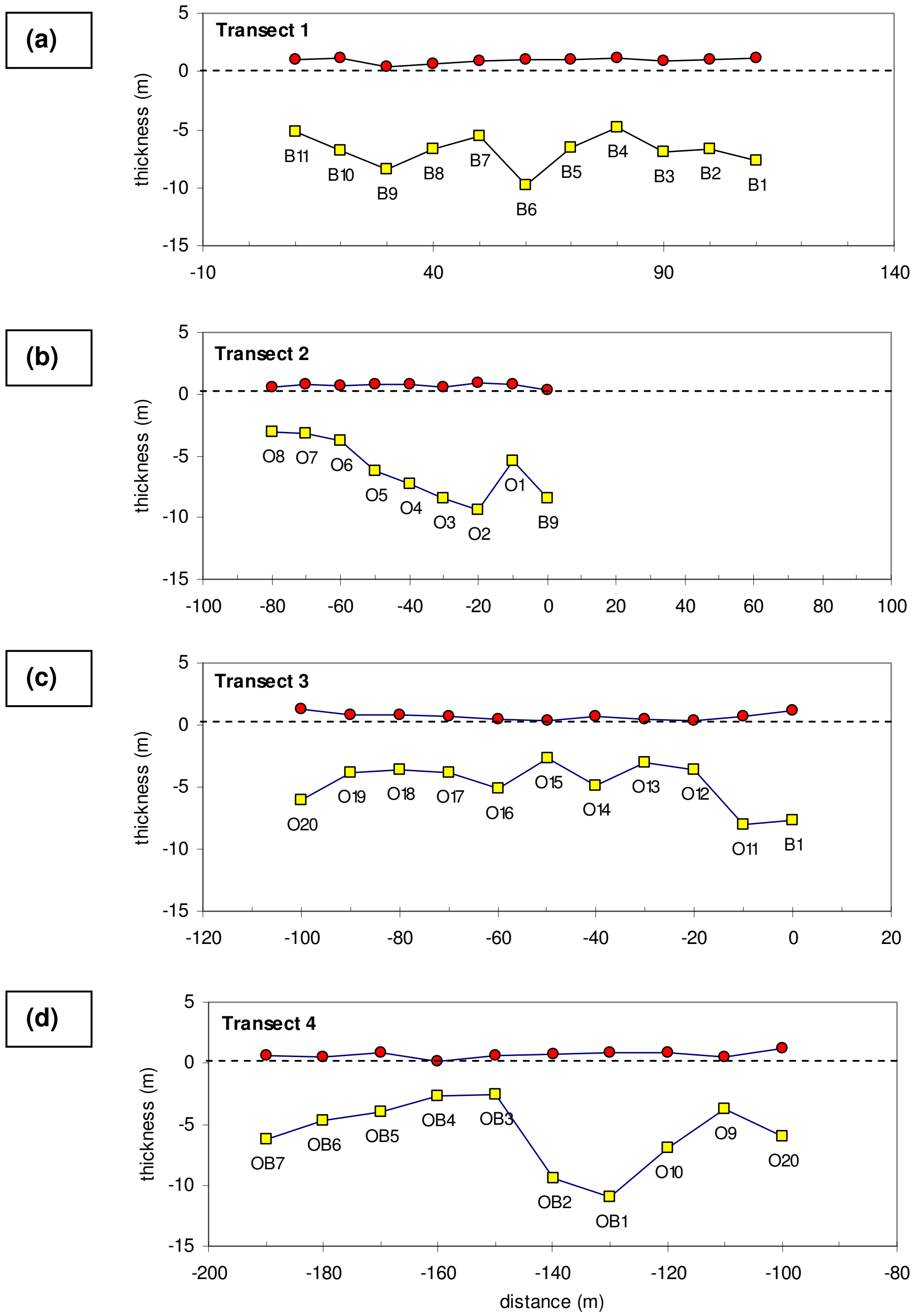


Figure 29 Floe L06: Surface and bottom topography from drill hole measurements

5.6.2 Average thicknesses from the HEM

The HEM made two passes over Floe L06 while the field team worked. The HEM measured a maximum thickness of 7.9 m (Figure 30, Figure 31) over the sampling area, compared to a maximum drill-hole thickness of 11.8 m (38 drill holes). The average thickness from the HEM along the two flight segments was 6.5 m and 4.1 m (Table 10), compared to an average thickness of 5.5 to 7.8 m along the four drill-hole transects. Missing data from the two flight segments indicate "drop outs", which sometimes occur during the flight because very strong winds or significant turning maneuvers needed to align the helicopter with the drill-hole profile induce a strong roll or sway in the EM sensor (C. Hass, personal communication).

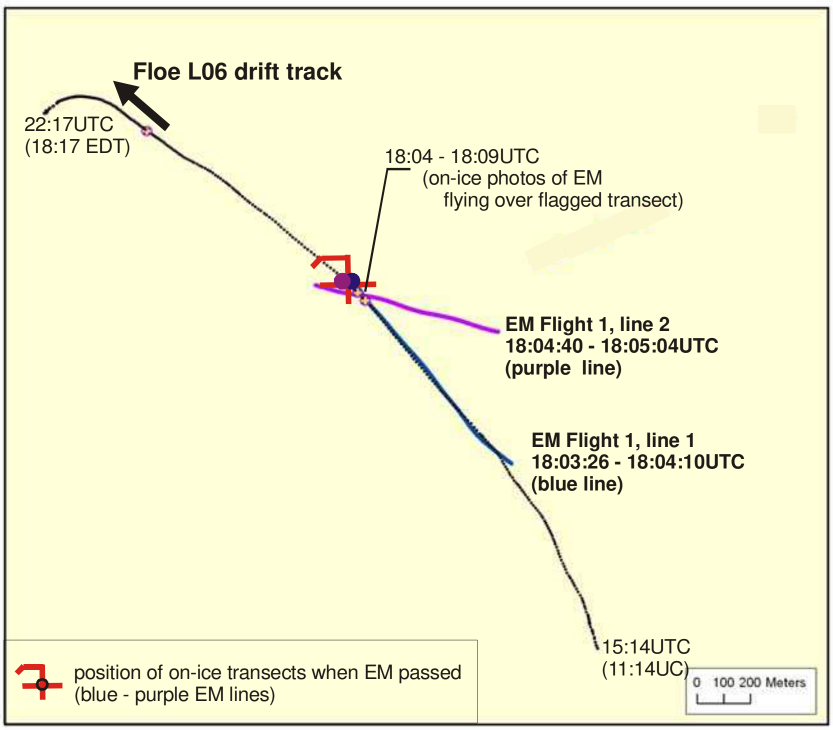


Figure 30 Floe L06: HEM flight segments coinciding with on-ice measurements (HEM data courtesy of C. Haas)

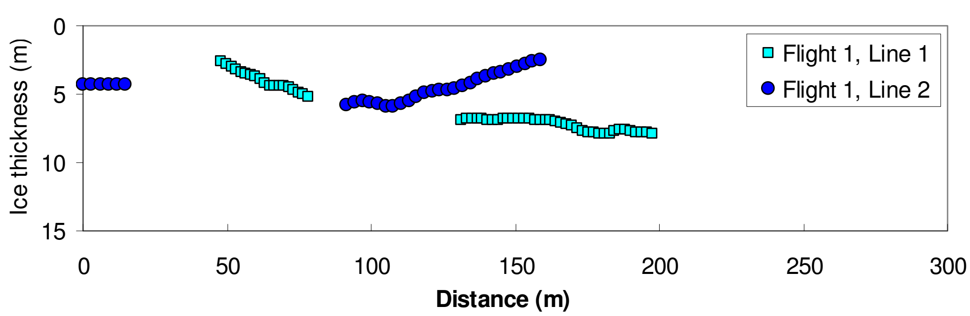


Figure 31 Floe L06: Results from the HEM where floe trajectory and flight segment overlapped (HEM data courtesy of C. Haas)

Table 10 Floe L06: Average Thicknesses from Drill Hole and HEM

	Ice thickness	Drill hole	HEM
Transect 1	avg ± st dev (m)	7.8 ± 1.4	
	max (m)	10.8	
	min (m)	5.9	
Transect 2	avg ± st dev (m)	6.8 ± 2.4*	
	max (m)	10.4	
	min (m)	3.7	
Transect 3	avg ± st dev (m)	5.5 ± 2.0	
	max (m)	8.8	
	min (m)	3.0	
Transect 4	avg ± st dev (m)	6.4 ± 2.9	
	max (m)	11.8	
	min (m)	2.8	
Transect 5	avg ± st dev (m)	--	
	max (m)	--	
	min (m)	--	
Flight 1, line 1	avg ± st dev (m)	--	6.1 ± 1.7
	max (m)		7.9
	min (m)		2.6
Flight 1, line 2	avg ± st dev (m)	--	4.5 ± 1.0
	max (m)		5.9
	min (m)		2.5

*includes only a portion of transect

5.7 Floe L07: Nares Strait, Aug 19

Once measurements on Floe L06 had been completed, the ship departed south for Nares Strait. Although ice conditions had been favorable coming north to Hall Basin, that was not the case when it came time to depart the area. The landscape had changed during the intervening days; the ship now faced a high concentration of closely packed, formidable multi-year ice floes. Captain Vanthiel worked tirelessly into the early morning hours to navigate the ship through the closely-spaced pack ice. Hours were spent at the control, but very little forward progress was made. The experience is mentioned here for good reason: even though the late-season multi-year floes had ponded surfaces and frequently contained voids at various depths, the floes proved challenging to an icebreaker. The hard impacts that the CCGS *Henry Larsen* withstood working its way out of Hall Basin testifies to the fact that multi-year ice can remain hazardous, even in late summer.

Back in Nares Strait, the ship was able to navigate more easily through the open pack ice. For the on-ice measurements, it was decided to fly north to a region where higher concentrations of ice persisted. A suitable floe was first identified about 12 n.mi north of the ship, but it was thought prudent to look elsewhere because the 500 m diameter floe appeared to be drifting right towards Hans Island. After finding no other suitable floes in the area, it was decided to take a closer look at the floe that had been passed over, since it was considerably more hummocked and less heavily ponded than other floes in the area (Figure 32). The helicopter landed on the floe at 09:48 hrs, with the understanding that the field team would monitor the floe’s drift and communicate back to the ship on a regular basis. About mid-way through the afternoon, it was realized that Floe L07 would pass west of Hans Island. A full day was spent on Floe L07 as it drifted 6.1 km to the southwest at an average speed of 0.8 km/hr.

5.7.1 Surface and bottom topography

A total of 40 flags were positioned along two transects on Floe L07. Distributing that many flags on such a hummocked floe was ambitious to say the least, especially once it was realized that Floe L07 would be the thickest floe sampled so far. Hole after hole returned thicknesses of 10 m, or more. So, it is completely understandable that time permitted drilling only 18 holes on Floe L07. Drill-hole measurements returned an average thickness of 10.2 m (±3.4 m). The freeboard of the floe ranged from 0.3 to 2.5 m.

Figure 34 shows that the thickest ice was encountered along Transect 1 (13.7 m at hole B10) and the thinnest ice occurred near a drainage feature at the end of Transect 2 (1.7 m thick ice at hole O18). Thinner ice was also encountered along Transect 1 at holes B6, B8, B9 and B12. Table 11 describes the challenges met with drilling through Floe L07. After it was found that the drill team had reported ice thicknesses that did not seem to match their freeboard measurements, the author began taking detailed notes at a number of drill holes – and requested that a second drill hole be made alongside the suspect holes (B1, B3, B5 and B6). The initial thickness of 5.2 m that had been reported for hole B1 turned out to be 10.6 m at the adjacent hole; the 6.3 m thickness at hole B3 was 12.7 m at the adjacent hole; the 8.6 m thickness of hole B5 was 13.2 m when re-drilled at an adjacent hole; and the 7.3 m thickness of hole B6 was 9.2 m at an adjacent hole (Table 11). It is an open question as to whether the initial thickness measurements were incorrect, or whether two holes drilled in the same area really were characterized by vastly different thicknesses. Underwater images of deformed ice near Admiralty Inlet (B. Gorman, personal communication) indicate that even closely spaced holes can have very different thicknesses, depending on how the blocks of ice are oriented and where cavities occur.

Figure 32 Topography of Floe L07 beginning at Transect 1, with Hans Island in the background

Table 11 Drill holes on Floe L07 in which pockets or loose blocks were noted

Hole	thickness (m)	loose blocks noted	notes*
B1	10.6	No	pocket at 4.5 m, hard ice to 6 m then pocket, soft ice from 7 m to bottom. Thickness at first hole 5.2 m vs. re-drill adjacent hole is 10.6 m.
B2	10.9	Yes	pocket at 6 m
B3	12.7	Yes	pocket at 6.5 m, hard ice to 7 m, wet cuttings at 7 m, pocket at 9 m, soft ice at bottom of floe. Thickness at first hole 6.3 m vs. re-drill adjacent hole is 12.7 m.
B5	13.3	Yes	hard ice to 8 m, wet cuttings at 8 m depth, pocket at 8.5 m, soft ice at 10 m, hard ice at 12 m, encounter block of floating ice at 13 m. Thickness at first hole 8.6 m vs. re-drill adjacent hole is 13.2 m.
B6	9.2	No	hard ice to 5 m, wet cuttings at 5 m, pocket at 7.5 m, drilling tough after 7 m, pocket at 8 m, pocket at 9 m, soft ice from 8 m to bottom. Thickness at first hole 7.3 m vs. re-drill at adjacent hole is 9.2 m.
B7	12.1	No	pocket at 6 m & 7 m, hard ice at 9 m, pocket at 11 m, 12 m, & 13 m
B8	7.0	No	hard ice to 7 m, wet cuttings at 4 m, soft ice at bottom
B9	9.7	No	hard ice to 9 m, wet cuttings at 6 m, pocket at 9 m, soft ice at bottom
B10	13.7	Yes	hard ice to 9 m, wet cuttings at 8 m, soft ice at 9 m, must push drill rods through 10 to 14 m depths because they just won't drop down (unusual)
B11	13.0	No	hard ice to 5 m, wet cuttings at 5 m, pocket at 7 m, pockets at 9 m, 10 m, 11 m , 12 m & 13 m, but still feel ice at 12 m depth
B12	7.8	No	pocket at 6.0 m, drill hole near drainage feature
B13	13	No	pocket at 5.7 m, pockets between 6 to 10 m depths, thickness estimated from drill rods since it was unable to be measured with tape (soft ice at bottom of hole)
O14	10.4	No	pocket at 4.2 m, pocket at 8.0 m
O15	12	No	pocket at 9 m, 10 m and 11 m depths, thickness estimated from number of drill rods

*some drill holes were closely monitored as to where drill cuttings changed from dry to wet and where ice was hard or soft

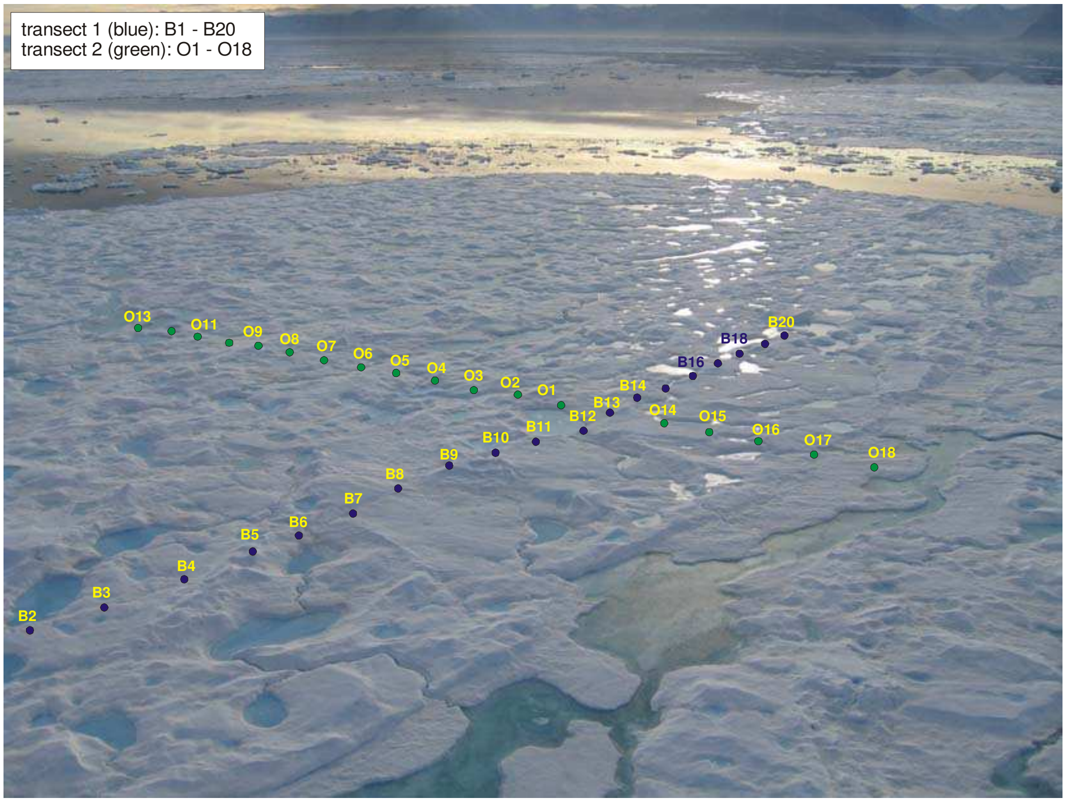


Figure 33 Aerial view of transects on Floe L07

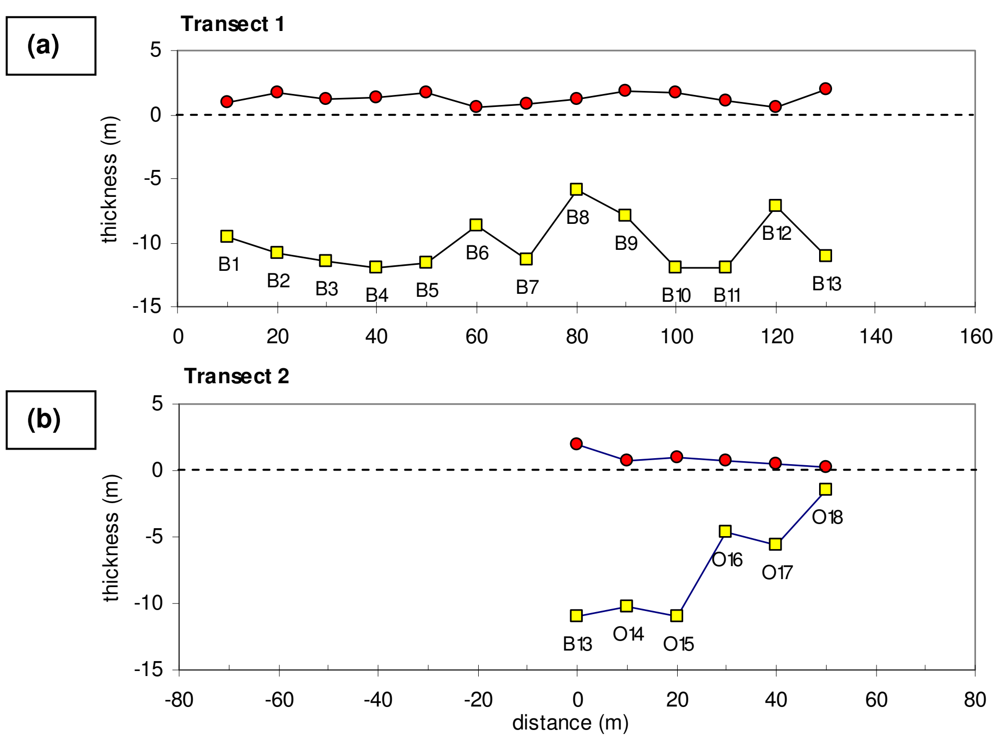


Figure 34 Floe L07: Surface and bottom topography from drill hole measurements

5.7.2 Average Thicknesses from the HEM

Three flight passes were made over the field team as Floe L07 drifted south in an undulating fashion (Figure 35). The HEM measured a maximum thickness of 9.8 m during the three flights and an average thickness of 8.7 m (±0.4 m). Thicknesses during the three flight segments were remarkably consistent, with a spread of only 2 m (from 7.8 to 9.8 m), compared to the 5.4 and 7.0 m spreads on the two previous floes sampled by the airborne EM sensor (Floes L04 and L06, respectively). This may have been because the HEM viewed the floe as uniformly thick (indicating the upper bound of thickness resolved by sensor) or it may have occurred because the sensor maintained a steadier altitude than previous flights. Table 12 shows that the HEM underestimated the thickness of Floe L07 when compared to the maximum drill-hole thickness (13.7 m) and average drill-hole thickness for the two transects (11.4 m and 8.1 m).

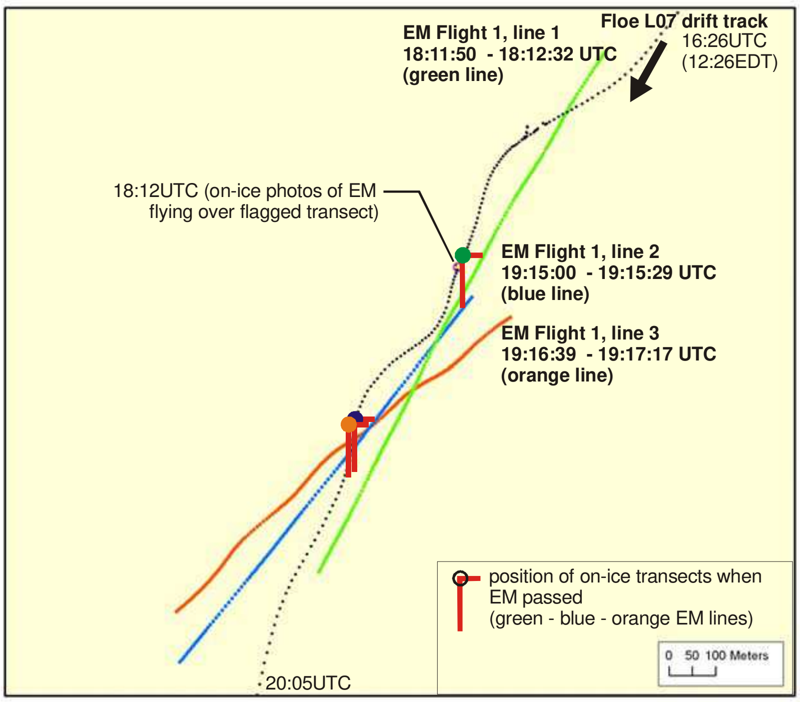


Figure 35 Floe L07: HEM flight segments coinciding with on-ice measurements (airborne EM data courtesy of C. Haas)

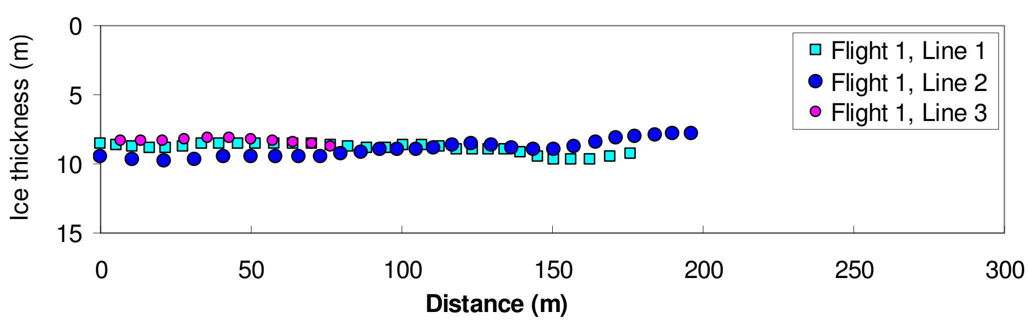


Figure 36 Floe L07: Results from HEM where floe trajectory and flight segment overlapped (airborne EM data courtesy of C. Haas)

Table 12 Floe L07: Average Thicknesses from Drill Hole and HEM

	Ice thickness	Drill hole	HEM
Transect 1	avg ± st dev (m)	11.4 ± 2.3*	
	max (m)	13.7	
	min (m)	7.0	
Transect 2	avg ± st dev (m)	8.1 ± 4.4**	
	max (m)	13.0	
	min (m)	1.7	
Flight 1, line 1	avg ± st dev (m)	--	8.9 ± 0.4
	max (m)		9.7
	min (m)		8.5
Flight 1, line 2	avg ± st dev (m)	--	8.9 ± 0.6
	max (m)		9.8
	min (m)		7.8
Flight 1, line 3	avg ± st dev (m)	--	8.4 ± 0.2
	max (m)		8.8
	min (m)		8.1

* includes overlapping data for holes B1 to B13 only
** includes overlapping data for holes B13 to O18 only

5.8 Floe L08: Belcher Channel (27 Aug 2009, 8 May 2010, 9 May 2010)

Upon concluding measurements on Floe L07 (17 Aug), the ship transited south to Alexander Fjord, re-visited Floe L03 in Kane Basin and then began its 700 km transit to Norwegian Bay and Penny Strait, further to the west. The ship arrived in Norwegian Bay on 27 August. An aerial reconnaissance of the area was conducted to determine whether ice conditions would permit the ship to access Penny Strait (where a mooring was to be deployed) via Belcher Channel. If ice conditions were unfavorable, the ship would need to take the longer – but virtually ice-free – route through Jones Sound and Wellington Channel (Figure 4).

The one hour aerial reconnaissance confirmed what satellite imagery showed to be congestion in Queens Channel. Some open water was noted, but not enough for the ship to comfortably transit the area. What satellite imagery did not convey however, was just how substantial the ice features in this area were. The multi-year floes in the northern part of Norwegian Bay, Belcher Channel and Queens Channel were not as deteriorated as many of the floes in Nares Strait. The region also had many ice island fragments. Figure 37 shows two of the more formidable features seen during the reconnaissance. The ice island fragment in Figure 37-a is believed to have calved from an ice shelf on the western coast of Ellesmere Island (D. Mueller, personal communication) whereas the massive multi-year hummock field in Figure 37-b may have dislodged from any number of areas along the northwest coast of the Queen Elizabeth Islands.

Figure 37 Two of the more formidable extreme ice features in Belcher Channel
(a) ice island fragments and (b) a floating multi-year hummock field; both features were several kilometers long

After the helicopter returned to the ship at 10:30 hrs a report was given to Captain Vanthiel. Upon hearing about the ice conditions in Belcher Channel, the Captain asked whether a floe had been selected for the second ice buoy. An attractive floe had been seen during the reconnaissance: it was surrounded by open water and had very rugged surface topography. It was decided that the field team could return to the floe while the ship made its way towards them.

At 11:08 hrs, the helicopter landed on Floe L08 with its first load: two people and half of the equipment. The second load followed immediately after. Faced with such a magnificent floe, a few minutes were taken to behold the awesome spectacle of hummock after hummock (Figure 38). The field team worked on the floe for about 8 hours, during which time the floe drifted 4.1 km (in a roughly circular pattern) at a speed of 0.6 km/hr. At 18:40 hrs, the helicopter returned to hastily collect the first load – although skies were clear at the floe itself, weather was closing in around the ship, about 35 km away[3]. The helicopter returned for the second load at about 19:00 hrs. With seconds ticking before the weather closed in completely, only one quick circle was made to photograph where the ice buoy had been installed. Since time was not permitted to document floe size, the 1.5 km diameter of the floe was determined from photographs taken during the morning's aerial reconnaissance.

[3] Because of the shoals in the area, the ship was unable to navigate around the formidable multi-year floe that stood between the ship and the floe on which the field team worked, 35 km away. It also meant that the helicopter was the only means of reaching the field team should something go wrong, which made inclement weather all the more troublesome.

Figure 38 Gazing upon the enormity of Floe L08

5.8.1 Surface and bottom topography

The two transects on Floe L08 included areas of relatively level ice and extensively hummocked ice. The far end of Transect 1 (holes B14 to B20) extended along the smaller of two prominent ridge crests, between which a large melt pond had formed (Figure 39). The 18 holes that were drilled on Floe L08 were all made along Transect 1. Holes were not drilled at the last two flags on Transect 1 (B19, B20) or along Transect 2. The average thickness of Transect 1 was 12.7 m (±3.3 m). Ice freeboards ranged from 1.1 to 4.2 m.

Transect 1 began at hole B1, an ice feature with an estimated 2.5 m high sail (Figure 39). The deformity appeared to be a massive slab of ice that had been tilted on its edge, forming a steep precipice on one side and sloping down to a narrow drainage feature on the other side. The drainage feature was fed by a large melt pond (60 m long by 20 m across) beneath which the silhouette of large blocks of ice could be seen (Figure 40). Hole B1 had a thickness of 9.1 m, which was comparable to the thickness of holes made nearby in level ice (Figure 41). The area of level ice between holes B2 and B8 was 8.3 to 14.5 m thick, with the thickest ice being noted at hole B6 (14.5 m). Holes B9 to B18 extended along the crest of a ridge that had a 4.2 m high sail (hole B17) and a maximum thickness of 17.9 m (B15). The ridge on the other side of the pond was even more massive, as shown by the photograph in Figure 39.

Table 13 describes the quality of ice encountered in some of the drill holes. After having witnessed discrepancies in holes drilled at a number of flags on Floe L07, it was thought prudent to document the integrity of the ice drilled at a number of holes on Floe L08. So, upon concluding the ice-based EM measurements along Transects 1 and 2, the author met up with the drill team to document drilling at holes B1, B14, B15, B16, B17 and B18 (Table 13). Each one of those holes contained a mixture of soft, medium and hard ice.

Table 13 Drill holes on Floe L08 in which pockets or loose blocks were noted, August 2009

Hole	thickness (m)	loose blocks noted	notes*
B1	9.1	No	hard ice to 8 m depth, wet cuttings at 8 m; 10 drill rods used in hole; the ice is quite thin (9.1 m) given the sail height of the feature (2.5 m).
B2	8.3	No	pocket at approx. 8 m – taken as bottom of ice, 9 drill rods used in hole
B5	12	No	pocket at approx. 10 to 11 m depth, thickness estimated from number of drill rods
B8	10.2	No	pocket at approx. 9 m; 12 rods used in hole
B14	13.4	No	hard ice to 10 m depth, wet cuttings at 10 m, soft at approx 12 m depth; medium hardness at approx 13 m depth
B15	17.9	No	pocket at 14.8 m, 15 rods used in hole and ice is still solid
B16	17.5	No	pocket at 12.8 m, pocket at 15.8 m, softer ice at approx. 13 to 15 m depth, medium hardness at approx. 16 to 17 m depth, wet cuttings not noted
B17	17.4	No	hard ice to 12 m depth, wet cuttings at approx 12 m, medium hardness at approx 13 m, soft ice at approx. 14 m (drill jams), medium hardness at approx 15 m, soft ice from approx 16 to 18 m
B18	17.1	No	hard ice to 10 m depth, wet cuttings at 10 m, softer ice at approx 13 to 17 m depth

*some of the drill holes were closely monitored to note where the drill cuttings changed from dry to wet, and where the ice was hard or soft

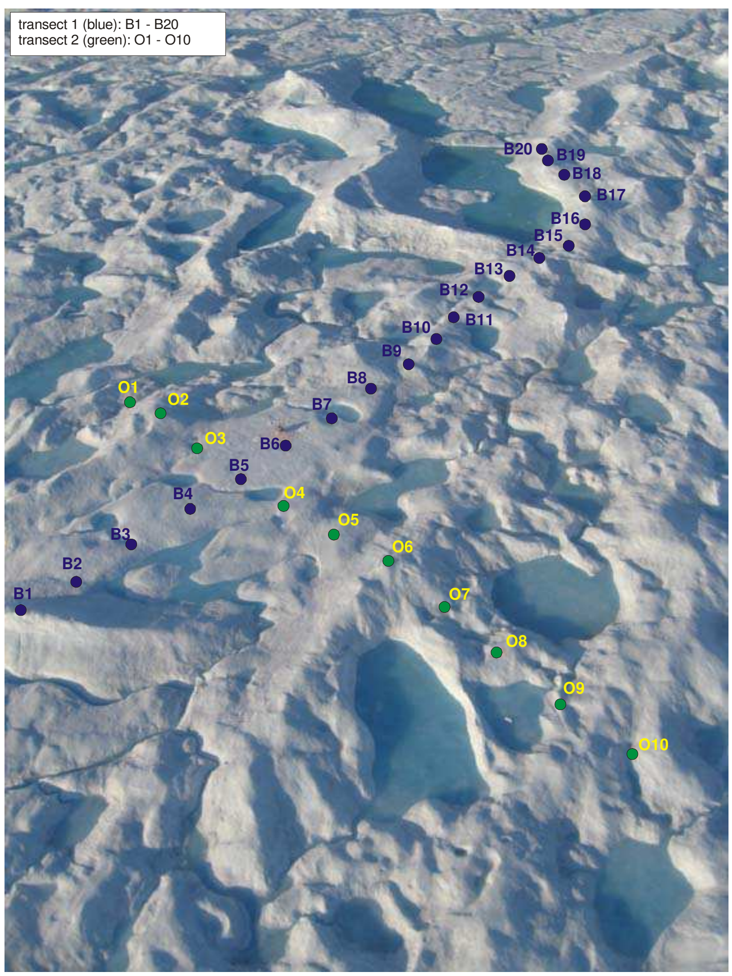


Figure 39 Aerial view of two transects made on Floe L08

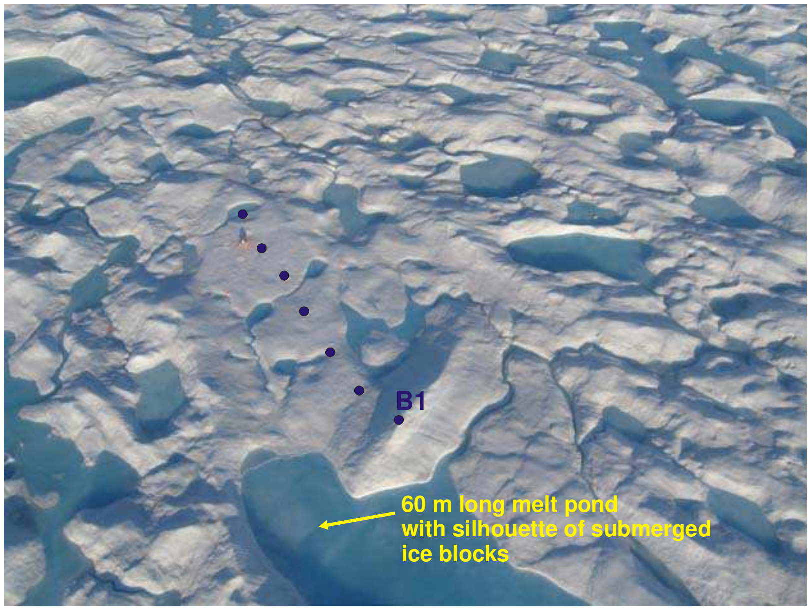


Figure 40 Aerial view of melt pond near hole B1

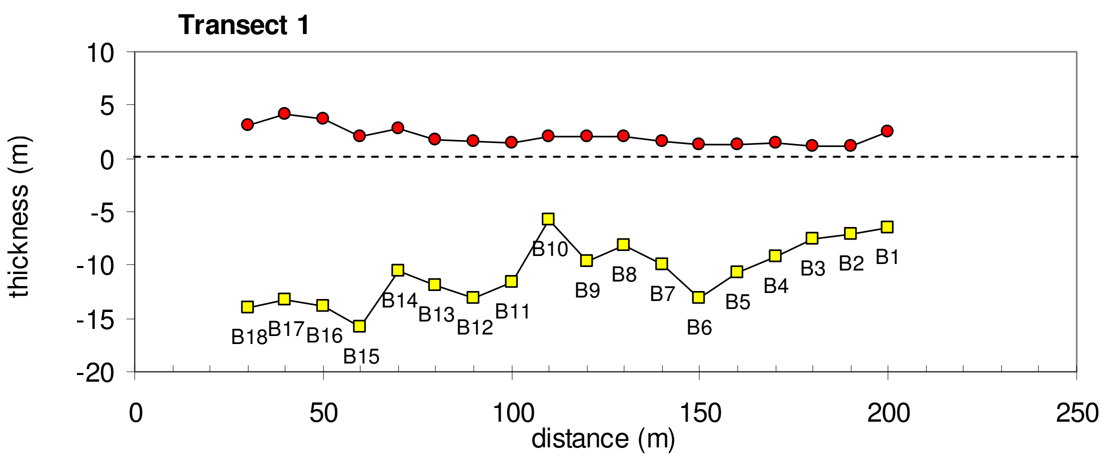


Figure 41 Floe L08: Surface and bottom topography from drill hole measurements

5.8.2 Average Thicknesses from the HEM

The HEM passed over Floe L08 three times throughout the day, as the floe drifted north, then east, and finally northwest in Belcher Channel (Figure 42). Most of the HEM data were obtained during the first and third overpasses; the second overpass produced mostly drop-outs. The HEM returned a maximum thickness of 11.8 m (Figure 43) and average thicknesses of 9.0 and 10.2 m for each flight (Table 14). In comparison, drill-hole measurements produced a maximum thickness of 17.9 m and an average thickness of 12.7 m (±3.3 m).

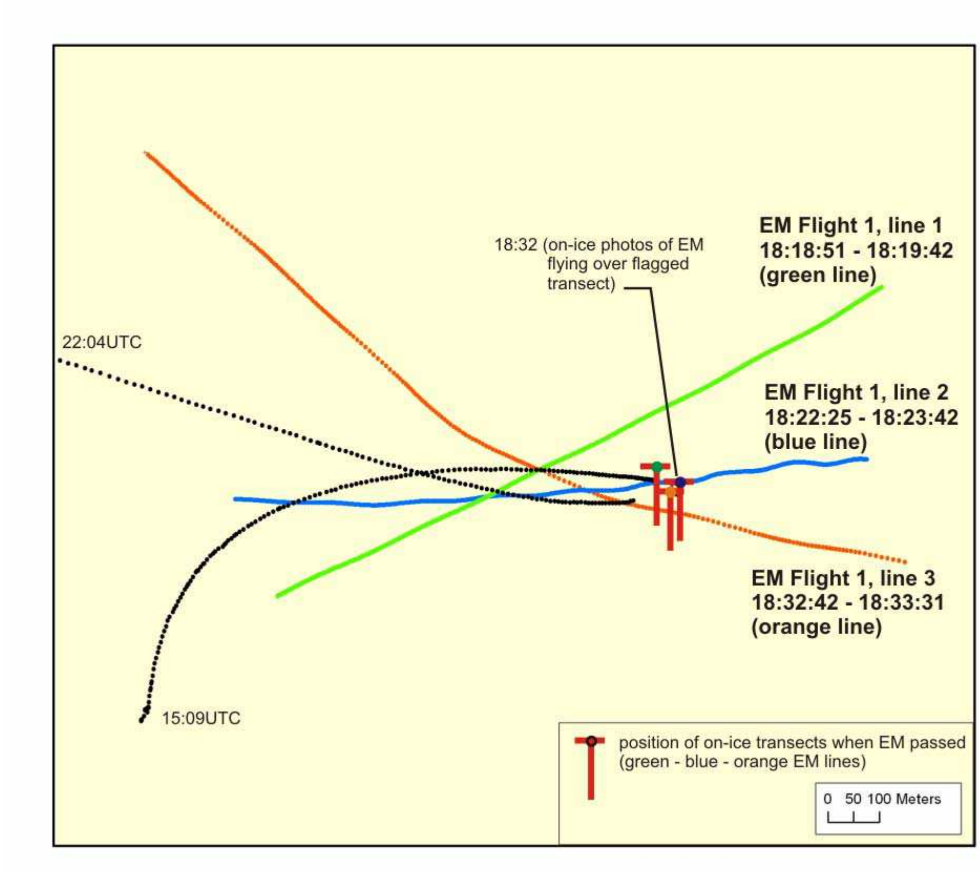


Figure 42 Floe L08: Three EM flight segments that coincided with on-ice measurements (HEM data courtesy of C. Haas)

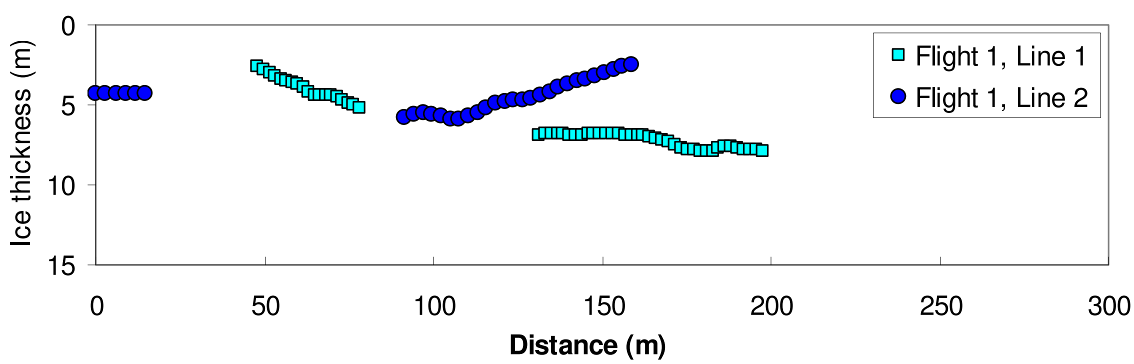


Figure 43 Floe L08: Results from HEM where floe trajectory and flight segment overlapped (HEM data courtesy of C. Haas)

Table 14 Floe L08: Average Thicknesses from Drill Hole and HEM

	Ice thickness	Drill hole	HEM
Transect 1	avg ± st dev (m)*	12.7 ± 3.3	
	max (m)	17.9	
	min (m)	7.9	
Transect 2	avg ± st dev (m)	--	
	max (m)	--	
	min (m)	--	
Flight 1, line 1	avg ± st dev (m)	--	10.2 ± 0.8
	max (m)		11.8
	min (m)		8.7
Flight 1, line 2	avg ± st dev (m)	--	--
	max (m)		--
	min (m)		--
Flight 1, line 3	avg ± st dev (m)	--	9.0 ± 1.1
	max (m)		10.9
	min (m)		7.3

*includes overlapping data along Transect 1, holes B1 to B18

5.8.3 Installing the Ice Buoy and Temperature Chain on Floe L08

At 17:10 hrs, drill hole measurements ceased, and focus shifted to installing the four supports for the ice buoy since it was scheduled to arrive at 19:00 hrs. The ice around hole B6 (14.5 m) was selected for the installation. Although the ice was thicker than preferred, time was not available to find a more suitable location. By 18:15 hrs, the four supports had been installed in relatively level ice near hole B6. About 2.2 m of the 3 m long supports were frozen into the ice, which left about 0.8 m of the support exposed (Figure 44-a). A call to the ship was made at 18:20 hrs to check in, only to learn that the ice buoy was due to arrive in about 10 minutes – inclement weather[4] meant that the schedule had been pushed 30 minutes ahead of time. Two more holes were drilled before the buoy arrived – holes B1 and B2. It was absolutely remarkable that the pilot set the 250 kg buoy down on its four supports on the very first try because, unlike Floe L03, he did not have the flight engineer on the ice to direct him.

After the buoy had been set down on its supports, the field team was informed that they would have only about 20 minutes to finish operations on the ice – which was the length of time needed to ferry the first load of equipment back to the ship, and return for the second. By 19:00 hrs, the temperature chain had been installed in 13.5 m thick ice. The uppermost temperature sensor was installed flush with the top ice surface, below which the sensors extended to the 11 m ice depth. As with Floe L03, it was not possible to measure the temperature of the seawater because the ice was 2.5 m thicker than the temperature chain. After the temperature chain had been installed, the CALIB tracking beacon that had been recovered from Floe L03 was strapped to one of the buoy's supports (Figure 49). The tracking beacon was meant to provide redundancy, should Iridium communications with the buoy fail. Figure 44 shows the ice buoy (a) as seen from the ice surface after its installation and (b) from the helicopter upon departing the floe.

[4] It was a miracle that the ice buoy made it to Floe L08 intact. The very experienced helicopter pilot, Robert Bartlett, later commented that he nearly pressed the "drop load" button several times on the way out. Flying below the clouds meant that it was essential he drop the load if it came too close to the ice.

By the time the ice floe team had returned to the ship, it had been decided to circumnavigate Devon Island in order to reach Penny Strait: transiting 1300 km of open water was preferable to the ship ramming it way through 200 km of congested ice in Belcher Channel and Queens Channel. Ramming very thick multi-year ice would consume a substantial amount of time and fuel which, understandably, the Captain was unwilling to do, particularly after having already battled multi-year ice in Hall Basin.

(a)

(b)

Figure 44 Ice buoy installed on Floe L08
(a) photo of ice buoy and the CALIB beacon after it was installed on 13.5 m thick ice (b) buoy was installed on a level part of the floe.

5.8.4 Repeat Thickness Measurements along Transect 1: August vs. May

Floe L08 was again visited in May 2010, 11 months later. The ice buoy telecommunicated its last ice temperature data on 31 October 2009, which made it difficult to know whether the ice buoy was still intact when it was decided to re-visit the floe the following spring. However, the continued stream of positional data from the CALIB beacon suggested that the floe had not been destroyed over the winter. In fact, data from CALIB beacon indicated that the floe had not moved since October 31. The CALIB beacon played an essential role in the making the return trip – had it stopped transmitting data, there would have been little or no justification for re-visiting the floe, since it would have been presumed destroyed.

The repeat visit to Floe L08 was scheduled for May in order to document the temperature, salinity and strength of the ice before significant ice warming had occurred. Two trips were made from Resolute in early May. The first trip would be used to verify that the floe was still intact, download temperature data from the ice buoy and to conduct repeat thickness measurements along the drill-hole transect. The second trip would be made to measure the temperature, salinity and strength of the ice in one or more boreholes. The plan was to use a helicopter to make the first visit (since it would facilitate searching for the ice buoy, but allowed minimal equipment to be transported) and the second trip by Twin Otter (to maximize the amount of equipment taken, since there would be no need to search for the ice buoy).

Once in Resolute, PCSP suggested that it would be more advantageous to use a Twin Otter to travel the 300 km from Resolute to Floe L08 in Belcher Channel. A Twin Otter would cover the distance much more quickly than a Bell 206L, it would not need to refuel en route, and it permitted taking more equipment. The disadvantages of making the first trip by Twin Otter was that searching for the ice buoy would be more difficult than from a helicopter and the Twin Otter would not be able to land on hummocked multi-year ice like Floe L08. In this regard, fate smiled upon the field party because satellite imagery showed that a refrozen lead had formed at the edge of Floe L08 (Figure 45). The refrozen lead made a perfect landing strip for the Twin Otter. The snow cover and frozen meltponds gave Floe L08 a very different appearance than it had when it was first visited in August 2009, but searching for the ice buoy by snow machine was relatively straightforward because the floe's prominent hummocks allowed the domed ice buoy to be spotted from afar.

After downloading data from the ice buoy, a new set of flags were laid over what was believed to have been the same transect that had been drilled in August 2009. In May, snow thickness ranged from 0 to 16 cm along that transect. Once the snow had been removed at each station, most of the stations still showed evidence of the biodegradable marking paint[5] that had been used the previous summer, confirming that the repeat drill holes were being made along the same line as measurements during the first visit to the floe. Table 15 shows a comparison of the total ice thicknesses measured at ten holes along the transect in August 2009 and May 2010. The ice at every one of the ten drill holes was thinner in May than it was in August, by as much as four to five metres at two of the drill holes (B5 and B6). On average, the decrease in thickness was 1.8 m. The ice freeboard at nine of the ten drill holes was less in May than it had been in August, hole B1 being the exception. The ice freeboard ranged from 1.2 to 2.5 m in August, compared to 0.9 to 3.0 m in May.

[5] Biodegradable marking paint was used to identify the location of drill holes from aerial photographs.

It is important to note that the change in ice thicknesses on Floe L08 was not due to melt alone. Perovich et al. (1997) state that thinning on the top of the ice begins after the snow cover melts in June, continues into July and then tapers off in early August. That suggests very little thinning of Floe L08 occurred between the time that the floe was first visited (late August 2009) and its repeat visit (spring 2010). In comparison, thinning on the bottom of the ice likely continued for several months after Floe L08 was visited in late August, as the ocean continued to release heat to the bottom of the ice.

Determining the amount of bottom ablation from repeat drill hole measurements is wrought with error. As already discussed, the thickness of deformed multi-year ice can vary greatly over small distances, particularly when large voids are involved. Most of the voids encountered in the holes drilled in August 2009 had filled by May 2010, but two of the drill holes were still characterized by voids in May, despite the prolonged, cold temperatures of the Arctic winter (holes B4 and TC, see Table 15). The presence of blocks on the underside of the floe may have also complicated the thickness comparison, since those blocks may have shifted prior to the floe's becoming incorporated into landfast ice in the fall.

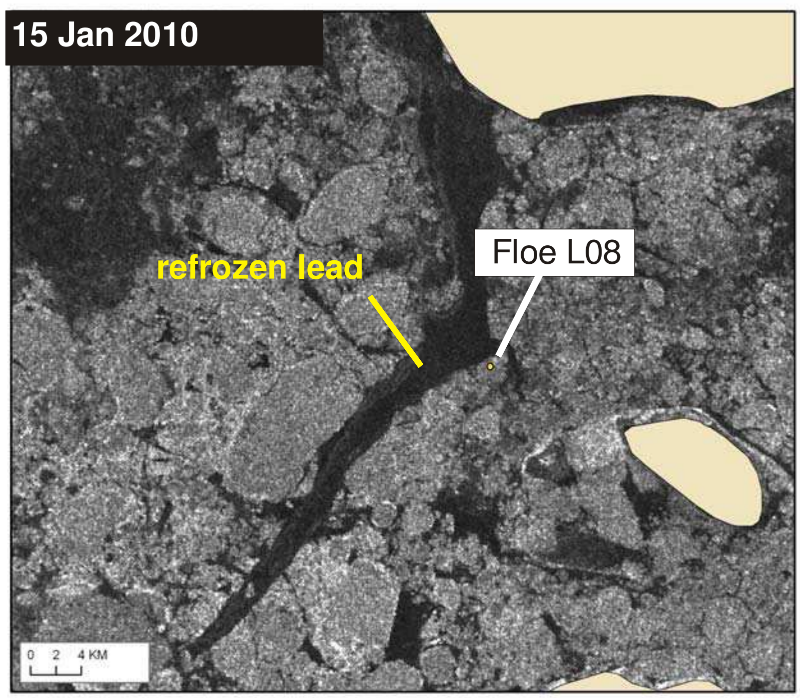


Figure 45 RADARSAT-2 image of refrozen lead in Belcher Channel, 15 Jan 2010
Beige outline shows land, frozen lead shown as smooth, black area, multi-year ice as grey, speckled areas (image courtesy of CIS)

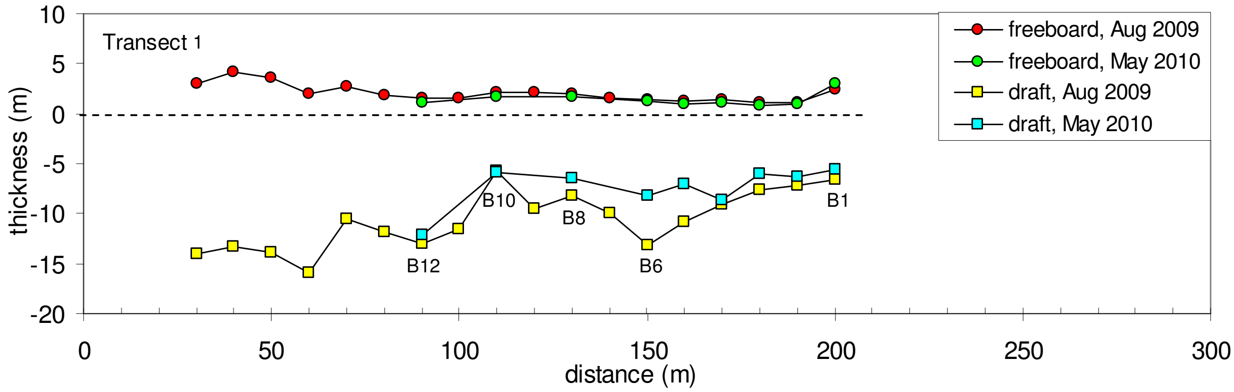


Figure 46 Ice thicknesses measured for Transect 1 in Aug 2009 and May 2010

Table 15 Repeat Thickness Measurements on Floe L08: August vs. May

Hole	August thickness (m)	May thickness (m)	Decrease in thickness (m)	Snow depth in May (cm)	notes
B1	9.1	8.7	0.4	11.0	
B2	8.3	7.2	1.1	3.0	August: pocket at approx 8 m. May: none noted
B3	8.7	6.9	1.8	0	
B4	10.5	9.8	0.8	1.5	August: no pocket noted May: pocket at 6.6 m
B5	12	8.0	4.0	3.5	August: pocket at approx. 10 to 11 m depth. May: none noted.
B6	14.5	9.5	5.0	3.0	
B7	11.5	--*	--		
B8	10.2	8.2	2.0	2.5	August: pocket at approx. 9 m. May: none noted.
B9	11.7	--*	--		
B10	7.9	7.7	0.2	3.0	
B11	13.1			16.0	
B12	14.7	13.3	1.4	0	
TC**	13.5	12.4	1.1		May: pocket at 7.3 m; drill auger drops between depths 8 and 10.5 m when it encountered a large void. Below 10.5 m depth, ice again solid until bottom at 12.4 m.

* no measurements were made at this hole in May
** TC refers to temperature chain

5.8.5 Temperature, Salinity and Strength Profiles of Floe L08 in May 2010

Two site visits were made to Floe L08 in May 2010, when air temperatures were about -10°C. The first visit to Floe L08 was made on 3 May and the second visit on 8 May. Due to time constraints, and the other tasks required on Floe L08, it was possible to sample only one borehole during each visit. During both visits, a corer was used to extract cores to a depth of 5 m, below which the an ice auger was used to extend the borehole to a depth of 6 m. The cores on 3 May were used to measure the temperature and salinity of the ice; measurements were not made on cores extracted on 8 May because they were packed and shipped to the laboratory facilities in Ottawa. Strength tests were conducted in both boreholes to a maximum depth of 5.4 m, at 30 cm depth intervals. Figure 47 shows the location of the borehole that was made on 3 May and on the 8 May. The two boreholes were separated by a distance of about 5 m.

The ice core that was extracted on 3 May had a top ice surface temperature of -7.8°C that decreased to a minimum temperature of -13.4°C at a depth of 2.8 m (Figure 48-a). The temperature of the ice from a depth of 2 to 3 m was steady at -13°C, below which the temperature increased to -8°C at the 5 m ice depth. The average temperature of the uppermost 5 m of ice on 3 May was -11.3°C.

After measuring the temperature of each 1 m long ice core, salinity specimens were prepared by cutting disc-shaped pieces from the core at 20 cm intervals. The discs were double-bagged, labeled and taken back to base camp where the salinity of the melt water was measured with an electrical conductivity meter. The salinity of the ice core that was extracted on 3 May was 1.5‰ or less to a depth of 2.4 m, increased to 2.2 to 3.2‰ from depths 2.6 to 3.2 m and then varied from 0.9 to 2.2‰ below a depth of 3.2 m (Figure 48-b). The average salinity of the uppermost 5 m of ice was 1.4‰ .

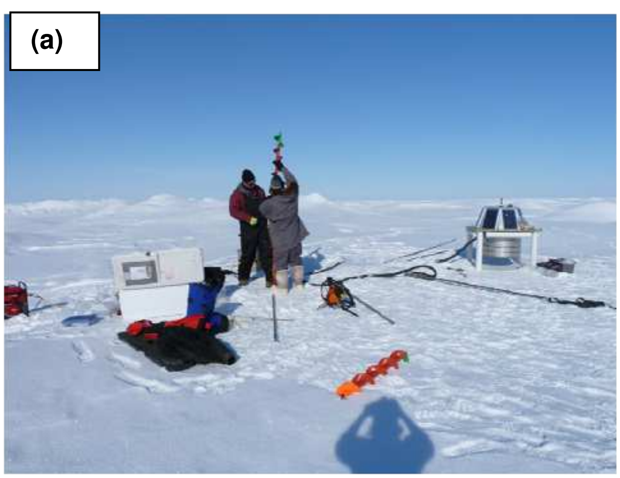


Figure 47 Site of borehole made on (a) 3 May and (b) 8 May 2010

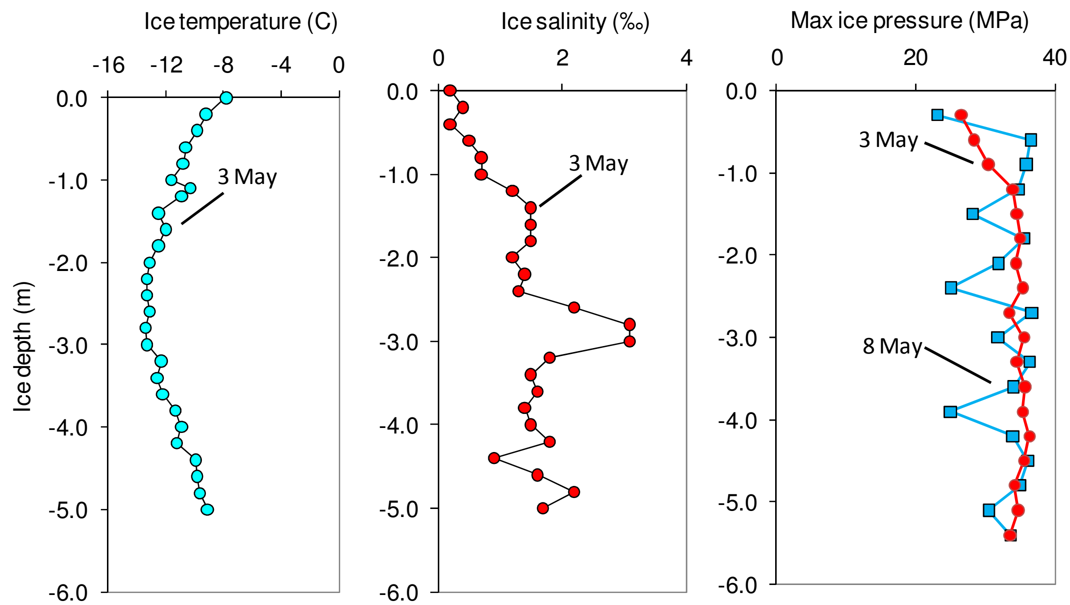


Figure 48 Temperature, salinity and maximum ice pressure measured on Floe L08 in May 2010
Note that the erratic maximum pressures attained at certain test depths during on 8 May suggest that the ice strength was influenced by cracking activity.

Depth profiles of the maximum ice pressure attained for individual tests in each borehole are included in Figure 48-c. It was hoped that the borehole strengths measured on 3 May and 8 May would be comparable because the boreholes were only about 5 m apart and the surface of the ice in that area looked uniform. The two boreholes produced very different strength profiles however. Borehole strengths on the 3 May were consistent with increasing depth, whereas the strengths measured in the 8 May borehole were much more variable.

Was ice in the 8 May borehole actually weaker than the 3 May borehole, or were the test results affected by conducting multiple borehole tests in the same hole – or from tests in the borehole that was made 5 m away on 3 May? Both factors may have played a role, but it is more likely that the variable strengths on 8 May resulted from damage caused by tests conducted in the same borehole. Significant cracking activity occurred during 7 of the strength tests on 8 May (0.30 m, 2.10 m, 2.40 m, 2.70 m, 3.0 m, 3.60 m and 4.20 m). Ice in the 8 May borehole cracked repeatedly during that first test (0.30 m depth), and then no cracking activity was heard until the 2.10 m test depth. In comparison, substantial cracking was noted during only one test in the 3 May borehole (depth 4.20 m) and that damage did not adversely affect results from subsequent tests deeper in the ice. Although this phenomenon needs to be looked into further, results suggest that ice in the two boreholes may have been non-uniform, despite its similar surface appearance.

Here, it should also be noted that reporting the maximum pressure attained during a borehole test may not be the best approach for reporting the strength of the ice: it relays nothing about the abrupt advance of the indentor(s) that occurs when the ice cracks, the length of time needed to attain the peak pressure is not taken into account and the maximum pressure is sometimes underestimated for cold multi-year ice at some test depths due to limitations in the capacity of the borehole system. One would expect the ice strength profile and the ice temperature profile to be similar, since the ice strength is dependent upon ice temperature. That is not the case here, as Figure 48 shows. One can only surmise that the improper representation of 'maximum pressure' as 'ice strength' is the cause. This matter will be examined further in subsequent publications.

5.8.6 A Year in the Life of Floe L08

Floe L08 has an interesting history, indeed, as illustrated by the map in Figure 49 and the photos in Figure 50. On 27 August 2009, the ice buoy and CALIB beacon were installed on Floe L08 in Belcher Channel. The ice buoy documented the temperature of the ice at various depths and provided data about the floe's position. Data from the ice buoy were downloaded on a daily basis from laboratory in Ottawa until communications with the system failed 31 October 2009[6]. The CALIB beacon continued to transmit data (about once every 10 minutes) until September 2010, which is the best that can be expected from its one-year battery capacity.

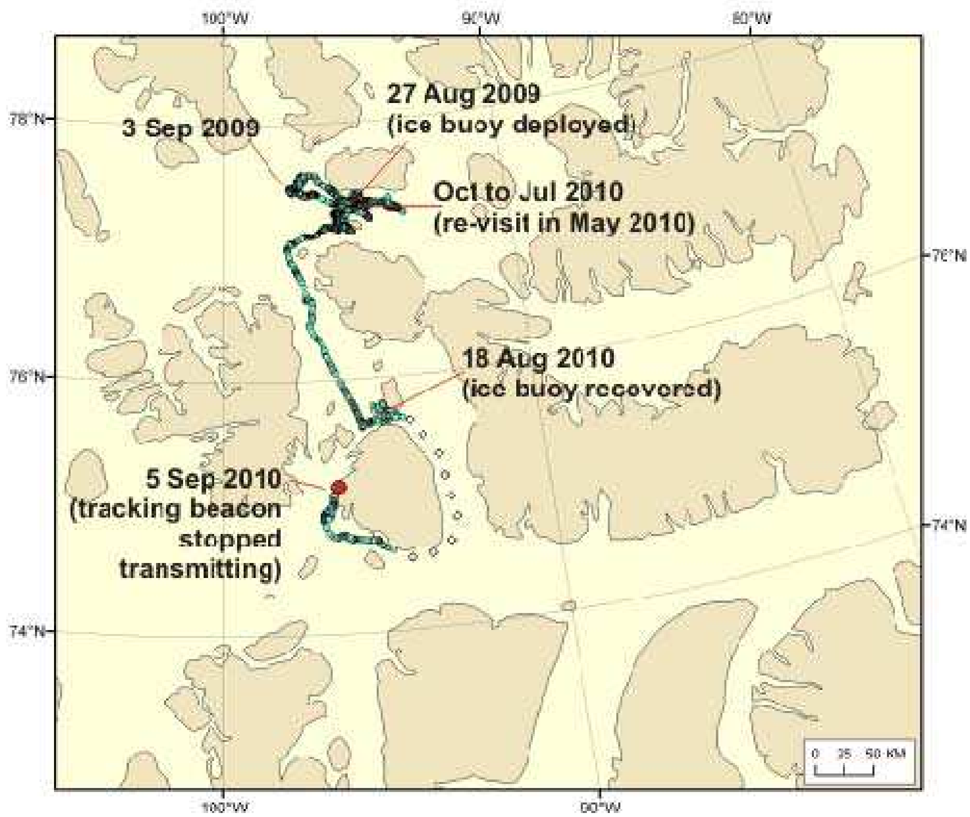


Figure 49 Drift of Floe L08 from 27 August 2009 to 1 Sep 2010
The ice buoy was installed on 27 Aug 2009 and was recovered on 18 Aug 2010. The CALIB beacon remained on the floe and continued to transmit (intermittently) until 5 Sep 2010.

[6] On 22 June 2010, about one year after installing the instrumentation package on Floe L08, NRC-CHC was informed of an incompatibility between Campbell Scientific's instrumentation and the Iridium A3LA-MPT modem (see Appendix B). Due to this disruption, which occurred randomly, communication with Floe L08could not be established after 31 October 2010 (neither remotely nor directly during the May 2010 site visit).

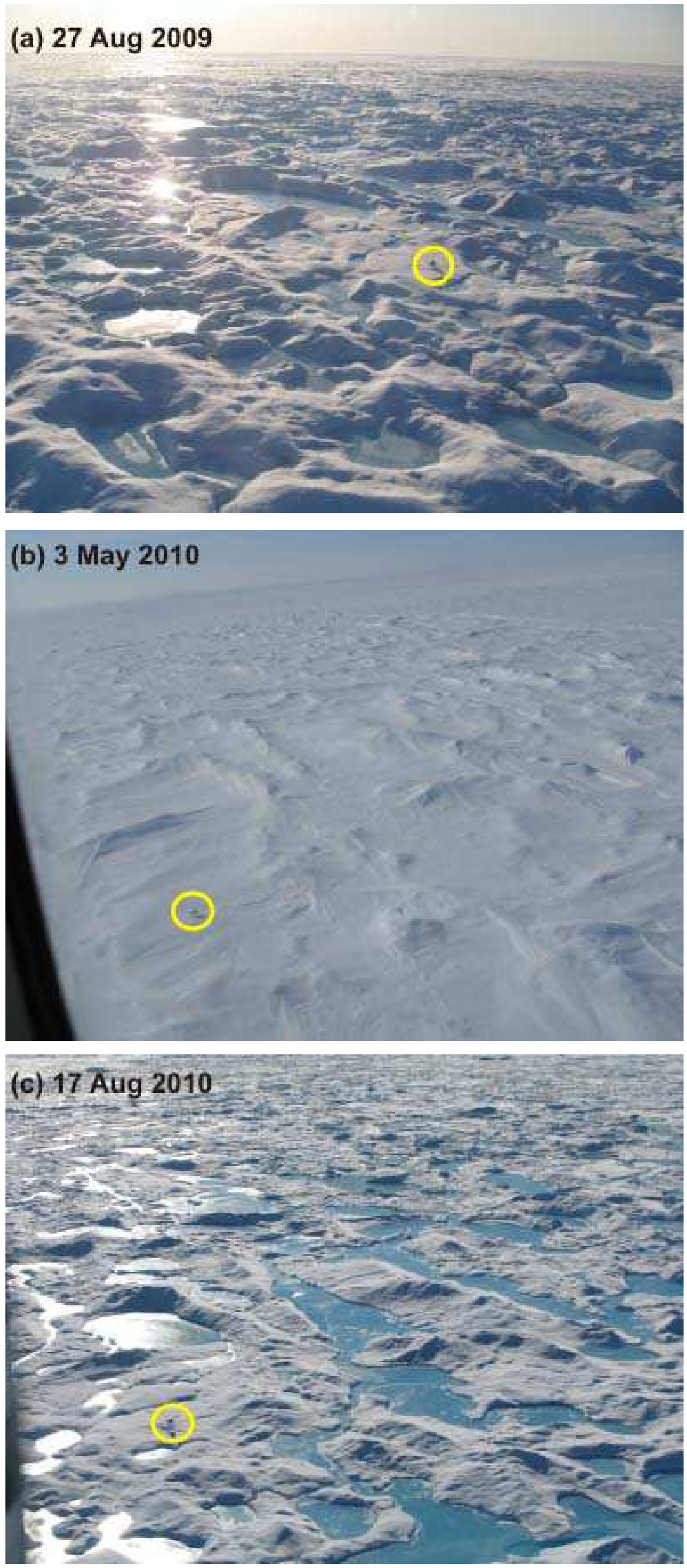


Figure 50 Aerial views of Floe L08 at three points in time
(a) the first visit to the floe on 27 Aug 2009, (b) the second visit to the floe on 3 May 2010 and (c) the day before the 18 August recovery, courtesy of PCSP. Ice buoy circled in yellow.

By mid-July 2010, Floe L08 had drifted enough to qualify it as “free of landfast ice”. The floe drifted within a 20 km radius of its winter position until 8 August, when it began to migrate along the Grinnell Peninsula, through Penny Strait and towards Maury Channel. Floe L08 lingered in Maury Channel for about one week, providing an excellent opportunity to recover the buoy. The author asked PCSP to conduct an aerial reconnaissance of Floe L08 (based upon updated coordinates from the CALIB beacon) to ensure that the ice buoy was still intact before planning a trip north later that week. PCSP was willing to do this, and even more remarkable was their willingness to recover the buoy on their own, the day after the reconnaissance was made.

Figure 50-c includes one of photographs taken during the PCSP’s 17 August reconnaissance of Floe L08. Here, it should be mentioned that “recovery” of the 250 kg ice buoy was a complicated business that involved slinging the buoy from Maury Channel to Resolute, a distance of more than 100 km. Thankfully, PCSP was willing to do this because had the buoy not been recovered while it was in Maury Channel, it may not have been recovered at all: the ice temperature data from May 2010 to August 2010, the expensive instrumentation and the buoy’s battery[7] would have been lost.

When PCSP recovered the buoy on 18 August, it stood about 1.8 m above the ice surface, “teetering on its supports” (helicopter pilot, personal communication). Note that only about 0.7 m of each 3 m long support had been exposed when the buoy was installed on 27 August 2009 (Figure 44-a). That information, combined with photographs of the newly exposed buoy supports and exposed temperature chain casing (Figure 51) indicate that the surface of Floe L08 had ablated by 1.0 to 1.2 m during the summer of 2010.

As requested, PCSP recovered the ice buoy, but left the CALIB beacon on the floe because it would continue to provide valuable information about the floe’s drift trajectory. On 24 August, just six days after the ice buoy had been recovered, the CALIB beacon stopped transmitting data, as it rounded the northern part of Cornwallis Island and passed into Wellington Channel. Imagine the surprise when the CALIB again began transmitting data again on 28 August – having migrated along coast of Cornwallis Island to within 10 km of Resolute – right to PCSP’s doorstep!

Floe L08 continued to drift south along Cornwallis Island before moving into McDougall Sound. The floe drifted 20 km north in McDougall Sound until it was pushed against the western edge of Cornwallis Island, and then turned south once again. The last stream of GPS data from the CALIB beacon came on 5 September, as Floe L08 made its way south towards Lancaster Sound. Did the CALIB stop transmitting data because its battery expired or because the floe broke up? It is difficult to say which, but given the floe’s appearance on 18 August, it was likely because the CALIB’s one-year battery expired.

[7] although the ice buoy initially had two alkaline batteries, one of them had been removed during the May 2010 site visit, to minimize negative effects should recovery of the buoy prove impossible.

Figure 51 Ice buoy when PCSP recovered it on 17 Aug 2010, one day before it was recovered. Note that extensive thinning of the top surface exposed 2 m of the buoy's 3 m long support legs. The tracks surrounding the ice buoy are from a curious polar bear. Polar bear activity probably also explains why the CALIB beacon (circled in red) is lying about 2 m from the support leg to which it had been strapped. Photo courtesy of PCSP.

5.8.7 Seasonal Changes in Temperature of Floe L08

The 42 sensors in the temperature chain logged data from 27 August 2009 to 18 August 2010. The data provide unique information about how the temperature of a very thick multi-year floe changed throughout the year. Similar instruments have been installed on multi-year floes up to 6 m thick (Perovich et al., 1997), but this kind of information is non-existent for very thick, deformed multi-year ice.

Figure 52 illustrates the changes that Floe L08 underwent from August 2009 to August 2010 based upon its temperature-depth profiles (at 06:00 hrs). The figure clearly shows that the temperature sensors functioned well from late August to mid-October, when many sensors reported higher temperatures than the neighboring sensors. For example, the two sensors at depths 4.75 m and 6.75 m began reporting spurious results towards the end of October. The 6.75 m deep sensor returned to normal in January, but the 4.75 m deep sensor continued to malfunction throughout winter, although it returned to normal in mid-July. It is believed that many of the sensors in the temperature chain malfunctioned because of water infiltration/moisture penetration. Because different sensors were affected at different times, it is believed that the moisture likely migrated between sensors. The sensor at a depth of 8.5 m produced the wildest results when it registered temperatures of almost +4°C *within* the ice sheet.

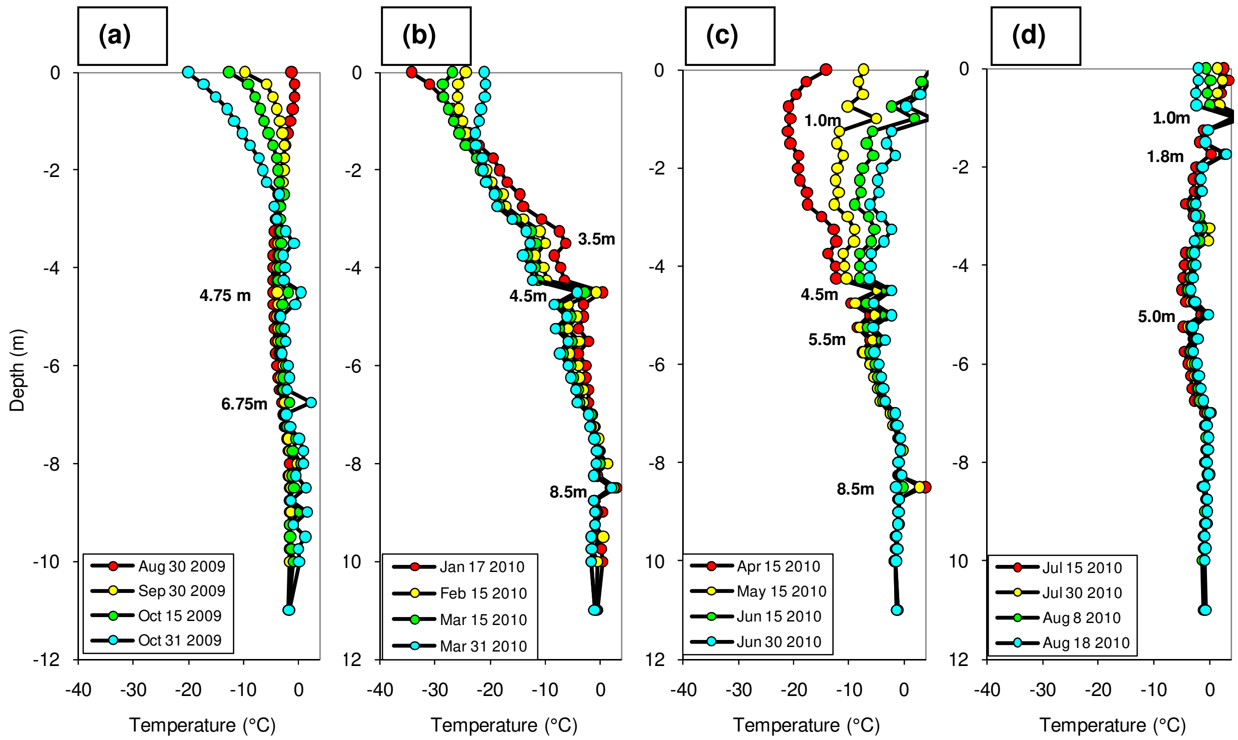


Figure 52 *In situ* Temperature profiles for Floe L08, 30 Aug 2009 to 18 Aug 2010
Some sensors showed erratic warming at different points throughout the year. This erratic behavior was likely caused when water infiltrated the cable jacket and migrated between the different sensors, as discussed in the text.

Understandably, the behavior of the errant temperature sensors caused results from all of the sensors to be suspect. The 5.4 m long ice core that was extracted on 3 May 2010 provided an excellent means of validating the data from the temperature chain. Figure 53 shows that temperatures from the ice core are in good agreement with the *in situ* temperatures: by early May, the snow-free surface layer of Floe L08 had warmed to a depth of about 2 m and the coldest ice occurred at depths 2 to 3 m, where temperatures were close to -13°C. Results from the *in situ* temperature sensors at depths 0.50 m, 1.0 m, 3.0 to 3.5 m, 4.5 to 5.0 m and 8.5 m were indeed suspect.

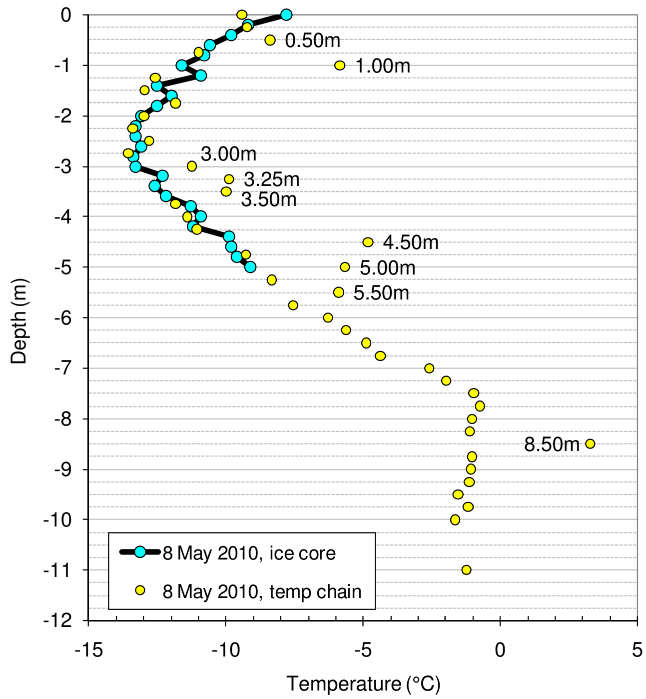


Figure 53 Comparison of *in situ* temperatures to ice core temperatures

Having established the validity of measurements from the temperature chain, the discussion now turns to general trends exhibited by Floe L08 over the course of one year. Figure 52 shows that on 30 August 2009, three days after the temperature chain had been installed, the ice was characterized by a "C-shaped" temperature profile. The "C-shaped" profile extended from the top ice surface to a depth of 7.75 m, below which the ice was isothermal at -1.7°C to the 11 m depth. In late August 2009, the coldest temperature occurred at a depth of 4.25 m (-4.6°C). By late September, cold air temperatures had penetrated 1.5 m below the top ice surface (-2.6°C). Although the uppermost 1.5 m of ice was cooling in late September, it is interesting to note that the bulk layer of ice (depths 1.5 to 7.75 m) continued to warm. By mid-October, the cold wave had penetrated further into the ice (to a depth of 2.25 m, where the ice temperature was -3.5°C). At that point, temperatures below the 2.25 m ice depth, which had been warming over the past weeks, stabilized.

Since many of the sensors began reporting erratic temperatures in late October, it is difficult to draw conclusions about the depth to which cold air temperatures penetrated the ice. Nevertheless, the temperature profiles do show that a linear temperature gradient extended from the top ice surface (where the ice was coldest) to a depth of about 8 m in January. Temperatures in the uppermost layer of ice had begun to warm by mid-February. The uppermost sensor (0.0 m) reported a temperature of -34.3°C on 17 January, -24.4°C on 15 February, -26.8°C on 15 March and -21.0°C on 31 March. By late March, temperatures at a depth of 1.5 m began increasing and by mid-April temperatures at a depth of 2.75 m began increasing (although ice at that depth remained very cold, -17.5°C). The warming trend steadily continued after mid-April, until the last measurements were acquired on 18 August 2010. When the ice buoy was recovered on 18 August, the entire full thickness of ice was nearly isothermal, with the ice at a depth of 4.5 m having the coldest temperature (-3°C).

It is notable that the most marked temperature changes occurred in the uppermost 7 m of ice. In fact, all of the sensors within the uppermost 7 m of ice showed a measurable amount of warming or cooling over the course of the year. Equally notable is evidence suggesting that the bottommost layer of ice remained isothermal throughout the year. That is surprising, in light of prior evidence showing that cold air temperatures penetrated throughout the full depth of two multi-year floes in Wellington Channel, which is only about 200 km south of Belcher Channel (Johnston, 2009). Both of the floes in Wellington Channel were just over 10 m thick and both floes had a "C-shaped" temperature profile that extended *to the bottom of the ice* in late May/early June, when the temperature chains were installed.

It is interesting that Floe L08 had such a different temperature profile than the two Wellington Channel floes at a comparable time of year. One might have expected the multi-year floes in Wellington Channel to have been warmer than Floe L08, not colder, since the floes were 200 km south of Belcher Channel. The air temperatures for Resolute reveal a marked difference between the two years. Table 16 shows that the mean monthly air temperatures for the winter-spring of 2007/08 were colder than the winter-spring of 2009/2010, particularly during the months of November, December and February. The shaded regions in the table denote the winter/spring months of relevance to the two Wellington Channel floes (2007/08) and the Belcher Channel floe (2009/10). The difference in air temperature could partly explain the thermal response of the multi-year ice floes, but the different morphology of the ice floes is believed to provide a better explanation (as discussed below).

Table 16 Resolute Mean Monthly Air Temperatures for Resolute

	Air Temperature (°C)*			
	2007	**2008**	**2009**	**2010**
Jan	-31.5	**-31.9**	-28.9	**-30.6**
Feb	-30.5	**-35.1**	-31.7	**-26.5**
Mar	-34.2	**-32.2**	-21.9	**-24.2**
Apr	-19.8	**-18.5**	-20.9	**-15.0**
May	-13.5	-7.1	-10.3	-8.7
Jun	1.3	2.2	1.0	2.2
Jul	7.4	5.3	5.3	5.3
Aug	4.9	2.3	4.9	4.3
Sep	-3.1	-5.0	-3.5	-3.0
Oct	**-12.3**	-10.8	**-13.6**	-8.9
Nov	**-25.4**	-20.5	**-18.1**	-17.6
Dec	**-27.7**	-27.5	**-23.1**	-21.5

*data courtesy of Environment Canada, shaded regions show months of interest for winter/spring/summer 2007/08 and 2009/10.

Floe L08 may have had a different thermal response than the two floes in Wellington Channel because it had a different morphology. Floe L08 was an extremely deformed multi-year ice floe, whereas the floes in Wellington Channel were both relatively level. Cold winter temperatures may not have produced a linear temperature profile in Floe L08 because it did not provide enough energy to freeze the large pore spaces/voids that characterized Floe L08. Drill hole measurements made near the temperature chain in May 2010 revealed that a 2.5 m void extended from a depth of 8 m, to a depth of about 10.5 m (as noted in Table 15). The *in situ* temperatures from the temperature chain suggest that the 2.5 m void did not freeze over the winter, which may also explain why the ice below it remained isothermal for the entire winter. That said, it is important to note that drill-hole measurements revealed that the ice below where the void terminated (10.5 m) was solid until the bottom of the ice was reached at 12.4 m. This is important, because it means that the bottom two metres of multi-year ice remained quite solid, despite *in situ* temperatures showing that the ice below a depth of about 8 m was isothermal.

5.9 Floe L09: Penny Strait , Aug 30

The last floe that was sampled in August 2009 was located in Penny Strait. On the morning of 30 August, the helicopter was loaded with three passengers and equipment to conduct a reconnaissance of the area. Most of the multi-year floes in the area had some areas of ice that had melted through the full thickness of ice. By 9:24 hrs, an approximately 2 km diameter aggregate floe containing a decidedly rugged 500 m diameter multi-year sub-floe had been selected for sampling (Figure 55). The massive ice boulders that had been incorporated into Floe L09 (Figure 54) produced sail heights of 5 m or more. Needless to say, walking on Floe L09 was extremely challenging. The light drizzle that fell throughout the day made scaling the steep ridges very difficult, all the more so because many of the ridges had a knifelike crest and were bounded on either side by deep melt ponds. The ice floe team sampled Floe L09 for about nine hours, returning to the ship at about 18:30 hrs. During that time, the floe drifted 7.9 km at an average speed of 0.9 km/hr. Strong winds from the south drove the floe north throughout the morning, but once the winds died down at about mid-day, the floe began to drift south.

Two transects were made on Floe L09. The thick layer of fog that descended upon the floe prevented the author from photographing the ice to document the location of individual drill holes and to obtain the floe size upon departing the floe. The location of the transects was instead obtained from the photograph of the floe that was taken during the morning reconnaissance. Key hummocks and melt ponds were used to superimpose the drill hole transect on the aerial photograph in Figure 55. Transect 1 began at a 5 m high pile-up (Figure 56-a) and extended 200 m through a hummocked area of ice (Figure 56-b). Transect 2 began near hole B7 and terminated in a low lying area of the floe (hole O10), about 30 m away from a drainage feature.

Figure 54 Floe L09 and the extreme roughness created by discrete boulders of ice

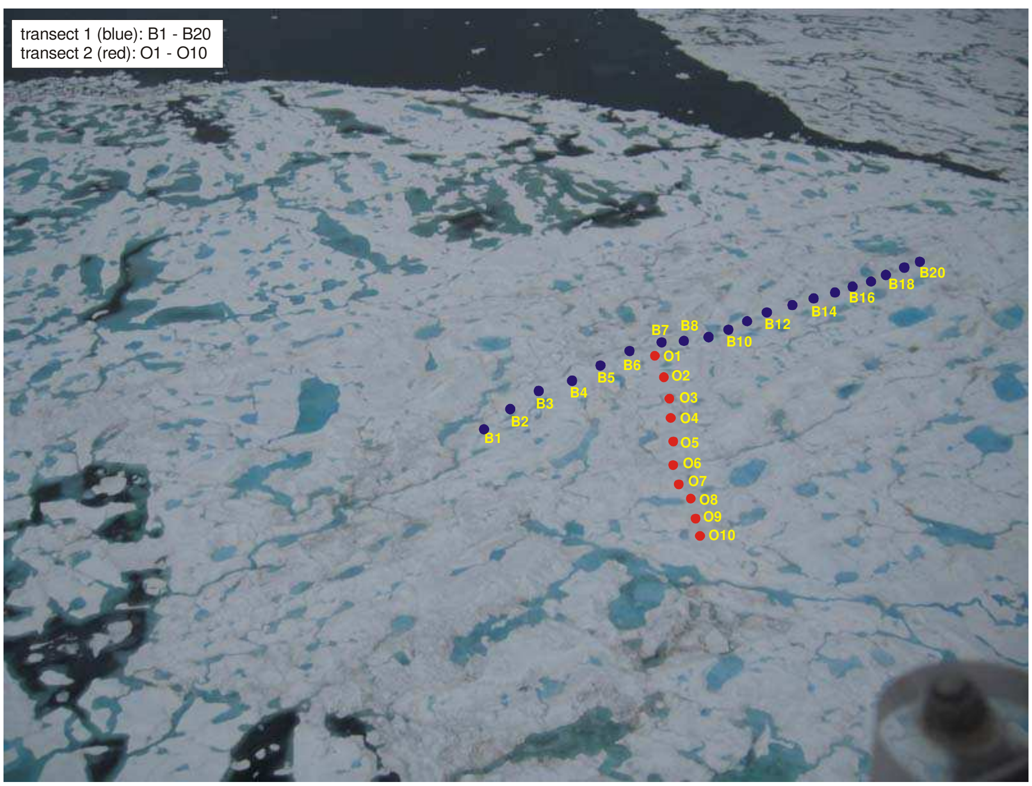


Figure 55 Floe L09 as seen from the air prior to landing
(approximate location of drill hole transects superimposed)

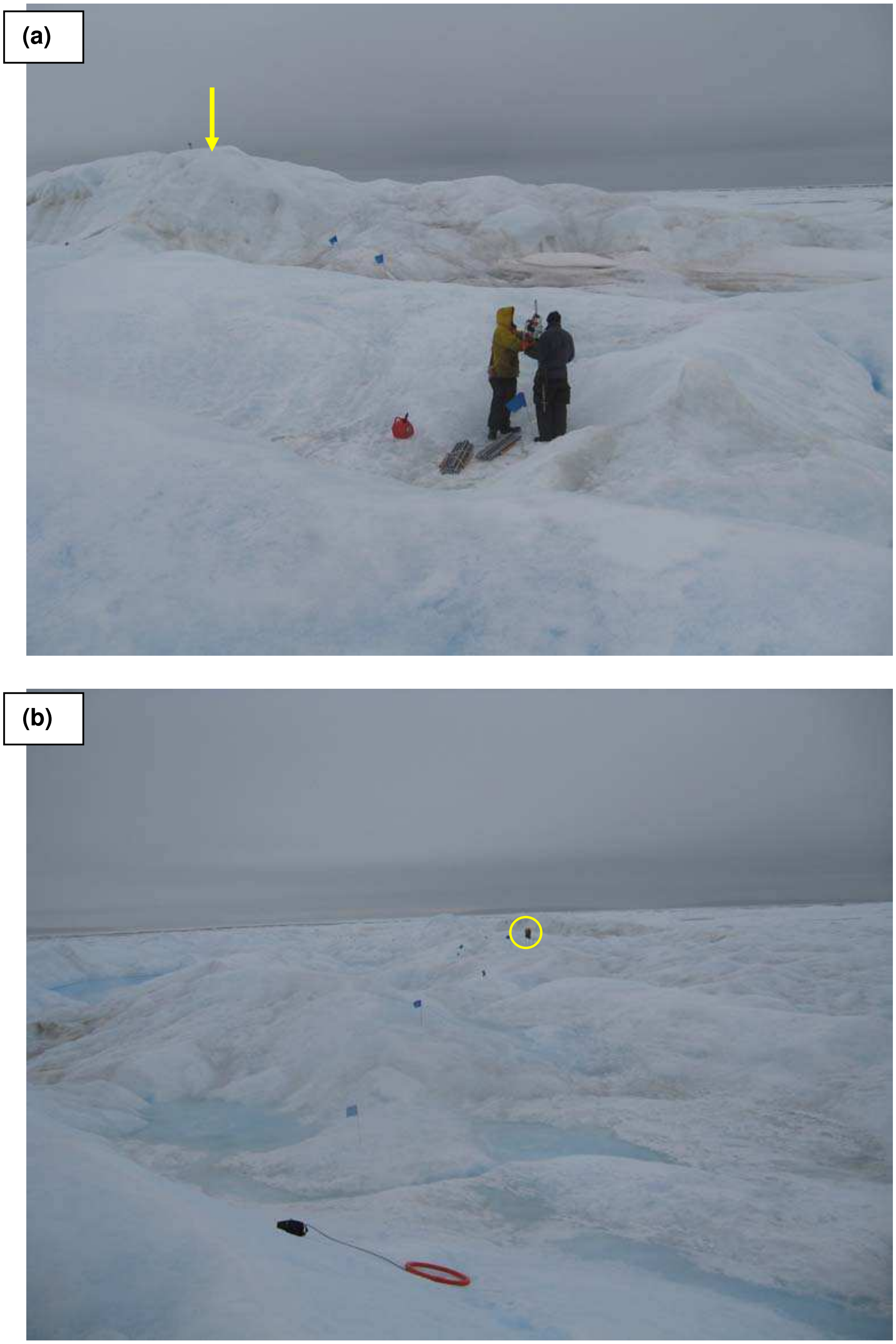


Figure 56 Surface conditions along Transect 1
(a) drill team at hole B8, with arrow showing approximately 5 m high pile-up at hole B1 and (b) Transect 1 extending over hummocked ice with drill team circled in distance

5.9.1 Surface and bottom topography

The surface and bottom topography of Floe L09 was documented from 20 drill hole measurements (Figure 57). The thickest ice (21.1 m) was measured at hole B1 where the sail was estimated to be about 5 m high (Figure 56-a)[8]. The thinnest ice was measured along Transect 2, where the ice was 8.5 to 8.8 m thick (holes O5, O9, O10). The freeboard of the floe ranged from near zero at the end of Transect 2 (hole O10) to 2.8 m (hole B9). The average thickness of the 20 drill holes was 14.7 m (±3.8 m).

Pockets were only encountered in one of the holes on Floe L09 (hole B1, at depth of 3 to 4 m). None of the drill holes revealed loose blocks on the underside of the floe. Quite the contrary – drilling though this multi-year floe was exceedingly difficult, particularly in the holes along Transect 2. Holes O6 (15.4 m thick) and O8 (10.2 m thick) were the most problematic, although conditions were only marginally better at the other holes. Evidently, this highly deformed multi-year floe was thoroughly consolidated, and had not decayed extensively over the summer – despite its appearance from the air. The fact that only 20 holes were drilled during the nine hour sampling period illustrates the extreme challenge posed by Floe L09 (compared to 61 holes drilled on Floe L02, average thickness of 3.4 m, during the course of a day).

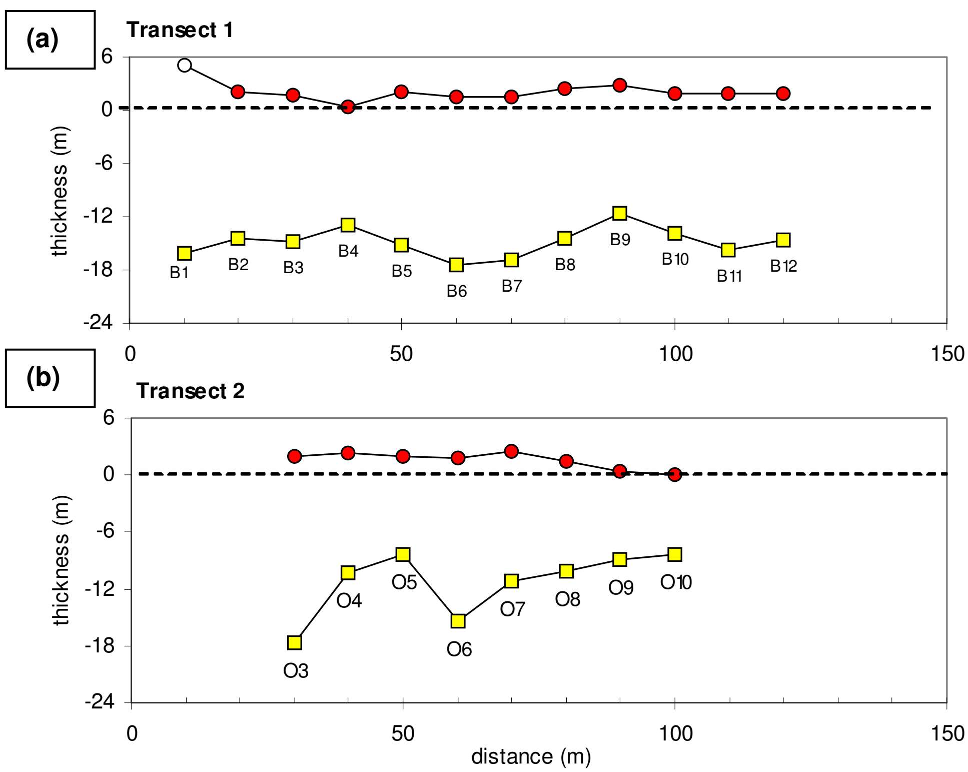


Figure 57 Floe L09: Surface and bottom topography from drill hole measurements (freeboard of hole B1 estimated from its approximately 5 m sail height)

[8] the freeboard at hole B1 was estimated from its approximately 5 m high sail. Freeboard measurement at that hole was a problem because the distance to the top of the thickness tape was too far into the hole to see seen. No other measurement device was available at the time.

Table 17 Drill holes on Floe L09 in which pockets or hard ice were noted

Hole	thickness (m)	loose blocks noted	notes
B1	21.1	No	pocket at rods 3 to 4; no freeboard given (sail to high, can't see down hole)
O6	15.4	No	very hard at rods 13-14-15-16; have to hammer auger to get through it
O8	10.2	No	very hard drilling

5.10 Floe W01: Wellington Channel, 9 May 2010

Satellite imagery acquired on 9 May 2010 showed that a number of multi-year ice floes were embedded in landfast ice in Wellington Channel. Four target floes were selected in relatively close proximity to Resolute, each having a diameter of at least 2 km. Poor weather on the morning of 9 May prevented the helicopter from flying, but by early afternoon conditions had improved enough to permit reaching Wellington Channel by following the coastline of Cornwallis Island, a distance of 120 km (Figure 58). Severe weight restrictions were imposed by the helicopter pilot, which meant that only two passengers and a limited amount of equipment could be taken during the trip.

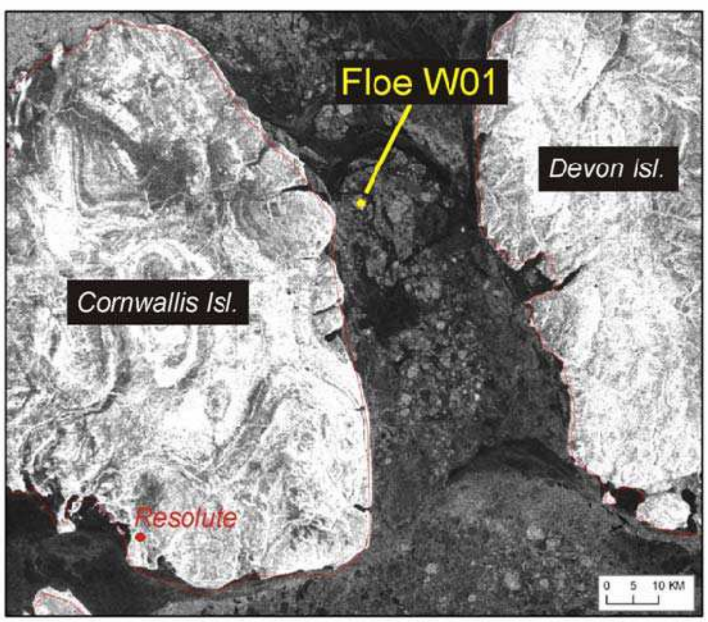


Figure 58 Satellite image acquired on 9 May 2010
(image courtesy of Canadian Ice Service, coastline outlined in red)

Floe W01was the first of the four targeted multi-year floes to be encountered in Wellington Channel. Realizing that the early afternoon departure from Resolute left only a limited amount of time for sampling, it was decided that the helicopter would land on Floe W01, so that the team could begin the on-ice measurements as soon as possible. The floe was 3.2 km in diameter and, provided plenty of level ice on which to land, despite its undulating surface. The two-person field team landed on the floe at 14:30 hrs and departed at 19:30 hrs.

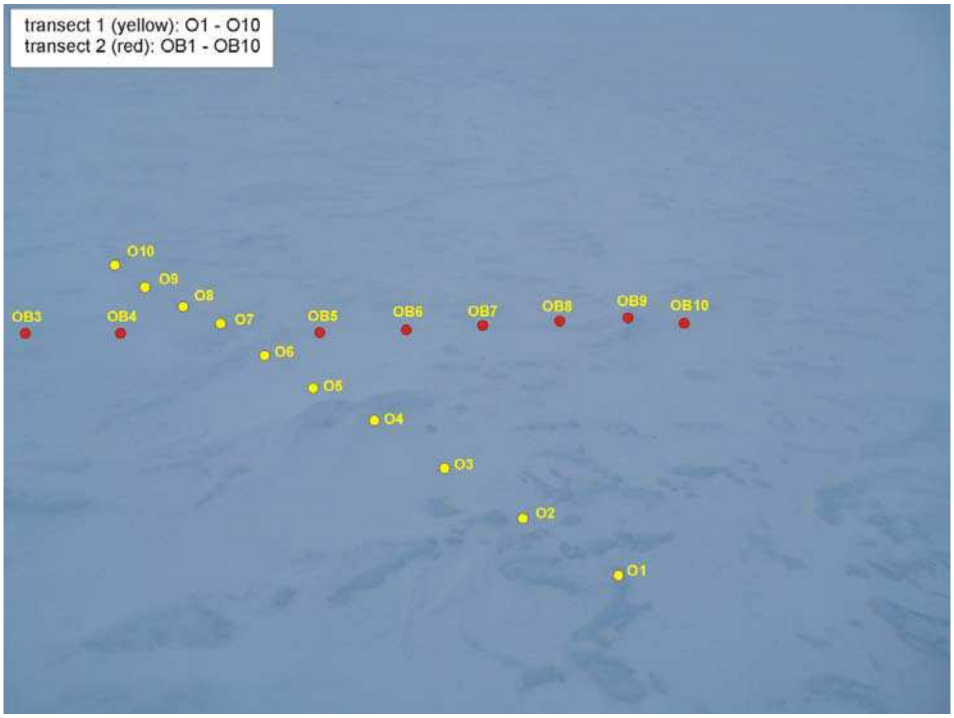


Figure 59 Drill hole transects on Floe W01

Figure 60 Transect 1 on Floe W01 showing surface relief and exposed hummocks

Two transects were made on the floe, each having 10 flags separated by 10 m intervals (Figure 59). A total of 20 holes were drilled along two transects, resulting in an average thickness of 6.2 m (±2.0 m). Floe W01 had up to 70 cm of snow in some places, but the hummocks were devoid of snow. As with all of the sampled multi-year floes discussed in this report, the bottom side of Floe W01 had much more topography than its top side, there being little visible correlation between the two surfaces (Figure 61). Note that the most prominent ridge-like feature in the sampling area was encountered at hole OB9, where the ice was 10.4 m thick and the sail was 2.0 m high, compared to the 1 m sail height of most hummocks in the sampling area.

A void was encountered in only one of the holes on Floe W01 (hole OB3) – but it was a substantial one, measuring about 2 m deep, and it produced wet cuttings (see Table 18). The ice cuttings from the other holes were dry until the bottom ice was approached, which is quite a different situation than in late summer, when wet drill cuttings are usually encountered well above the bottom ice, regardless of the ice thickness. Clearly the quality of ice, and its level of saturation, is very different in winter/spring than in late summer.

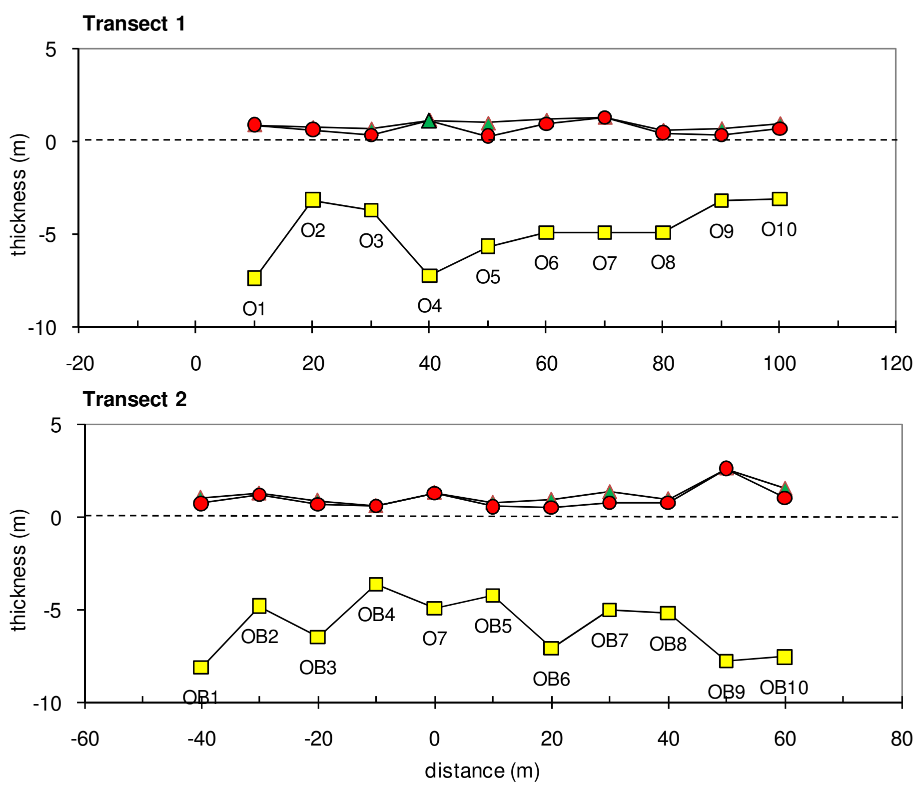


Figure 61 Floe W01: Surface and bottom topography from drill hole measurements
(green markers show the snow cover superimposed on top ice surface)

Table 18 Snow and Ice Thickness at Drill holes on Floe W01

Hole	total ice thickness (m)	freeboard (cm)	snow depth (cm)	notes
O1	8.3	0.9	0	hummock
O2	3.8	0.6	13	
O3	4.1	0.3	34	
O4	8.3	1.1	7	
O5	5.9	0.3	70	
O6	5.9	0.9	22	
O7	6.2	1.3	0	hummock
O8	5.4	0.4	15	
O9	3.5	0.3	38	
O10	3.8	0.7	28	
OB1	8.8	0.7	32	
OB2	6.0	1.2	8	
OB3	7.2	0.7	19	large pocket extended from 4 m depth to 6 m depth
OB4	4.2	0.6	0	
OB5	4.8	0.5	22	
OB6	7.6	0.5	45	
OB7	5.8	0.8	54	
OB8	6.0	0.7	20	
OB9	10.4	2.6	0	hummock highest in area with 2 m high sail
OB10	8.6	1.0	47	

6.0 Discussion and Conclusions

6.1 Multi-year ice thickness by direct drilling

Ice thicknesses were measured at 18 to 61 drill-holes on each of the ten floes sampled during the 2009 and 2010 field programs. Average floe thicknesses ranged from 3.4 to 14.7 m, with standard deviations ranging from 1.3 to 4.3 m (Table 19). The two thickest floes were encountered in the Sverdrup Basin (Belcher Channel and Penny Strait). It should be noted that, although a maximum thickness of 21.1 m was measured, time and equipment did not permit measuring the thickness of the most severe features on Floe L08 and Floe L09.

Figure 62 compares the average thickness and standard deviations of the multi-year floes on which drill-hole measurements have been made during the past four years[9]. The average thickness of the floes ranged from 3.4 to 14.7 m (±0.7 to 4.3 m). More than half of the floes had an average thickness greater than 8 m. The thicker types of multi-year floes occurred in all of the sampled regions (Nares Strait, Kane Basin, Resolute area, and Sverdrup Basin). The two thickest floes (Floe L08 and Floe L09) were sampled in Sverdrup Basin, suggesting that a greater proportion of the floes in Sverdrup Basin are deformed, compared to elsewhere in the Arctic.

Table 19 Summary of Floe Measurements made during 2009 Field Program

Floe ID	date sampled	avg. floe size (m)	number of holes drilled	avg. drill hole thickness ± st. dev. (m)	min/max. thickness (m)	min/max freeboard (m)
L01 Kane Basin	10-Aug	2200	42	4.2 ± 3.0	0.9/12.9	0/3.0
L02 Nares Str.	11-Aug	2000	61	3.4 ± 1.3	1.2/5.8	0/0.9
L03 Kane Basin	13-Aug	1500	32	8.6 ± 4.3	2.7/19.9	0/2.5
L04 Hall Basin	16-Aug	3500	23	8.3 ± 3.6	1.4/14.6	-0.3/1.8
L05 Hall Basin	17-Aug	2400	40	4.7 ± 1.5	2.4/8.0	0.2/1.0
L06 Hall Basin	18-Aug	1000	38	6.5 ± 2.3	2.8/11.8	0.1/1.3
L07 Nares Str.	19-Aug	500	18	10.2 ± 3.4	1.7/13.7	0.3/2.0
L08 Belcher Ch.	27-Aug	2000	18	12.7 ± 3.3	7.9/17.9	1.1/4.2
L09 Penny Str.	30-Aug	1500	20	14.7 ± 3.8	8.4/21.1	0.1/5.0
L08 Belcher Ch.	8 May	2000	9	9.2 ± 2.2	6.9/13.3	0.9/3.0
W01 Wellington Ch.	9 May	3200	20	6.2 ± 2.0	3.5/10.4	0.3/2.6

[9] Average floe thicknesses were often underestimated in 2007 due to the limited number of auger flights available (see '+' for Floes N01, N06, N08, N09, N10).

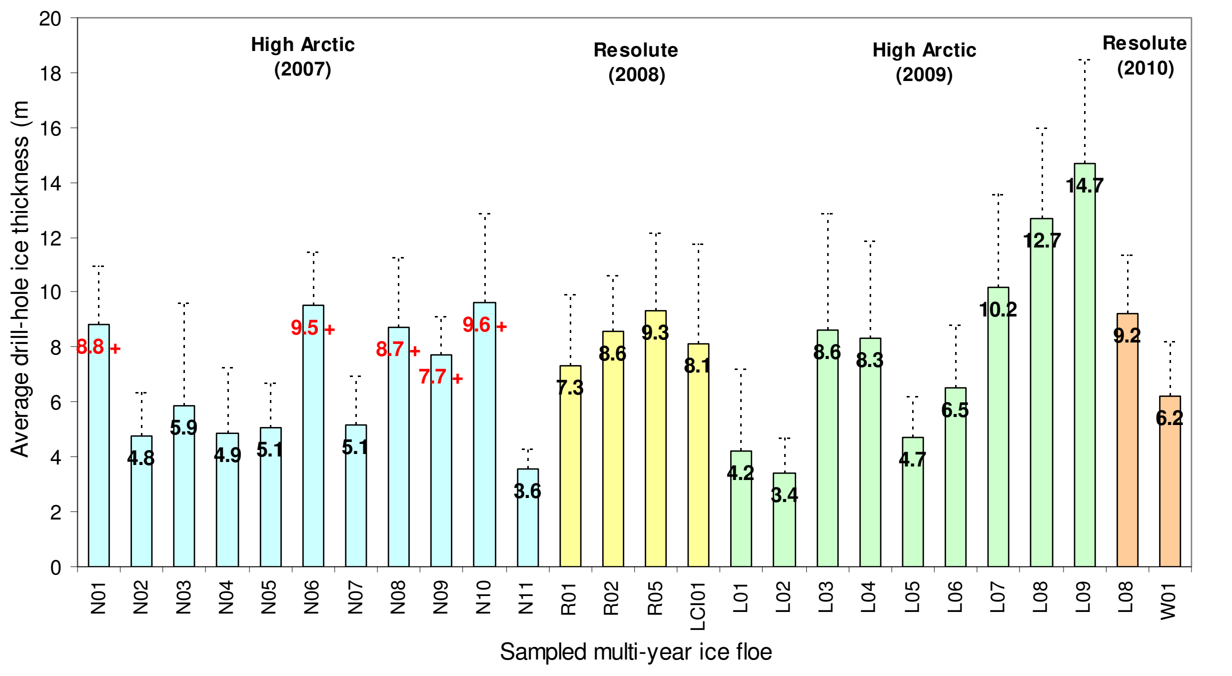


Figure 62 Comparison of four years of drill hole measurements on multi-year floes
Average thicknesses with a "+" indicate floes that the bottom of the ice was not reached in some holes, producing a lower bound for the average thickness.

Voids, pockets and loose blocks on the underside of the ice were sometimes noted while drilling through multi-year ice in August 2009 and, less frequently in May 2010. Qualitatively speaking, cavities, voids and loose blocks were not encountered as frequently in the multi-year floes sampled during the 2007 Nares Strait expedition, which suggests that the multi-year floes may have been more deteriorated in 2009 than in 2007. Part of the explanation may be that oceanographic conditions were different for the two years: during the summer of 2009, Nares Strait and Kane Basin had unusually low concentrations of ice until mid-July, which meant that solar radiation went into warming the water, rather than melting the ice. The lower concentration of ice in 2009 also meant that less ice melt water was available to cool the waters in Nares Strait and Kane Basin. The altered oceanography of the region may have caused the multi-year floes to be warmer, less consolidated and to thin to a greater extent than in previous years. Quantifying the oceanographic effects on sea ice warrants further investigation, particularly since this information could also explain the dramatic changes reported for the perennial polar pack of the Beaufort Sea.

6.2 Comparison of Thicknesses from Drill holes and HEM

The thicknesses obtained from drill-hole measurements on four very thick multi-year ice floes were compared to thicknesses obtained over the same profile areas by a helicopter-based electromagnetic induction (HEM) system, as shown in Figure 63. The drill-hole technique provided the most accurate means of measuring ice thickness, and the greatest level of detail about thickness variations along a transect. Compared to drill-hole measurements, the average thickness of the four floes was underestimated by the HEM by 23% for the Floe L04 (6.7 m thick), 18% for Floe L06 (7.7 m thick), 15% for Floe L07 (9.1 m thick) and 24% for Floe L08 (12.9 m thick).

Figure 64 includes the probability of exceedance curves for the drill-hole and HEM thicknesses. The probability of exceedance curves show two limitations of the HEM: it did not reproduce thicknesses greater than about 12 m and it overestimated the amount of ice from 3 to 7 m thick. The HEM did not capture important information about the maximum thickness of the most massive ice features, which caused the average thickness of very thick multi-year floes to be underestimated. The reason that the HEM provided no data about multi-year ice thicker than 12 m was not due to limitations in the sensor itself, but because the thickness of deformed multi-year ice was so variable within the sensor's footprint and because of the attenuating effect that large, sea-water filled voids have on the EM soundings.

Here, it should be noted that 50% of the multi-year floes on which more than 600 drill-hole measurements have been made over the past four years were very thick, having average thicknesses of 8 m, or more. The importance of this, is that first, it suggests that HEM surveys under-represent the amount of extremely thick ice and second, that ice features described as "extreme" may indeed, be very thick but they are not rare.

The drill-hole thicknesses from the 2009 field season included a greater proportion of 8 to 18 m thick ice than reflected in the compilation of past measurements on multi-year ice (Figure 64), which suggests that the amount of thick and/or deformed ice sampled in 2009 was proportionately greater than past ice measurements. That is reasonable, since past field programs have generally avoided heavily deformed areas, apart from a few, well-known studies in the Beaufort Sea, as summarized in Johnston et al. (2009).

The 2009 Nares Strait field program included only one drill-hole measurement more than 20 m thick, but the compiled data include 35 thicknesses in the range 20 to 42 m, all of which were measured in the Beaufort Sea. The difference is believed due to the limited depth (22 m) to which a two-person team can drill without a support frame, whereas Kovacs (1975) used sonar ranging to measure the thickness of extreme ice features in the Beaufort Sea. Therefore, the lack of extreme ice thicknesses during the 2009 field program does not mean that those kinds of features did not exist – quite the contrary: three of the floes sampled during the 2009 field program contained features more massive than could be measured by a two-person team, judging by the sail height of those features. The 5 to 6 m high ridge in Figure 63-d was just one of the massive features that was not drilled during the program.

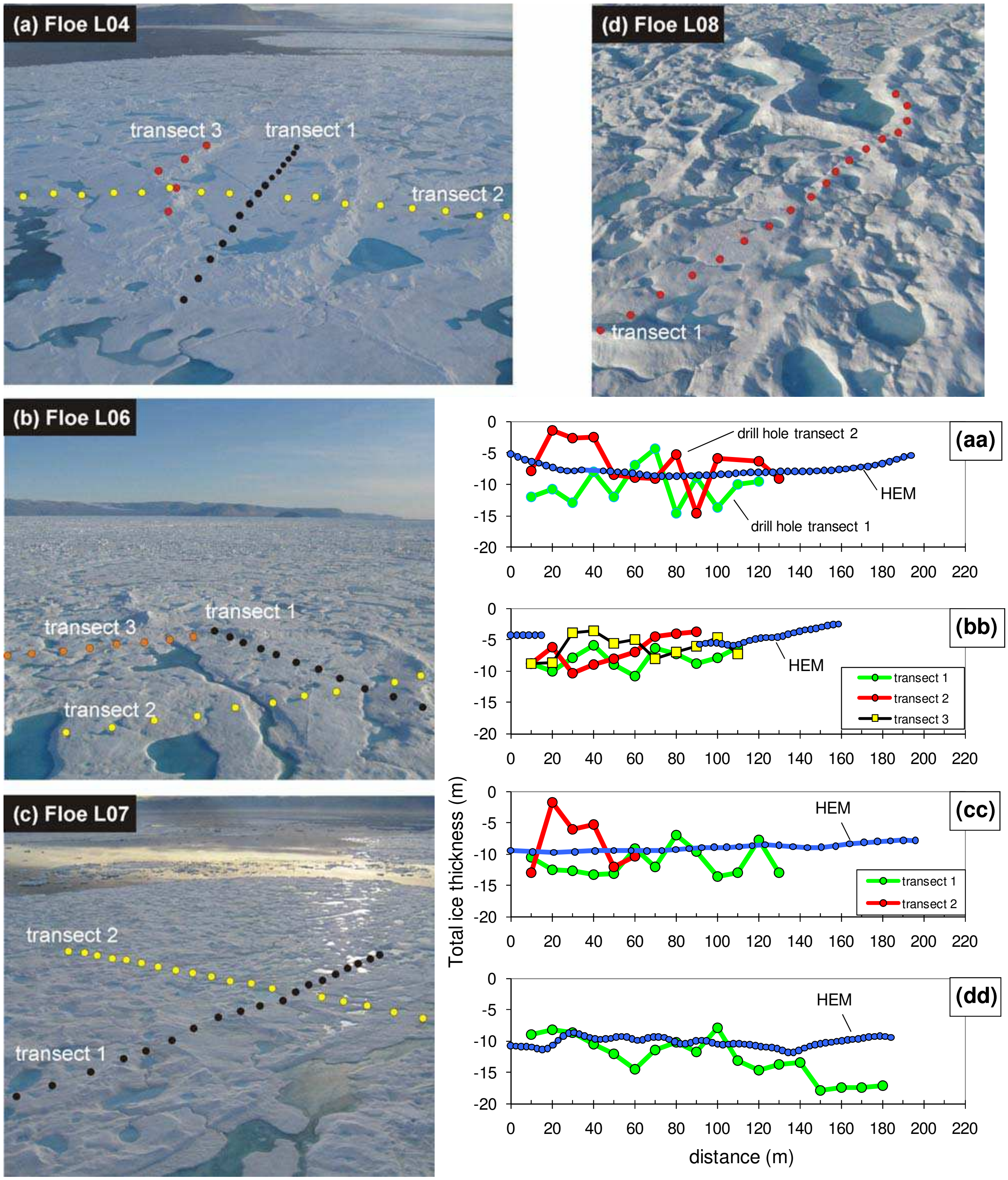


Figure 63 Comparison of ice thicknesses from drill hole and HEM

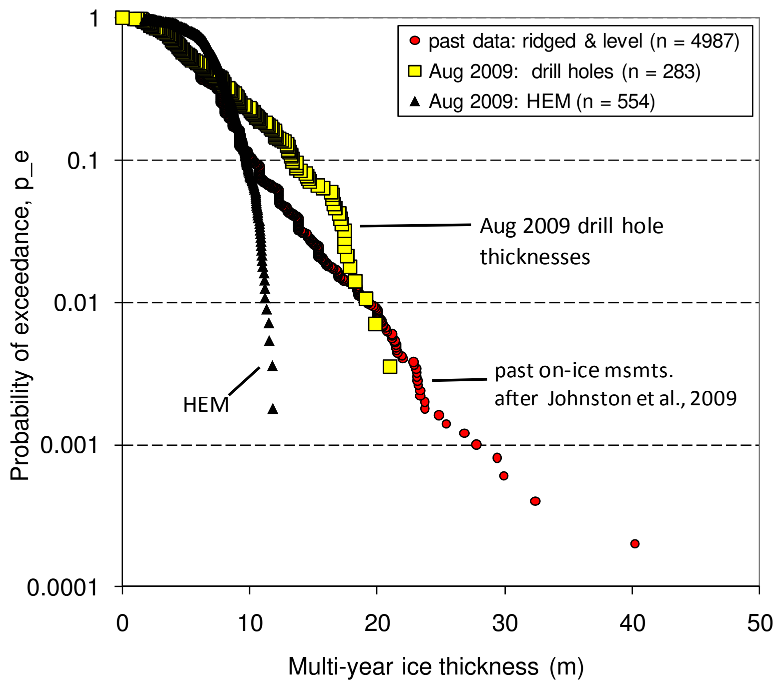


Figure 64 Probability of Exceedances for Thicknesses
(a) drill hole measurements, (b) HEM and (c) past on-ice measurements

6.3 Seasonal Temperature Changes in Thick Multi-year Ice

Two highly deformed, multi-year ice floes were instrumented in August 2009 to document temperature-induced changes in the ice. Floe L03 (12.4 m thick) was instrumented in Kane Basin and Floe L08 (13.5 m thick) was instrumented in Belcher Channel. Temperatures from Floe L03 were obtained for just a few weeks, but temperature data span a full year for Floe L08. In August 2009, the two floes had remarkably similar temperature profiles: both floes had a ‘C-shaped’ temperature profile to a depth of about 7.5 m, below which the ice was isothermal at near melting temperatures. In late August 2009, the coldest temperature in the two floes (-5°C) occurred towards the interior of the floe (4 to 5 m depth). The similarities are surprising given their different thicknesses (12.4 m vs. 13.5 m) and the 500 km distance that separated the floes.

Preliminary results indicate that the Floe L03 thinned by 4 m as it drifted from Kane Basin to the northern part of Baffin Bay, from 8 to 13 September 2009. Thinning from the top ice surface is believed to have been minimal since it was late summer. Most of the change in thickness occurred at the bottom of ice, due to what is believed to have been a combination of thermal ablation, mechanical erosion and possibly the re-orientation of loose ice blocks on the underside of the floe.

Floe L08 (13.5 m) became landfast in Belcher Channel in October 2009, resumed drifting in mid-July 2010 and then stopped reporting its position in early September 2010, by which time it had nearly circumnavigated Cornwallis Island. The last full-thickness temperatures from Floe

L08 were obtained in mid-August 2010, one year after the instrumentation had been installed. In August 2010, Floe L08 was near-isothermal throughout its full thickness, with the coldest temperature being -3°C at an ice depth of 4 to 5 m (see Figure 65). About 1 m of ice ablated from the top ice surface during the summer of 2010 and an undetermined amount of thinning occurred on the underside of the ice.

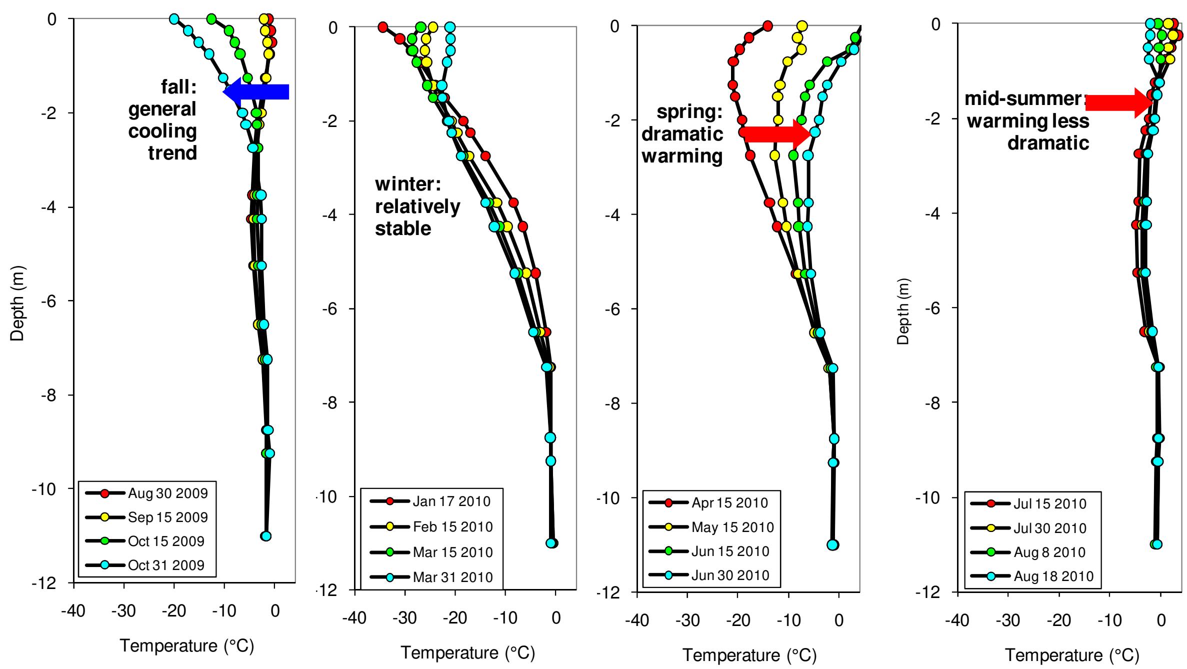


Figure 65 One year of temperatures from Floe L08

6.4 Temperature, Salinity and Strength of Floe L08 in spring 2010

Ice cores extracted (to a depth of 5 m) in May 2010, revealed that the temperature of Floe L08 ranged from -13.3°C (at the 2 to 3 m ice depth) to a maximum of -8.4°C (at a depth of 5.4 m). The average temperature of the uppermost 5.4 m of ice was -11.3°C and the average salinity of the uppermost 5 m of ice was 1.4‰ . Strength tests were conducted in two boreholes, to a depth of 5.40 m. The maximum ice pressure attained in each borehole was 37 MPa, which is the capacity of the pump/borehole system. The peak ice pressures for each test depth were very consistent in the first borehole, but the second borehole, just 5 m away, showed greater variability. Results suggest that either the morphology of the multi-year ice (hence its strength) was non-uniform, despite its level-looking surface, or that the damage introduced by repeated borehole strength tests in the same area can have far reaching consequences in cold multi-year ice.

Figure 66 includes the peak ice pressure attained at each depth from borehole strength tests in multi-year ice over the past four years. Strength measurements were obtained from multi-year floes sampled during the Nares Strait expeditions (August 2006 and August 2007) and from land-based operations out of Resolute (May 2007 and May 2010). As expected, the strength of the ice is highly dependent upon the ice temperature – colder ice producing higher strengths, all things being equal. Note that the figure shows a ‘plateau’ in ice strength at cold temperatures, but that is only because the pump/borehole system has a limited capacity – for cold multi-year ice, the strength test was often terminated before the peak pressure was actually attained. It should also be noted that much of the variability in ice borehole strength that occurred at cold temperatures resulted from fracturing during a test.

The temperature-strength relation in Figure 66 is included here because it illustrates how ice temperature and ice strength are interdependent. That is the premise of using *in situ* temperature chains to monitor how drifting multi-year floes change over the course of a year in terms of their temperature, thickness and strength. Strictly speaking however, the temperature-strength relation in Figure 66 is simplistic. It does not take into account for the time needed to attain the maximum pressure during a strength test or differences in the porosity of multi-year ice. One of the most unique characteristics of multi-year ice is that solid ice, soft ice and voids/cavities often occur at different depths in the same hole, as hundreds of drill hole measurements in this report showed.

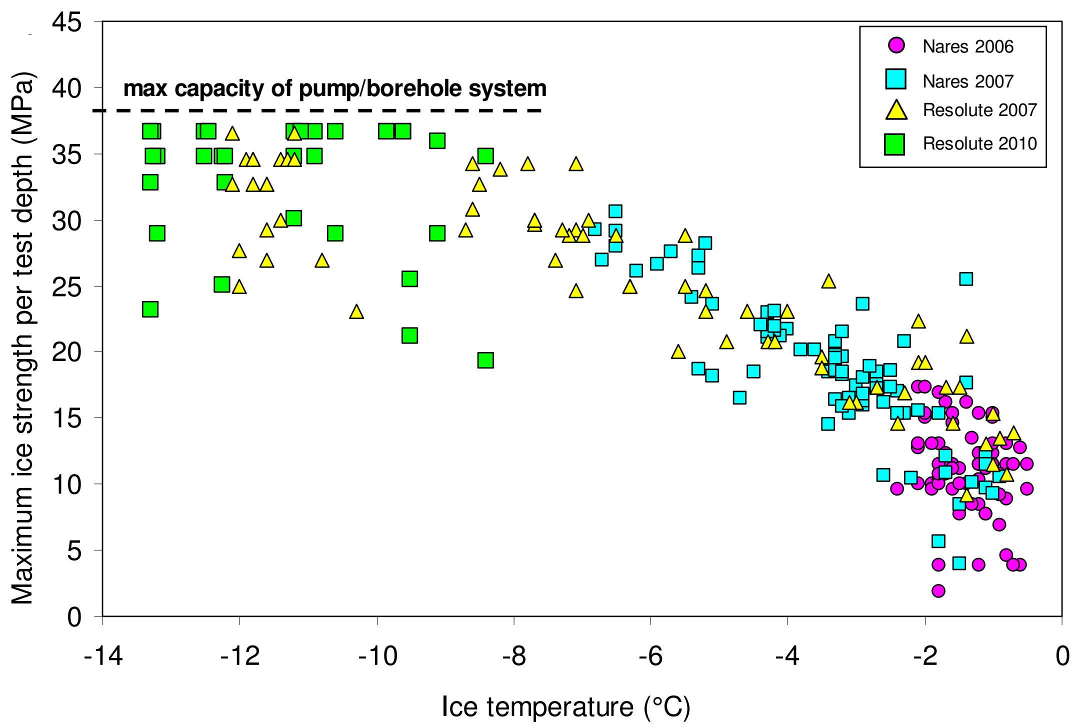


Figure 66 Peak ice pressure measured from borehole strength tests in multi-year ice

7.0 Recommendations

More than 2000 m of multi-year ice was drilled during the August 2009 field program. The drill hole technique proved relatively fast and accurate (albeit labor intensive) when measuring ice up to 25 m thick. Changes in the temperature and thickness of two extremely thick multi-year floes were documented as the floes drifted through the Arctic. Previous documentation of this kind has been limited to multi-year floes less than about 6 m thick[10]. The results described in this report are unique because they provide concrete data about extremely thick multi-year ice – in terms of whether the ice reaches an isothermal state in late summer. The overarching objective of this project is to be able to document seasonal variations in the temperature, thickness and strength of multi-year ice, in order to determine whether some types of multi-year ice become less hazardous to ships and structures. It is critical that field measurements of multi-year ice continue – given the number of unknowns – and that these results be widely disseminated, in light of what may be overly optimistic publications about the deterioration of the Arctic pack ice and what that means for engineering ships and structures.

8.0 Acknowledgments

This Joint Industry Project (JIP) was made possible through the financial support of Transport Canada (TC), the Program for Energy Research and Development (PERD), ConocoPhillips Canada Resources Corp. and the Government of Nunavut. TC has been instrumental in providing the resources to conduct measurements on multi-year ice in the past, and they were a key element in the success of this field project. PERD contributed to this project, realizing that multi-year ice is one of the greatest unknowns when it comes to predicting loads on structures. ConocoPhillips provided the resources to investigate the viability of using the ice-based EM induction sensor to measure multi-year ice thickness. The support of officers and crew of the Canadian Coast Guard icebreaker CCGS *Henry Larsen* is sincerely appreciated, as is the support from H. Melling, Fisheries and Oceans Canada and the Canadian Federal Programme for the International Polar Year Programme's for the Canadian Arctic Through-flow study (IPY 2006-SR1-CC-135). Polar Continental Shelf Program (PCSP) played an essential role in the project by providing both financial support and superb logistical support (Project 516-10). R. Lanthier and C. Fillion deserve much of the credit for the project's success, because without their fortitude, strength and dedication only a fraction of the work would have been conducted. The ongoing support of the National Research Council's Design and Fabrication Services (DFS) is sincerely appreciated because they provide the highly customized equipment needed to tackle multi-year ice. Many thanks to A. Collins and D. Pelletier, who greatly added to the value and success of the project.

[10] http://polar.crrel.usace.army.mil/projects/project-autonomous_buoys.html

9.0 References

Haas, C., Lobach, J., Hendricks, S., Rabenstein, L., and A. Pfaffling (2009) Helicopter-borne Measurements of Sea Ice Thickness using a Small and Lightweight Digital EM System, Journal of Applied Geophysics, No. 67, pp. 234 – 241.

Johnston, M. (2009) Thickness and Temperature Measurements on Multi-year Ice in the Canadian Arctic Archipelago, 2008 Field Season. Controlled Technical Report CHC-CTR-090, National Research Council Canadian Hydraulics Centre, Ottawa, Canada, March 2009, 65 p. plus appendices.

Johnston, M. (2008-a). Extremely Thick Multi-year Ice Still Exists, but Will it Last? Proceedings ICETECH'08, paper ICETECH08-150-RF, Banff, AB, Canada.

Johnston, M. (2008-b) Characterizing Multi-year Ice Floes in the High Arctic: Evaluating Two, Ground-based EM Sensors. Controlled Technical Report CHC-CTR-073. National Research Council Canadian Hydraulics Centre, Ottawa, Canada, March 2008, 70 p. plus appendices

Johnston, M., Masterson, D. and B. Wright (2009) Thickness of Multi-year Ice: Knowns and Unknowns, Proceedings 20th International Conference on Port and Ocean Engineering under Arctic Conditions, Paper POAC09-120, Luleå, Sweden, 13 p.

Kovacs, A. and S. Holladay (1995) The Footprint/Altitude Ratio for Helicopter Electromagnetic Sounding of Sea ice Thickness: Comparison of Theoretical and Field Estimates. Geophysics, Vol. 60, No. 2, Mar-Apr. pp 374 – 380.

Kubat, I. and Timco, G. (2003) Vessel Damage in the Canadian Arctic. Proceedings 17th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'03, Vol. 1, pp 203-212, Trondheim, Norway.

Perovich, D. Elder, B. and Ricther-Menge J. (1997) Observations of the annual cycle of sea ice temperature and mass balance. Geophysical Research Letters, Vol. 24, No. 5, 1 March 1997, pp. 555-558.

Peterson, I., Prinsenberg, S., Pittman, M. and L. Desjardins (2009) The Drift of and Exceptionally Large Ice Island from Petermann Glacier in 2008, Proceedings 20th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'09, 9 – 12 June 2009, Luleå, Sweden, POAC09-130, 9 p.

Timco, G. and M. Johnston (2004) Ice loads on the caisson structures in the Canadian Beaufort Sea. 2004, Cold Regions Science and Technology, Vol. 38, No 2-3, pp. 185-209.

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Appendix A: NIRB Screening Report

SCREENING DECISION REPORT
NIRB FILE NO.: 09YN055

July 24, 2009

Honourable Daniel Shewchuck
Minister of Environment
Iqaluit, NU

Via email: dshewchuck@gov.nu.ca or salainga@gov.nu.ca

Re: Screening Decision for Michelle Johnston's "Quantifying changes in multi-year floes drifting through the Arctic" Project Proposal, NIRB File No. 09YN055

Dear Honourable Daniel Shewchuck:

The primary objectives of the Nunavut Impact Review Board (NIRB) are set out in section 12.2.5 of the Nunavut Land Claims Agreement (NLCA) as follows:

> *In carrying out its functions, the primary objectives of NIRB shall be at all times to protect and promote the existing and future well-being of the residents and communities of the Nunavut Settlement Area, and to protect the ecosystemic integrity of the Nunavut Settlement Area. NIRB shall take into account the well-being of the residents of Canada outside the Nunavut Settlement Area.*

Section 12.4.4 of the NLCA states:

> *Upon receipt of a project proposal, NIRB shall screen the proposal and indicate to the Minister in writing that:*
>
> a) *the proposal may be processed without a review under Part 5 or 6; NIRB may recommend specific terms and conditions to be attached to any approval, reflecting the primary objectives set out in Section 12.2.5;*
> b) *the proposal requires review under Part 5 or 6; NIRB shall identify particular issues or concerns which should be considered in such a review;*
> c) *the proposal is insufficiently developed to permit proper screening, and should be returned to the proponent for clarification; or*
> d) *the potential adverse impacts of the proposal are so unacceptable that it should be modified or abandoned.*

NIRB ASSESSMENT AND DECISION

After a thorough assessment of all material provided to the Board (please see *Procedural History* and *Project Activities* in **Appendix A**), in accordance with the principles identified within Section 12.4.2 of the NLCA, the decision of the Board as per Section 12.4.4 of the NLCA is:

> **12.4.4** (a): the proposal may be processed without a review under Part 5 or 6; NIRB may recommend specific terms and conditions to be attached to any approval, reflecting the primary objectives set out in Section 12.2.5.

RECOMMENDED PROJECT-SPECIFIC TERMS AND CONDITIONS
(pursuant to Section 12.4.4(a) of the NLCA)

The Board is recommending that the following or similar project-specific terms and conditions be imposed upon the Proponent through all relevant legislation:

General

1. Michelle Johnston (the Proponent) shall maintain a copy of the Project Terms and Conditions at the site of operation at all times.
2. The Proponent shall forward copies of all permits obtained and required for this project to the Nunavut Impact Review Board (NIRB) prior to the commencement of the project.
3. The Proponent shall operate in accordance with all commitments stated in correspondence provided to NIRB (Nunavut Research Institute (NRI) Application, June 29, 2009)
4. The Proponent shall operate the site in accordance with all applicable Acts, Regulations and Guidelines.

Waste

5. The Proponent shall keep all garbage and debris in bags placed in a covered metal container or equivalent until disposed of. All wastes shall be kept inaccessible to wildlife at all times.

Wildlife

6. The Proponent shall ensure that there is no damage to wildlife habitat in conducting this operation.
7. The Proponent shall not harass wildlife. This includes persistently worrying or chasing animals, or disturbing large groups of animals. The Proponent shall not hunt or fish, unless proper Nunavut authorizations have been acquired.
8. The Proponent shall ensure all project staff are trained in appropriate bear/carnivore detection and deterrent techniques.
9. The Proponent shall restrict aircraft/helicopter activity related to the project to a minimum altitude of 610 metres above ground level unless there is a specific requirement for low-level flying, which does not disturb wildlife and migratory birds.
10. The Proponent shall cease activities that may interfere with migration or calving of caribou or muskox, until the caribou or muskox have passed or left the area.

Other

11. The Proponent should, to the extent possible, hire local people and consult with local residents regarding their activities in the region.

Other NIRB Concerns and Recommendations

In addition to the project-specific terms and conditions, the Board is recommending the following:

1. The Proponent review the bear/carnivore detection and deterrent techniques outlined in "Safety in Grizzly and Black Bear Country" which can be down-loaded from this link: http://www.nwtwildlife.com/Publications/safetyinbearcountry/safety.htm. Note that some recommendations in this manual are also relevant to polar bears. There is a DVD about polar bears and safety available from Nunavut Parks at the following link http://www.nunavutparks.com/english/visitor-information/suggested-resources.html and a "Safety in Polar Bear Country" pamphlet from Parks Canada at the following link http://www.pc.gc.ca/pn-np/nu/auyuittuq/pdf/PolarBearEnglish2007final.pdf.

2. All garbage and toilet paper should be brought to a designated waste disposal site either in town or aboard ship.

3. Proponent should consider designing the equipment for more accurate recovery (i.e. bear proofing containers to reduce potential for equipment to be damaged, and floatation containers to keep units accessible if ice melts), and working with local community HTO's for quicker recovery when signals are lost for best chance of recovering equipment.

Regulatory Requirements

The Proponent is also advised that the following legislation may apply to the project:

1. The *Species at Risk Act* (http://laws.justice.gc.ca/en/showtdm/cs/S-15.3). Attached in **Appendix B** is a list of Species at Risk in Nunavut.

2. The *Nunavut Wildlife Act* which contains provisions to protect and conserve wildlife and wildlife habitat, including specific protection measures for wildlife habitat and species at risk.

3. The *Nunavut Act* (http://laws.justice.gc.ca/en/showtdm/cs/N-28.6). The Proponent must comply with the proposed terms and conditions listed in the attached **Appendix C.**

4. The *Navigable Waters Protection Act (NWPA)* (http://laws.justice.gc.ca/en/N-22/index.html).

5. The *Aeronautics Act* (http://laws.justice.gc.ca/en/A-2/).

Validity of Land Claims Agreement

Section 2.12.2
Where there is any inconsistency or conflict between any federal, territorial and local government laws, and the Agreement, the Agreement shall prevail to the extent of the inconsistency or conflict.

Dated _____July 24, 2009_____ at Sanikiluaq, NU.

Lucassie Arragutainaq, Chairperson

Attachments: Appendix A: Procedural History and Past Activities
Appendix B: Species at Risk in Nunavut
Appendix C: Archaeological and Palaeontological Resources Terms and Conditions for Land Use Permit Holders

P.O. Box 1360 Cambridge Bay, NU X0B 0C0 Phone: (867) 983-4600 Fax: (867) 983-2594

Appendix A
Procedural History and Project Activities

Procedural History

On June 29, 2009 the NIRB received Michelle Johnston's "Quantifying changes in multi-year floes drifting through the Arctic" project proposal from the Nunavut Research Institute (NRI). On July 7, 2009 the NIRB received a positive conformity determination (North Baffin Regional Land Use Plan) from the Nunavut Planning Commission for this file. The NIRB has assigned this project proposal file number **09YN055**.

This project proposal was distributed to community organizations in Arctic Bay, Resolute, and Grise Fiord, as well as to relevant federal and territorial government agencies, and Inuit organizations. The NIRB requested that interested parties review the proposal and the NIRB's *proposed* project-specific terms and conditions, and provide the Board with any comments or concerns by July 20, 2009 regarding:

- Whether the project proposal is likely to arouse significant public concern; and if so, why;
- Whether the project proposal is likely to cause significant adverse eco-systemic and socio-economic effects; and if so, why;
- Whether the project is of a type where the potential adverse effects are highly predictable and mitigable with known technology, (providing any recommended mitigation measures); and
- Any matter of importance to the Party related to the project proposal.

On or before July 20, 2009 the NIRB received comments from the following interested parties (see Comments and Concerns section below):

- Transport Canada (TC)
- Government of Nunavut–Department of Culture, Language, Elders and Youth (CLEY)
- Government of Nunavut–Department of Environment (DOE)
- Environment Canada (EC)

All comments provided to NIRB regarding this project proposal can be viewed on NIRB's ftp-site, at the following location: http://ftp.nirb.ca/SCREENINGS/COMPLETED%20SCREENINGS/

Project Activities

The activities/components associated with this proposal include:

- Nares Strait (August 9 to August 25, 2009):
  - Research conducted in conjunction with Dr. Humphrey Melling, NIRB File No. 09YN025
  - Survey 12 ice floes over 12 days (1 floe per day) to measure ice thickness by drilling 2 inch holes through the ice
  - Installation of instrumentation packages (floatation buoys) on 2 of these ice floes to measure changes in the temperature, thickness and strength of the ice as it drifts through the Arctic
- Penny Strait (August 26 to September 2, 2009):
  - Measure the thickness of 2 additional multi-year floes
  - Instrumentation packages will be installed on 1 of these floes, a 25 meter thick multi-year ridge
- Accommodations for research staff in:
  - Thule, Greenland
  - aboard (Canadian Coast Guard Ship) CCGS Henry Larsen, and
  - Resolute, NU.

Appendix B
Species at Risk in Nunavut

This list includes species listed on one of the Schedules of SARA (*Species at Risk Act*) and under consideration for listing on Schedule 1 of SARA. These species have been designated as at risk by COSEWIC (Committee on the Status of Endangered Wildlife in Canada). This list may not include all species identified as at risk by the Territorial Government.

- Schedule 1 is the official legal list of Species at Risk for SARA. SARA applies to all species on Schedule 1. The term "listed" species refers to species on Schedule 1.
- Schedule 2 and 3 of SARA identify species that were designated at risk by the COSEWIC prior to October 1999 and must be reassessed using revised criteria before they can be considered for addition to Schedule 1.
- Some species identified at risk by COSEWIC are "pending" addition to Schedule 1 of SARA. These species are under consideration for addition to Schedule 1, subject to further consultation or assessment.

Schedules of SARA are amended on a regular basis so it is important to periodically check the SARA registry (www.sararegistry.gc.ca) to get the current status of a species.

Updated: January 3, 2007

Species at Risk	COSEWIC Designation	Schedule of SARA	Government Organization with Lead Management Responsibility [1]
Eskimo Curlew	Endangered	Schedule 1	EC
Ivory Gull	Endangered [2]	Schedule 1	EC
Peregrine Falcon (subspecies anatum)	Threatened	Schedule 1	Government of Nunavut
Ross's Gull	Threatened	Schedule 1	EC
Harlequin Duck (Eastern population)	Special Concern	Schedule 1	EC
Felt-leaf Willow	Special Concern	Schedule 1	Government of Nunavut
Peregrine Falcon (subspecies tundrius)	Special Concern	Schedule 3	Government of Nunavut
Short-eared Owl	Special Concern	Schedule 3	Government of Nunavut
Fourhorn Sculpin	Special Concern	Schedule 3	DFO
Peary Caribou	Endangered [3]	Pending	Government of Nunavut
Beluga Whale (Eastern Hudson Bay population)	Endangered	Pending	DFO
Beluga Whale (Cumberland Sound population)	Threatened	Pending	DFO
Beluga Whale (Western Hudson Bay population)	Special Concern	Pending	DFO
Beluga Whale (Eastern High Arctic –	Special Concern	Pending	DFO

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Baffin Bay population)			
Bowhead Whale (Hudson Bay-Foxe Basin population)	Threatened [4]	Pending	DFO
Bowhead Whale (Davis Strait-Baffin Bay population)	Threatened [4]	Pending	DFO
Porsild's Bryum	Threatened	Pending	Government of Nunavut
Atlantic Walrus	Special Concern	Pending	DFO
Narwhal	Special Concern	Pending	DFO
Rusty Blackbird	Special Concern	Pending	Government of Nunavut
Barren-ground Caribou (Dolphin and Union population)	Special Concern [3]	Pending	Government of Nunavut
Grizzly Bear	Special Concern	Pending	Government of Nunavut
Polar Bear	Special Concern	Pending	Government of Nunavut
Wolverine (Western Population)	Special Concern	Pending	Government of Nunavut

[1] Environment Canada has a national role to play in the conservation and recovery of Species at Risk in Canada, as well as responsibility for management of birds described in the Migratory Birds Convention Act (MBCA). Day-to-day management of terrestrial species not covered in the MBCA is the responsibility of the Territorial Government. Populations that exist in National Parks are also managed under the authority of the Parks Canada Agency. EC = Environment Canada, DFO = Department of Fisheries and Oceans

[2] Designated as Endangered by COSEWIC in April 2006 and it is expected that the category of concern in SARA will also be changed from Special Concern to Endangered.

[3] Peary Caribou was split into three separate populations in 1991: Banks Island (Endangered), High Arctic (Endangered) and Low Arctic (Threatened) populations. The Low Arctic population also included the Barren-ground Caribou - Dolphin and Union population. In May 2004 all three population designations were de-activated, and the Peary Caribou, Rangifer tarandus pearyi, was assessed separately from the Barren-ground Caribou (Dolphin and Union population), Rangifer tarandus groenlandicus. The subspecies pearyi is composed of a portion of the former "Low Arctic population" and all of the former "High Arctic" and "Banks Island" populations, and it was designated Endangered in May 2004. Although SARA lists Peary Caribou on Schedule 2 as three separate populations, the most current designation is the COSEWIC designation of the subspecies pearyi as Endangered.

[4] The "Eastern and Western Arctic populations" of Bowhead Whale were given a single designation of Endangered in April 1980 by COSEWIC. These were split into two populations to allow separate designations in April 1986. The Eastern population was not re-evaluated in April 1986, but retained the Endangered status of the original "Eastern and Western Arctic populations". The Eastern Arctic population was further split into two populations (Hudson Bay-Foxe Basin population and Davis Strait-Baffin Bay population) in May 2005, and both these populations were designated as Threatened. Both these populations are under consideration for addition to Schedule 1. Although SARA lists the Eastern Arctic population as Endangered (Schedule 2), the most current designation is the COSEWIC designations of the Hudson Bay-Foxe Basin and Davis Strait-Baffin Bay populations as Threatened.

Appendix C
Archaeological and Palaeontological Resources Terms and Conditions
for Land Use Permit Holders

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Nunavut

***BACKGROUND:* Archaeology**

As stated in Article 33 of the Nunavut Land Claims Agreement:

The archaeological record of the Inuit of Nunavut is a record of Inuit use and occupancy of lands and resources through time. The evidence associated with their use and occupancy represents a cultural, historical and ethnographic heritage of Inuit society and, as such, Government recognizes that Inuit have a special relationship with such evidence, which shall be expressed in terms of special rights and responsibilities. [33.2.1]

The archaeological record of Nunavut is of spiritual, cultural, religious and educational importance to Inuit. Accordingly, the identification, protection and conservation of archaeological sites and specimens and the interpretation of the archaeological record is of primary importance to Inuit and their involvement is both desirable and necessary. [33.2.2]

In recognition of the cultural, spiritual and religious importance of certain areas in Nunavut to Inuit, Inuit have special rights and interests in these areas as defined by Article 33 of the Nunavut Land Claims Agreement. [33.2.5]

***BACKGROUND:* Palaeontology**

Under the Nunavut Act1, the federal Government can make regulations for the protection, care and preservation of palaeontological sites and specimens in Nunavut. Under the *Nunavut Archaeological and Palaeontological Sites Regulations2*, it is illegal to alter or disturb any palaeontological site in Nunavut unless permission is first granted through the permitting process.

Definitions

As defined in the *Nunavut Archaeological and Palaeontological Sites Regulations*, the following definitions apply:

"archaeological site" means a place where an archaeological artifact is found.

1 s. 51(1)
2 P.C. 2001-1111 14 June, 2001

"archaeological artifact" means any tangible evidence of human activity that is more than 50 years old and in respect of which an unbroken chain of possession or regular pattern of usage cannot be demonstrated, and includes a Denesuline archaeological specimen referred to in section 40.4.9 of the Nunavut Land Claims Agreement.

"palaeontological site" means a site where a fossil is found.

"fossil" includes:

(a) natural casts
(b) preserved tracks, coprolites and plant remains; and
(c) the preserved shells and exoskeletons of invertebrates and the eggs, teeth and bones of vertebrates.

Terms and Conditions

1) The permittee shall not operate any vehicle over a known or suspected archaeological or palaeontological site.

2) The permittee shall not remove, disturb, or displace any archaeological artifact or site, or any fossil or palaeontological site.

3) The permittee shall immediately contact the Department of Culture, Language, Elders and Youth (867) 934-2046 or (867) 975-5500 or 1 (866) 934-2035 should an archaeological site or specimen, or a palaeontological site or fossil be encountered or disturbed by any land use activity.

4) The permittee shall immediately cease any activity that disturbs an archaeological or palaeontological site encountered during the course of a land use operation, until permitted to proceed with the authorization of the Department of Culture, Language, Elders and Youth, Government of Nunavut.

5) The permittee shall follow the direction of the Department of Culture, Language, Elders and Youth and DIAND in restoring disturbed archaeological or palaeontological sites to an acceptable condition.

6) The permittee shall provide all information requested by the Department of Culture, Language, Elders and Youth concerning all archaeological sites or artifacts and all palaeontological sites and fossils encountered in the course of any land use activity.

7) The permittee shall make best efforts to ensure that all persons working under authority of the permit are aware of these conditions concerning archaeological sites and artifacts, and palaeontological sites and fossils.

8) The permittee shall avoid the known archaeological and/or palaeontological sites listed in Attachment 1.

9) The permittee shall have an archaeologist or palaeontologist perform the following functions, as required by the Department of Culture, Language, Elders and Youth:

a. survey
b. inventory and documentation of the archaeological or palaeontological resources of the land

use area

c. assessment of potential for damage to archaeological or palaeontological sites
d. mitigation
e. marking boundaries of archaeological or palaeontological sites
f. site restoration

The Department of Culture, Language, Elders and Youth shall authorize by way of a Nunavut Archaeologist Permit or a Nunavut Palaeontologist Permit, all procedures subsumed under the above operations.

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Appendix B: Specifics of Temperature Chain

INSTRUCTION MANUAL

Model 107 Temperature Probe

Revision: 10/08

Copyright © 1983-2008
Campbell Scientific, Inc.

2009 Field Season:

Wednesday, 5 Aug 2009
arrive in St. John's 11:30 pm.

WARRANTY AND ASSISTANCE

This equipment is warranted by CAMPBELL SCIENTIFIC (CANADA) CORP. ("CSC") to be free from defects in materials and workmanship under normal use and service for **twelve (12) months** from date of shipment unless specified otherwise. ***** **Batteries are not warranted.** ***** CSC's obligation under this warranty is limited to repairing or replacing (at CSC's option) defective products. The customer shall assume all costs of removing, reinstalling, and shipping defective products to CSC. CSC will return such products by surface carrier prepaid. This warranty shall not apply to any CSC products which have been subjected to modification, misuse, neglect, accidents of nature, or shipping damage. This warranty is in lieu of all other warranties, expressed or implied, including warranties of merchantability or fitness for a particular purpose. CSC is not liable for special, indirect, incidental, or consequential damages.

Products may not be returned without prior authorization. To obtain a Return Merchandise Authorization (RMA), contact CAMPBELL SCIENTIFIC (CANADA) CORP., at (780) 454-2505. An RMA number will be issued in order to facilitate Repair Personnel in identifying an instrument upon arrival. Please write this number clearly on the outside of the shipping container. Include description of symptoms and all pertinent details.

CAMPBELL SCIENTIFIC (CANADA) CORP. does not accept collect calls.

Non-warranty products returned for repair should be accompanied by a purchase order to cover repair costs.

CAMPBELLSCIENTIFIC
CANADA CORP.
11564 - 149 street - edmonton - alberta - T5M 1W7
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www.campbellsci.ca

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Figures

Tables

Model 107 Temperature Probe

1. General

The 107 Temperature Probe uses a thermistor to measure temperature. The probe is designed for measuring air/soil/water temperatures. For air temperature, a 41303-5A radiation shield is used to mount the 107 Probe and limit solar radiation loading. The probe is designed to be buried or submerged in water to 50' (21 psi).

For the –L option, the probe's cable terminates in pigtails that connect to a Campbell Scientific datalogger. For the –LC option, the probe's cable is fitted with a connector that attaches to an ET107, ET106, or MetData1 Weather Station. Throughout this manual, 107 will refer to both the 107-L and 107-LC unless specified otherwise.

Lead length for the 107-L and 107-LC is specified when the sensor is ordered. Table 1-1 gives the recommended lead length for mounting the sensor on a tripod or tower.

TABLE 1-1. Recommended Lead Lengths

2 m Height		Atop a tripod or tower via a 2 ft crossarm such as the CM202							
Mast/Leg	**CM202**	**CM6**	**CM10**	**CM110**	**CM115**	**CM120**	**UT10**	**UT20**	**UT30**
9'	11'	11'	14'	14'	19'	24'	14'	24'	37'

Note: *Add two feet to the cable length if you are mounting the enclosure on the leg base of a light-weight tripod.*

The 107 ships with:

(1) Resource CD

1.1 Specifications

Sensor:	BetaTherm 100K6A Thermistor
Temperature Measurement Range:	-35° to +50°C
Thermistor Interchangeability Error:	Typically <±0.2°C over 0°C to 60°C; ±0.4 @ -35°C
Temperature Survival Range:	-50°C to +100°C
Steinhart-Hart Equation Error:	≤±0.01°C over -35° to +50°C (CRBasic dataloggers only)

Polynomial Linearization Error: <±0.5°C over -35°C to +50°C (Edlog dataloggers only)

Time Constant In Air: Between 30 and 60 seconds in a wind speed of 5 m s^{-1}

Maximum Lead Length: 1000 ft.

NOTE The black outer jacket of the cable is Santoprene® rubber. This compound was chosen for its resistance to temperature extremes, moisture, and UV degradation. However, this jacket will support combustion in air. It is rated as slow burning when tested according to U.L. 94 H.B. and will pass FMVSS302. Local fire codes may preclude its use inside buildings.

2. Accuracy

The overall probe accuracy is a combination of the thermistor's interchangeability specification, the precision of the bridge resistors, and the Steinhart-Hart equation error (CRBasic dataloggers) or polynomial error (Edlog dataloggers). In a "worst case" all errors add to an accuracy of ±0.4°C over the range of -24° to 48°C and ±0.9°C over the range of -38°C to 53°C. The major error component is the interchangeability specification of the thermistor, tabulated in Table 2-1. For the range of 0° to 50°C the interchangeability error is predominantly offset and can be determined with a single point calibration. Compensation can then be done with an offset entered in the measurement instruction. The bridge resistors are 0.1% tolerance with a 10 ppm temperature coefficient. Polynomial errors are tabulated in Table 2-2 and plotted in Figure 2-1.

TABLE 2-1. Thermistor Interchangeability Specification

Temperature (°C)	Temperature Tolerance (±°C)
–40	0.40
–30	0.40
–20	0.32
–10	0.25
0 to +50	0.20

TABLE 2-2. Polynomial Error for Edlog Dataloggers

-40 to +56	<±1.0°C
-38 to +53	<±0.5°C
-24 to +48	<±0.1°C

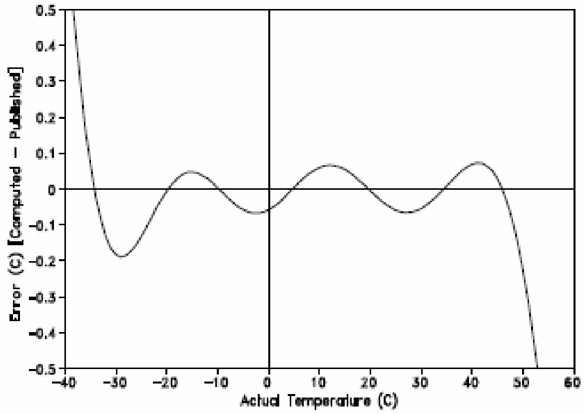


FIGURE 2-1. Error Produced by Polynomial Fit to Published Values (Edlog dataloggers only)

3. Installation

3.1 Air Temperature

3.1.1 Siting

For air temperature measurements, sensors should be located over an open level area at least 9 m (EPA) in diameter. The surface should be covered by short grass, or where grass does not grow, the natural earth surface. Sensors should be located at a distance of at least four times the height of any nearby obstruction, and at least 30 m (EPA) from large paved areas. Sensors should be protected from thermal radiation, and adequately ventilated.

Standard air temperature measurement heights:

1.5 m +/- 1.0 m (AASC)
1.25 – 2.0 m (WMO)
2.0 m (EPA)
2.0 m and 10.0 m temperature difference (EPA)

The probe is designed to be buried or submerged in water to 50' (21 psi).

3.1.2 Assembly and Mounting

Tools required for installing on a tripod or tower:

- 1/2" open end wrench
- small screw driver provided with datalogger
- small Phillips screw driver
- UV resistant cable ties
- small pair of diagonal-cutting pliers

The 107 must be housed inside a radiation shield when the sensor will be exposed to solar radiation (i.e., air temperature measurements made in the field). The 41303-5A Radiation shield has a U-bolt for attaching the shield to tripod mast / tower leg (Figure 3-1), or CM200 series crossarm (Figure 3-2). The radiation shield ships with the U-bolt configured for attaching the shield to a vertical pipe. Move the U-bolt to the other set of holes to attach the shield to a crossarm.

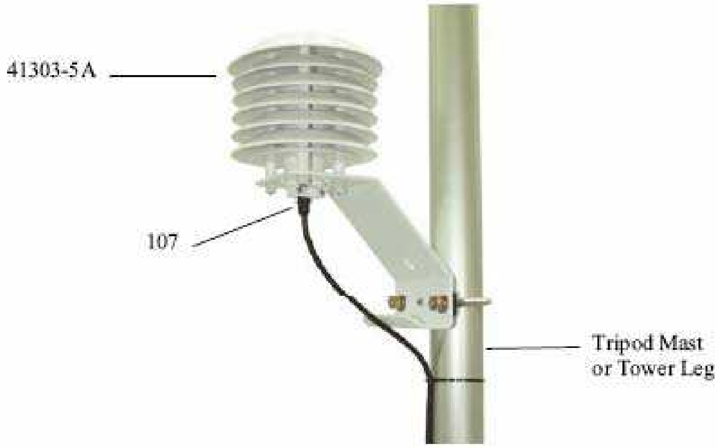


FIGURE 3-1. 107 and 41303-5A Radiation Shield on a Tripod Mast

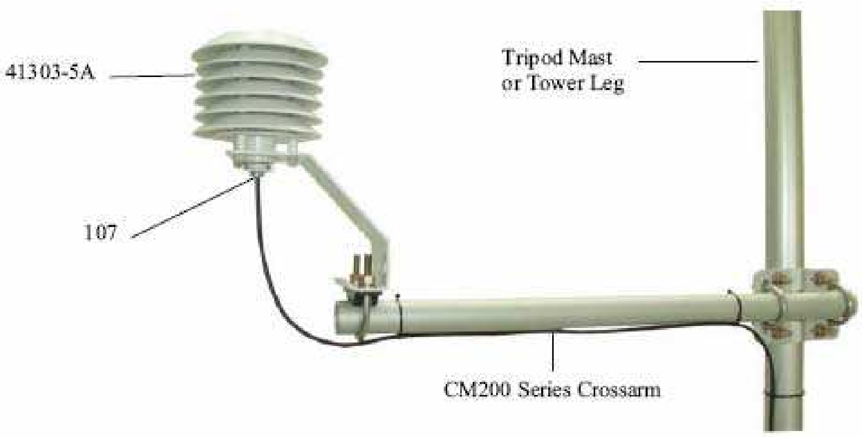


FIGURE 3-2. 107 and 41303-5A Radiation Shield on a CM200 Series Crossarm

The 107 is held within the 41303-5A by a mounting clamp on the bottom plate of the 41303-5A (Figure 3-2). Loosen the two mounting clamp screws, and insert the sensor through the clamp and into the shield. Tighten the screws to secure the sensor in the shield, and route the sensor cable to the instrument enclosure. Secure the cable to the tripod/tower using cable ties.

3.2 Soil Temperature

The 107 is suitable for shallow burial only. It should be placed horizontally at the desired depth to avoid thermal conduction from the surface to the thermistor. Placement of the cable inside a rugged conduit may be advisable for long cable runs, especially in locations subject to digging, mowing, traffic, use of power tools, or lightning strikes.

3.3 Water Temperature

The 107 can be submerged to 50 feet. Please note that the 107 is not weighted. Therefore, the installer should either add a weighting system or secure the probe to a fixed or submerged object such as piling.

4. Wiring

The connection of a 107-L to a Campbell Scientific datalogger is given in Table 4-1. Refer to the ET107, ET106, or MetData1 manual for connecting a 107-LC to the weather station. Temperature is measured with one Single-Ended input channel and a Voltage Excitation channel. Multiple 107-L probes can be connected to the same excitation channel (the number of probes per excitation channel is physically limited by the number of lead wires that can be inserted into a single excitation terminal, approximately six).

TABLE 4-1. Connections to Campbell Scientific Dataloggers

Color	**Description**	**CR800 CR850 CR5000 CR3000 CR1000**	**CR510 CR500 CR10(X)**	**21X CR7 CR23X**
Black	Voltage Excitation	Switched Voltage Excitation	Switched Excitation	Switched Excitation
Red	Temperature Signal	Single-Ended Input	Single-Ended Input	Single-Ended Input
Purple	Signal Ground	⏚	AG	⏚
Clear	Shield	⏚	G	⏚

5. Programming

NOTE This section is for users who write their own datalogger programs. A datalogger program to measure this sensor can be generated using Campbell Scientific's Short Cut Program Builder software. You do not need to read this section to use Short Cut.

The datalogger is programmed using either CRBasic or Edlog. Dataloggers that use CRBasic include our CR800, CR850, CR1000, CR3000, CR5000, and CR9000(X). Dataloggers that use Edlog include our CR510, CR10(X), CR23X, and CR7. CRBasic and Edlog are included with LoggerNet, PC400, and RTDAQ software.

If applicable, please read "Section 5.4—Electrically Noisy Environments" and "Section 5.5—Long Lead Lengths" prior to programming the datalogger. Measurement details are provided in Section 6.

5.1 CRBasic

The Therm107 measurement instruction is used with dataloggers that are programmed with CRBasic to measure the 107 probe. Therm107 makes a half bridge voltage measurement, and converts the measurement result to temperature using the Steinhart-Hart equation. With a multiplier of 1 and an offset of 0, the output is temperature in degrees C. With a multiplier of 1.8 and an offset of 32, the output is temperature in degrees F.

5.2 Edlog

The Temp(107) measurement instruction (P11) is used with dataloggers that are programmed with Edlog to measure the 107 probe. P11 makes half bridge voltage measurement, and converts the measurement result to temperature using a fifth order polynomial. With a multiplier of 1 and an offset of 0, the output is temperature in degrees C. With a multiplier of 1.8 and an offset of 32, the output is temperature in degrees F.

5.3 Example Programs

TABLE 5-1. Wiring for Example Programs

Color	Description	CR1000	CR10X
Black	Excitation	EX1 or VX1	E1
Red	Signal	SE1	SE1
Purple	Signal Ground	⏚	AG
Clear	Shield	⏚	G

Both example programs measure a 107 temperature probe every second and store a 60 minute average temperature.

5.3.1 Example Program for CR1000 Datalogger

```
'CR1000
'This example program measures a single 107 Thermistor probe
'once a second and stores the average temperature every 60 minutes.

'Declare the variables for the temperature measurement
Public T107_C

'Define a data table for 60 minute averages:
DataTable(Table1,True,-1)
    DataInterval(0,60,Min,0)
    Average(1,T107_C,IEEE4,0)
EndTable

BeginProg
    Scan(1,Sec,1,0)
        'Measure the temperature
        Therm107(T107_C,1,1,Vx1,0,_60Hz,1.0,0.0)
        'Call Data Table
        CallTable(Table1)
    NextScan
EndProg
```

5.3.2 Example Program for CR10X Datalogger

```
;{CR10X}
*Table 1 Program
  01: 1.0000      Execution Interval (seconds)

1: Temp (107) (P11)
  1:  1           Reps
  2:  1           SE Channel
  3:  21          Excite all reps w/E1, 60Hz, 10ms delay
  4:  1           Loc [ T107_C   ]
  5:  1.0         Multiplier
  6:  0.0         Offset

3: If time is (P92)
  1:  0           Minutes (Seconds --) into a
  2:  60          Interval (same units as above)
  3:  10          Set Output Flag High (Flag 0)

4: Set Active Storage Area (P80)
  1:  1           Final Storage Area 1
  2:  101         Array ID

5: Real Time (P77)
  1:  1220        Year,Day,Hour/Minute (midnight = 2400)

6: Average (P71)
  1:  1           Reps
  2:  1           Loc [ T107_C   ]
```

5.4 Electrically Noisy Environments

AC power lines can be the source of electrical noise. If the datalogger is in an electronically noisy environment, the 107 temperature measurement should be measured with 60 Hz rejection. For CRBasic loggers, the Therm107 Integration parameter has options for 50 and 60 Hz rejection. Sixty and 50 Hz rejection is available as an option in the Excitation Channel parameter of Instruction 11 for the CR10X, CR510, and CR23X dataloggers. For the CR10, CR21X and CR7, the 107 should be measured with the AC half bridge (Instruction 5).

Example 5.4-1. CR1000 measurement instruction with 60 Hz rejection:

Therm107(T107_C,1,1,1,0,_60Hz,1.0,0.0)

Example 5.4-2. Sample CR10(X) Instructions Using AC Half Bridge

```
1:  AC Half Bridge (P5)
  1:          1        Reps
  2:         22        7.5 mV 60 Hz Rejection Range
  3:          9        SE Channel
  4:          3        Excite all reps w/Exchan 3
  5:       2000        mV Excitation ;Use 4000 mV on 21X and CR7
  6:          1        Loc [ Air_Temp  ]
  7:        800        Mult
  8:          0        Offset

2:  Polynomial (P55)
  1:          1        Reps
  2:          1        X Loc [ Air_Temp  ]
  3:          1        F(X) Loc [ Air_Temp  ]
  4:     -53.46        C0
  5:     90.807        C1
  6:    -83.257        C2
  7:     52.283        C3
  8:    -16.723        C4
  9:      2.211        C5
```

5.5 Long Lead Lengths

For CRBasic loggers, the 60 and 50 Hz integration options include a 3 ms settling time; longer settling times can be entered into the Settling Time parameter. The 60 and 50 Hz rejection options for the CR10X, CR510, and CR23X include a delay to accommodate long lead lengths. For the CR10, 21X, and CR7, if the 107 has lead lengths of more than 300 feet, use the DC Half Bridge instruction (Instruction 4) with a 20 millisecond delay to measure temperature.

The delay provides a longer settling time before the measurement is made. Do not use the 107 with long lead lengths in an electrically noisy environment.

Example 5.5-1. CR1000 measurement instruction with 20 mSec (20000 µSec) delay:

```
Therm107(T107_C,1,1,1,20000,_60Hz,1.0,0.0)
```

Example 5.5-2. CR10X Measurement Instructions Using DC Half Bridge with Delay

```
1:  Excite-Delay (SE) (P4)
  1:         1        Reps
  2:         2        7.5 mV Slow Range
  3:         9        SE Channel
  4:         3        Excite all reps w/Exchan 3
  5:         2        Delay (units 0.01 sec)
  6:      2000        mV Excitation ;Use 4000 mV on 21X and CR7
  7:         1        Loc [ Air_Temp  ]
  8:        .4        Mult ;Use 0.2 on 21X and CR7
  9:         0        Offset

2:  Polynomial (P55)
  1:         1        Reps
  2:         1        X Loc [ Air_Temp  ]
  3:         1        F(X) Loc [ Air_Temp  ]
  4:    -53.46        C0
  5:    90.807        C1
  6:   -83.257        C2
  7:    52.283        C3
  8:   -16.723        C4
  9:     2.211        C5
```

6. Measurement Details

Understanding the details in this section are not necessary for general operation of the 107 Probe with CSI's dataloggers.

6.1 Therm107 Instruction

Therm107 instruction applies a precise 2500 mV excitation voltage and measures the voltage drop across the 1K ohm resistor (Figure 6-1). The ratio of measured voltage (Vs) to the excitation voltage (Vx) is related to thermistor resistance (Rs), and the 1000 and 249K ohm fixed resistors as shown below:

$$Vs/Vx = 1000/(Rs+249000+1000)$$

Therm107 calculates Rs from the voltage ratio, and converts Rs to temperature using the Steinhart-Hart equation:

$$T = 1/(A+B(LnRs)+C(LnRs)^3) - 273.15$$

Where T is the temperature returned in degrees Celsius, and A, B, and C are coefficients provided by the thermistor manufacturer:

A = 8.271111E-4
B = 2.088020E-4
C = 8.059200E-8

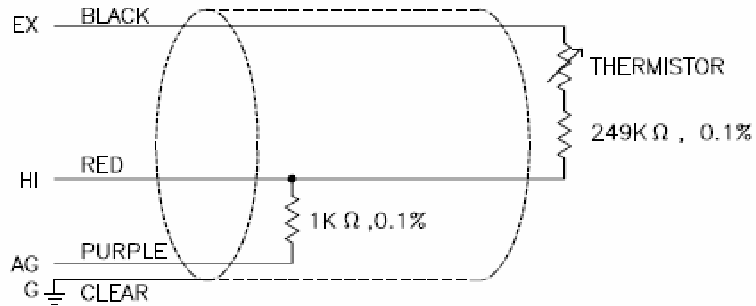


FIGURE 6-1. 107 Thermistor Probe Schematic

6.2 Temp(107) Instruction (P11)

The Temp(107) instruction (P11) applies a precise 2VAC (4VAC with the 21X and CR7) excitation voltage and measures the voltage drop across the 1K ohm resistor (Figure 6-2). The ratio of measured voltage (Vs) to the excitation voltage (Vx) is related to thermistor resistance (Rs), and the 1000 and 249K ohm fixed resistors as shown below:

Vs/Vx = 1000/(Rs+249000+1000)

Instruction P11 converts the ratio Vs/Vx * 800 to temperature using a 5^{th} order polynomial. The polynomial coefficients are shown in Table 6-1. Thermistor resistance, and computed temperature over a -40 to +60 degree Celsius range is shown in Table 6-2.

Parameter 3 specifies the excitation channel to be used for the measurement, with options to increment the excitation channel for each repetition, integration options for 60 or 50Hz noise rejection, and 10 ms delay for use with long lead lengths (Sections 5.4 and 5.5):

Excitation/Integration Codes

Code	**Result**
0x	excite all rep with channel x
1x	increment chan x with each rep
2x	excite all reps with channel x, 60 Hz rejection, 10 ms delay
3x	excite all reps with channel x, 50 Hz rejection, 10 ms delay
4x	increment chan x with each rep, 60 Hz rejection, 10 ms delay
5x	increment chan x with each rep, 50 Hz rejection, 10 ms delay

TABLE 6-1. Polynomial Coefficients

Coefficient	Value
C0	-53.4601
C1	90.807
C2	-83.257
C3	52.283
C4	-16.723
C5	2.211

TABLE 6-2. Temperature, Resistance, and Datalogger Output

Temperature °C	Resistance OHMS	Output °C
-40.00	4067212	-39.18
-38.00	3543286	-37.55
-36.00	3092416	-35.83
-34.00	2703671	-34.02
-32.00	2367900	-32.13
-30.00	2077394	-30.18
-28.00	1825568	-28.19
-26.00	1606911	-26.15
-24.00	1416745	-24.11
-22.00	1251079	-22.05
-20.00	1106485	-20.00
-18.00	980100	-17.97
-16.00	869458	-15.95
-14.00	772463	-13.96
-12.00	687276	-11.97
-10.00	612366	-10.00
-8.00	546376	-8.02
-6.00	488178	-6.05
-4.00	436773	-4.06
-2.00	391294	-2.07
0.00	351017	-0.06
2.00	315288	1.96
4.00	283558	3.99
6.00	255337	6.02
8.00	230210	8.04
10.00	207807	10.06
12.00	187803	12.07
14.00	169924	14.06
16.00	153923	16.05
18.00	139588	18.02
20.00	126729	19.99
22.00	115179	21.97
24.00	104796	23.95
26.00	95449	25.94
28.00	87026	27.93
30.00	79428	29.95
32.00	72567	31.97
34.00	66365	33.99
36.00	60752	36.02
38.00	55668	38.05
40.00	51058	40.07
42.00	46873	42.07
44.00	43071	44.05
46.00	39613	46.00
48.00	36465	47.91
50.00	33598	49.77
52.00	30983	51.59
54.00	28595	53.35
56.00	26413	55.05
58.00	24419	56.70
60.00	22593	58.28

7. Maintenance and Calibration

The 107 Probe requires minimal maintenance. For air temperature measurements, check monthly to make sure the radiation shield is clean and free from debris. Periodically check cabling for signs of damage and possible moisture intrusion.

For most applications it is unnecessary to calibrate the 107 to eliminate the thermistor offset. However, for those users that are interested, the following briefly describes calibrating the 107 probes.

A single point calibration can be performed to determine the 107 temperature offset (thermistor interchangeability). For Edlog dataloggers, the value of the offset must be chosen so that the probe outputs the temperature calculated by the polynomial, not the actual calibration temperature. For example, a 107 is placed in a calibration chamber that is at 0°C and the probe outputs 0.1°C. An offset of -0.16 is required for Edlog dataloggers, because at 0°C the polynomial calculates a temperature of -0.06°C (Table 6-2).

NOTE For all factory repairs and recalibrations, customers must get a returned material authorization (RMA). Customers must also fill out a "Declaration of Hazardous Material and Decontamination" form and comply with the requirement specified in it. Refer to the "Warranty and Assistance' page for more information.

8. Troubleshooting

Symptom: Temperature is NAN, -INF, -9999

Verify the red wire is connected to the correct Single-Ended analog input channel as specified by the measurement instruction, and the purple wire is connected to datalogger ground.

Symptom: Temperature is -86, -53

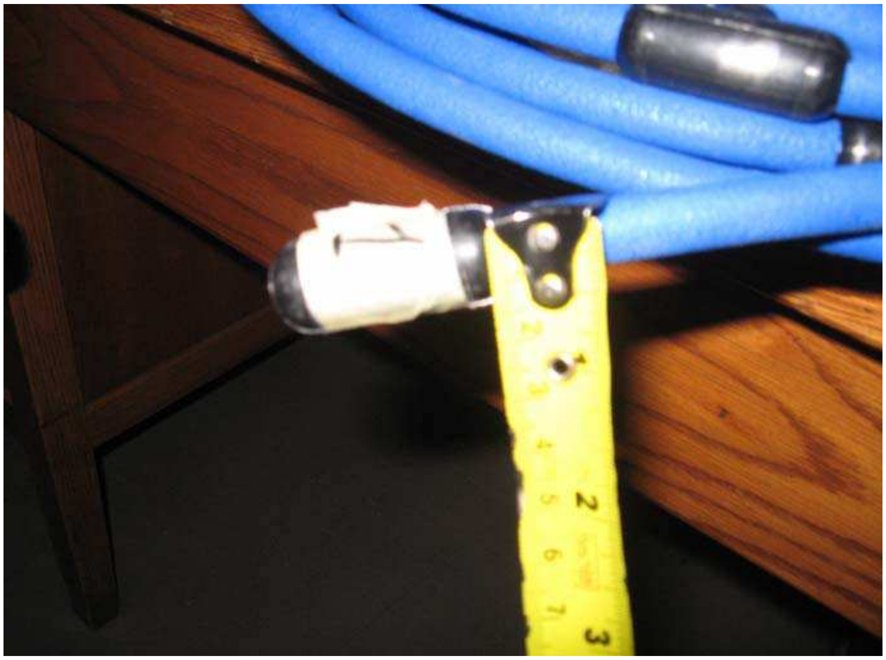
Verify the black wire is connected to the switched excitation channel as specified by the measurement instruction.

Symptom: Incorrect Temperature

Verify the multiplier and offset parameters are correct for the desired units (Section 5). Check the cable for signs of damage and possible moisture intrusion.

Symptom: Unstable Temperature

Try using the 60 or 50 Hz integration options, and/or increasing the settling time as described in Sections 5.4 and 5.5. Make sure the clear shield wire is connected to datalogger ground, and the datalogger is properly grounded.



Temperature cable showing ¾” diameter and black encasing around individual thermistors

CAMPBELLSCIENTIFIC
CANADA CORP.

June 22, 2010

RE: A3LA-MPT Modem Notification

You are receiving this notification because our records show that you purchased at least one A3LA-MPT Iridium L-Band Data Modem and SYN-DC-936(R) Remote Power & Data Kit. If you are not the individual using this equipment please forward this letter to the appropriate person. Two potential matters of concern have recently come to light.

Extensive testing by Campbell Scientific and confirmation with the manufacturer of the A3LA-MPT modem has brought to light a potential problem, which causes the random failure of the modem. This failure would render the modem inoperable for an extended period of time. Based on our research this problem started as far back as early 2009.

The manufacturer's course of action was to obsolete the A3LA line of modems and recommend the replacement of the field modem with the latest model. Reluctantly we are forced to put forward the same solution, as we have no other alternative. It is our hope to reduce the burden of this situation by offering the replacement 9522B modem, the C2462 interface, and antenna cable adaptor at a reduced price until December 15th 2010. If you determine this course of action is required for your application please contact a Campbell Scientific Applications Technician for details on pricing of replacements.

Campbell Scientific has also discovered a hardware conflict between the SYN-DC-936(R) and its connection to the RS232 9-pin port of Campbell Scientific dataloggers using a NULL modem cable. When connected in this configuration a conflict causes a decrease in the RS232 voltage levels from the A3LA-MPT, which has the potential to cause communication errors.

This problem can be resolved by connecting the SYN-DC-936(R) to the CS I/O port of your Campbell Scientific datalogger via a SC932A Interface. As part of this notification it is Campbell Scientific Canada's intention to offer you the SC932A at no cost in order to help rectify this problem. This offer is valid until December 15th 2010. Please note if you intend to deploy the 9522B modem that the SC932A is also necessary.

If you would like to take advantage of either resolution or require further clarification, please contact a Campbell Scientific Applications Technician at (780) 454-2505. We apologize for any inconvenience these issues may cause you.

Sincerely,

Jan Hall
Product & Marketing Administrator

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Appendix C Journal

Thursday, 6 Aug 2009
Call about delivery of dangerous goods (acrylic glue to repair crack in dome). Did not make the scheduled flight – arrange for another by calling PREP Services, who delivered the gear to Air Canada at the Ottawa airport. Glue will be in tonight on 6:40 flight. Deliver 2 aluminum boxes (50 lbs each) to Southside Base to ensure that equipment gets on the flight (given the 50 lb baggage limitation). Trip to airport to pick up dangerous goods (acrylic glue) – flight delayed and won't be in until 8:00. Meet at 7:00 for pre-Arctic meeting with Humfrey and all other scientists. Take another trip to airport at 11:00 to pick up glue.

Friday, 7 Aug 2009
Meet at Esso hanger for 5:50 a.m. Deposit gear and wait for plane to be loaded. First Air pilot unwilling to transport glue because I don't have the dangerous goods documents for St. John's to Thule part of trip (I asked PREP for only Ottawa – St. John's portion). I leave glue with Coast Guard and say that I will contact them in the fall to make arrangements. Depart St. John's. Stop in Iqaluit to refuel. Arrive in Thule at 12:00. Get detained for about 30 minutes at Thule airbase – check all passports. Board ship at about 1:00. Load all luggage. Cabins assigned while food being loaded aboard. Unpack. Confirm that all equipment arrived on ship. Depart for Smith Sound at 18:00.

Saturday, 8 Aug. 2009
Steam slowly to Smith Sound. Unpack equipment. Work in dive locker. Have supernumery briefing. Have boat/fire drill.

Sunday 9 Aug 2009
Take helicopter into Alexandra Fjord at 9:00 to pick up 700 lbs (8 items) that PCSP shipped for us. Richard, myself, Izzy and Bob (the pilot). Found that 6 students were still staying at Alex Fjord to study vegetation and methane production from soils. Took equipment back in 2 loads. All four of us return with 2nd load. Alex Fjord open within and at entrance. Some congestion along Ellesmere coast, but not too bad. Recall that in 2007, ship entered the Fjord while we went alongshore. Later that evening, about 22:00 hours, Captain Vanthiel asks Natasha (2nd Officer) to take a break: ice conditions are quite heavy in this region. Need to cancel some of Humfrey's CTD stations.

Mon. 10 Aug 2009 – Floe L01 (79°06.273'N, 71°10.770'W)
Sunny, very warm day. Take the chance to get out and sample first floe (L01). Leave ship at 9:26 and land on floe at 9:36. Must take 2 loads. Izzy, Richard and myself in first load (plus equipment). Carl in second load (plus equipment). Take four beacon containers full of drill rods (28 m total), EM-34 sensor, food, satellite phone & battery, flags, etc. Spend full day on floe. This floe has a recently formed ridge between two level floes. Quite heavily ponded. Maximum thickness (on ridge) about 13 m. At about 14:00 hours, two University of Alberta students fly over with EM bird (3.6 kHz). They make many passes over our transects. Had intended to make a patchwork arrangement of drill holes (four sides with one transect down centre) but cannot due to melt ponds. One transect made over ridge. Use EM-34 in 10 m coil configuration (6.4 kHz) and 20 m configuration (1.6 kHz). Depart floe in 2 stages: first at 17:30 (Rick and Carl) and second at 5:40 (MJ and Izzy). Use GPS odometer to measure floe size at 2.0 km. EM bird flew over this floe, but their GPS was not working, so we are wondering how to compare their data to mine (when did they actually cross the correct floe?).

Tues, 11 Aug 2009 – Floe L02 (80°36.079'N, 67°57.36'W)
Depart for second floe at 9:15. Since floes in area are all pretty level and thin (for multi-year ice), we decide to venture further north to take a look at the floe that Radarsat showed was lodged against Franklin Island. En route, the floes all look pretty similar – floe lodged against Franklin Island is also quite thin (and may have broken in two since image was acquired). Take many photos of ice against Franklin Island. Let helicopter pilot know that there isn't really any sense in being this far from the ship if the floes are not outstanding – we can have this type of ice closer to the ship, with less risk if something were

to go wrong. MJ settles upon a floe at 9:48 and we land in an area that is not too ponded. Rick starts to assemble things while Izzy and I lay out flags (mark the spots with water based paint, so the helicopter doesn't break the flags when he lands the 2nd time). Bob returns with 2nd shipment and Carl. Use EM-34 in 10 m and 20 m configuration. Helicopter returns for the first load at 4:30 (Rick and Carl) and then returns for second load at 4:40 (MJ, Izzy). No overflights with EM bird because they couldn't get it working until after we departed the floe. We left a bright orange paint mark to mark the floe, so they could try to recognize it – turns out, they couldn't find it. Humfrey recovered 3 moorings while we sampled Floe L02. That night, at about 00:30 MJ notices some hummocked looking floes on either side of the ship. Go to the bridge to check it out: ship's location at 80°29.505'N, 68°16.404'W. These floes are quite large (1 to 2 km diameter) but they look considerably more solid than most of the floes that we have been encountering. The conditions this year are definitely different than we saw in 2006 and 2007 – less variety of floes, large angular floes, thin ice, much more rubbling within the floes, more melt ponds. Satellite imagery animation shows that the ice being drawn into Kennedy Channel originated mostly from the eastern side of Lincoln Sea (Greenland side). While some ice is coming from the Ellesmere side, most of the ice entering Kennedy Channel since the bridge broke in early July comes from the Greenland side. EM bird for this floe, but well after we depart the floe. They weren't sure if they flew over the same floe that we had marked, because they didn't see the paint markers.

Wed. 12 Aug 2009
Day begins with considerable fog. Captain notes that the ship was alongside a very thick looking floe this morning. Spend day trying to make contact with Anne about ArcView and why it won't work. Turns out, the application is missing files (a complete folder) and cannot operate without them. It will require reinstallation of the software – which requires transferring 400 MB over the FTP site. That simply is not possible – 5 MB maybe, but the connection would never hold to transfer 400 MB of data and the cost would be prohibitive. Perhaps there is a module that can be installed in Mr Sid viewer that allows lat/long, GPS data, etc. to be viewed? She will get back to me. The Iridium phone gave superb reception, but the calls seem to be limited to about 3 to 6 minutes before communications cut out and the line goes dead (this provides insight as to why it was so difficult to download data from the instrumented floes in 2008 – it required many tries to download the temperature data completely. Humfrey spends the day recovering his moorings along the line visited in 2007 – a total of four moorings were recovered, thanks to the open concentration of ice. Compare this to 2007, when the ice floes were jammed against the Ellesmere coast making it very difficult to recover any of the moorings in that area (which is the area where data are needed most). Once he has recovered the 11 moorings, we will travel north to Franklin Island where he will deploy 6 moorings over the narrower part of Nares Strait.

Thurs. 13 Aug Floe L03
Call for flight deck ops at 08:00 hours – we have been offered the chance to sample another floe and we take it. We are ready and waiting in the helicopter – there seems to be a problem deciding whether Izzy or Yvonne will be going with us today. When everyone is ready, Yvonne, myself and Richard take the flight to find a suitable floe. We travel north, since the ship says that they will work their way north and, as we drift south, we won't be far from them by the end of the day. As we head south, we pass over a huge elliptical shaped ice fragment from the ice shelf. Finally, we find a suitable floe (all the floes seem to look alike this year). We land at 9:03 and unload the 1st shipment. The helicopter returns for the 2nd shipment (Carl and remaining equipment). We start laying transects. One is perpendicular to ridged ice (over the crest of the ridge and onto the other side). The other transect is perpendicular to that. The ice floe reminds me of the floe that we sampled in Norwegian Bay in 2007 (thick, dimpled and dirty surface). At 2:00 Richard gets the drill auger stuck in a shallow melt pool – at Flag 23. He and Carl manage to get it unstuck (thankfully) after working for about 10 minutes. Then at 2:15, they lose a drill bit in the hole. Since they can't drill over it, they start another hole (about 1 ft away, at the edge of the melt pool). I tell them to move on, since the hole is taking far too much time. They can return later (we never do). Richard and Carl drill about 33 holes on Floe L03. No EM bird for this floe.

Fri. 14 Aug 2009
Realizing that Floe L03 might have been a good candidate for the ice buoy (which has yet to be assembled), we decide to take advantage of the foggy day to assemble the buoy. The bosn' brings the buoy components up from the hold aft of the ship using the crane to bring them up to the helicopter deck, where we have gotten the go ahead to assemble it and leave it until it is deployed. Since the average thickness of Floe L03 was more than 8 m, we really don't want to lose track of it – should it be the only candidate for installing the ice buoy. We can't install the buoy because we haven't assembled it yet, and also because this floe might not be the best one on which to install the system. We have yet to head north, where thicker floes may exist. It is thought that we had lost Floe L03 since yesterday – so how will we find it? Turns out, at about 9:00, the Chief Officer (Shannon) spots the fluorescent orange paint (dots) that we left on the floe after sampling it - the ship was right by the floe. We decide to use the CALIB beacon that CIS provided to "mark" the floe, so that we can track it and return to it, if need be. I make sure to test the CALIB before deploying it, since it is the exact same beacon that we installed on one of the floes sampled last year from Resolute (the one that had to be retrieved because it malfunctioned). The test was done with the audio wand that Luc Desjardins of CIS provided for testing it. Since it is still foggy, we can't use the helicopter to install the CALIB beacon, so we are asked about using the FRC to access the floe. I decline because I mean for this to be a quick installation – the FRC likely would be problematic (how would be get up onto the floe). Captain Vanthiel suggests sending us over the side of the ship using the crane/basket. Izzy, Richard and I are over the side by 13:00 hours, with the beacon, 6" auger and paint. We install the beacon on the crest of the ridge between Flags 26 and 27. By 13:30 the beacon had been installed. We take the afternoon to assemble the buoy. The assembly takes the entire afternoon. Then, at 04:00 I quickly hook in the Iridium and GPS antennas to the system and use my own Iridium/laptop to call into the floe to check communications. I make the call from the helicopter deck, about 50 ft away from the actual ice buoy. The call goes through after several attempts. It looks like all is hooked up and functioning fine. The last few wires to attach (which do not affect communications) are the solar panel arrays for the CR1000/phone (5 solar panels) and the heater needed to heat the phone when temperatures drop below -5C (2 solar panels). Now we wait to see if the solar panels recharge the batteries as they are meant to.

Sat 15 Aug 2009
Foggy again. Can't access ice using helicopter or from ship. Having verified the battery voltage with the keypad (rather than downloading data), we permanently assemble ice buoy. Close up NEMA and heater box with putty, place aluminum tape around seams of heater box, add desiccant packs (2 NEMA, 1 heater box, 2 around solar panel mount), label mount with "NRC and phone number", put band around Iridium antenna with CHC main office phone number, silicone above and below dome's rubber gasket and then bolt on dome. Now the only way to access data is to connect via Iridium and download.

Sun 16 Aug 2009: Floe L04
Heading to Petermann Fjord because the way looks clear (lots of open water) and Humfrey's group needs some time to clear the recovered moorings on the decks, to make place for the moorings that will be deployed along a section of Nares Strait (out from Franklin Island). We are passing through ice that is quite soft – often I can see the ship's bow imprint in the floes. Day begins foggy, but clears off by afternoon. Captain asks if we would like to sample a floe in the afternoon. I ask what time we should be back – 18:00 hours, like previous days. He says we can have a little more time since we are getting a late start. We agree on a 19:00 return. At 13:20 the helicopter is starting with the first load (Izzy, Richard and myself and some of the gear). We select a floe from the helicopter that is not too far from the ship, since we won't have much time for sampling and land at 13:36. The helicopter returns for the second load (Carl and remaining gear). This sub-floe is ovular, bowl shaped with ridges all around it and is about 150 m long. Given the short sampling day, I make two transects, perpendicular to each other, capturing the ridged ice along the perimeter of this aggregate floe. We also use the EM-34 at the 20 m spacing along the ridge crest, even though it was not drilled (due to time constraints). Richard and Carl drill 24 holes. I notice that Richard and Carl are taking an especially long time at the first hole (edge of the floe closest to the ocean). When asked why, they say that blocks of ice are beneath the more solid sheet of ice.

The drill pushes them out of the way, but by the time they pull the flights up and put the thickness tape down the hole, the blocks of ice have moved back into position (but in a different orientation) and blocked the hole to prevent them from taking a reading with the thickness tape. I tell them to estimate the thickness using the number of flights in the hole. Even that is difficult, because he finds it difficult to know where the bottom of the hole is based upon the "feel" of the drill. Evidently, the ice has little integrity, so there is no clear boundary between ice vs. water – Richard says it is like drilling through grapefruit. This happens at a number of holes, so we only have the estimated thickness using the number of flights in the hole. I also have a question as to why the freeboard is so high (say, 1 m) but the ice is so thin (say, 7 m). Are the blocks of ice lifting the surface up, giving it a high freeboard? Is the rafted ice on top sitting high, giving a high apparent freeboard, but the ice sheet is quite thin in that area? As we are having tea, Richard notices a polar bear and her cub in the distance (about 1 km away). She was headed in our direction (at that distance) and then caught our smell (or saw us) turned around, and bolted in opposite direction with her cub in tow. That is the first bear I have seen in this region, and this is the 3rd year working here. It could be because we are working quite far north (Kennedy Channel), whereas in past years most of the floes were sampled further south (Nares Strait). We depart the floe at 19:00. EM bird flew over this floe (they uses File IDs as "event" markers, so it should be very easy for them to find the section that corresponds to our exact floe).

Mon 17 Aug 2009 Floe L05

The weather is extremely foggy. Captain Vanthiel asks us if we would like to sample a floe close to the ship, thinking that if the visibility improves slightly the helicopter could just pop us over onto the floe. By about 9:30, it is still very foggy, but Bob Bartlett (the pilot) says that he would be comfortable flying us on a part of the floe, so long as it is no more than 1000 ft from the ship. I agree, saying that we would be interested in a nearby part of the floe. The first load is me, Izzy and Richard. The second load is Carl and Yvonne. Both Yvonne and Izzy came out today. After landing, I realize how difficult it will be to lay transects. The ice is thick enough, but it is riddled with melt ponds and drainage features that will make the transects quite short and erratic. I manage to lay out three transects, although it took quite a while to figure out where we could avoid melt ponds. This particular floe was right on the edge of an aggregate floe. It had huge blocks of ice on one of its sides (easily 8 to 10 ft thick). As the day wears on, the fog lifts. Richard and Carl drill 40 holes. We depart the floe at 16:00. Richard and Carl set up the drill frame on level ice, and try it out. It takes a little bit of time to install, and it doesn't seem to operate as easily as it should. Both agreed that it does make drilling easier, but it needs to be tweaked (tightened with a pipe wrench for starters, to get a better fit). No EM bird data for this floe. Later that evening, the fog clears, making it possible for Humfrey to fly to Cape Baird to install a weather station. They depart at about 20:00 amid howling 27 kts winds. They return at 22:30, with one side of the ship up against the ice (winds are from the south, consolidating the ice to the north of the ship).

Tues 18 Aug 2009 Floe L06

The first order of the day is to conduct an aerial reconnaissance of Petermann Fjord. The helicopter takes off just after breakfast (8:30) with Chief Officer (Shannon) and Helen (scientist) onboard. They return about one hour later, noting that Petermann Fjord is clogged with ice. They will not be able to run their operations from the FRC, nor is the ship willing to fight its way into the Fjord. Instead, the Captain asks if I want to sample a floe in the area? Yes, of course – I had been sizing up the floe we had been sidled up to for the last hour! I rush around, find Carl, tell him we are "on" and that he should let Richard know. We take off at 11:00. Bob says "so, you just want to land right over there?". I reply, that it would be good to take a quick look around first, to see if there is anything better (maybe we could find a home for the ice buoy: 10 m thick ice, and more). We fly north towards Petermann Fjord. I see quite a lot of ridges, most of them very fresh. Some dirty ice. Lots of heavily ponded ice. We head back to the floe that is adjacent to the ship, especially given our late start (ridges would require a full, long day). We land at 11:14. Richard and the rest of the gear come out in the second load. I lay out four transects. One along the small rise that (evidently) separates two different floes (Transect 1 blue line). Another transect is made over in a dirty part of the floe. A third transect is made out from the ridge, into a rubbled area of ice. And a fourth extends further away from the ridge. Richard and Carl drill 38 holes. We depart floe at

16:00 hours. The ship immediately heads south, where Humfrey's team wants to do some rosettes in the ice-free waters (north of Hans Island) and then further south to the Franklin Island mooring transect.

Wed 19 Aug 2009 Floe L07

At 9:00 Carl, Izzy and I are in the helicopter for the next floe to be sampled. We do an aerial reconnaissance of the floes in the area. Again, I don't see too much variety. The floes are dispersed over Nares Strait and surrounded by large expanses of open water. We travel about 12 n.mi. north of the ship – up past Hans Island – when I see a decent looking floe. I hesitate because of its proximity to Hans Island. I ask Bob how far the floe is from the Island – he replies about 2 n.mi. We venture a little further west to see if there is anything else in the area. There is not. I request that he land on the floe that I had first seen – we will watch the floe drift throughout the day and give a pick up call if something arises. Izzy has trouble contacting the ship via the HF radio initially, but he can communicate with the pilot (in the air) and Dave/Ron refurbishing the weather station on Hans Island. I hook up the satellite phone in case we need it. At noon, we stop for lunch and I ask Izzy to call the ship to give our position and to ask them how close we are coming to Hans Island. He does – they reply that we are 1 mile from the island. We continue working – and watching. Our speed is 0.5 kts. As the afternoon wears on, we notice that the floe is passing alongside the island. I also notice that the drift speed of the floe has decreased to about 0.1 to 0.2 kts. Richard and Carl are drilling holes along the transect that I made on a ridge crest – although this whole region of ice is severely hummocked. Once Izzy and I start using the EM-34, I can see that the conductivity values are around 20 – which tells me the ice is very thick. I ask Carl what kind of thicknesses he is getting. He replies 5 m to 13 m. Where are the 5 m holes? He shows me. I ask about the freeboard, most of which are more than 1 m. Something does not make sense. I watch as they drill Flag 7. I see how Carl is keeping track of the number of augers in the hole (and doing a good job of this). He and I count 12 augers. The ice at flight 6, 7, 8 is soft (I can tell by the sound of the auger, after they add a flight and position it back down the hole – with a clunk); then the ice at auger 9 gets hard again. They measure a thickness of 12.96 m. I watch while they drill Flag 8: the first 7 auger flights show hard ice, wet cuttings after the 4th flight, soft ice at the 8th flight. They measure a thickness of 6.99 m and a freeboard of 1.15 m. I watch at Flag 9: hard ice for the first 9 flights; then they encounter a pocket, below with the ice is soft; a total of 10 flights were used, ice thickness 9.68 m, freeboard 1.80 m. At Flag 10: hard ice for 10 flights, soft ice for 4 flights, wet cuttings at 8 flights; total of 14 flights used; ice thickness 13.65 m, 1.70 m freeboard. At this hole there was so much slush deep down, that they had to force the augers into the hole. Apparently the cuttings would not clear properly – too heavy/saturated with water? Flag 11: hard ice for 8 flights, wet cuttings at 5th flight, total thickness 13.02 m, freeboard 1.12 m. Richard says he "feels something at 12 m using the ice thickness tape". There is a large pocket at 7 m; they use a total of 17 flights to explore the hole, making sure there is no ice below that depth. They then take a break, as I walk the line to see where they measured thin ice, given that the last few holes were all quite thick. After break, I ask them to re-drill Flags 1, 3, 5 and 6 – because their measurements just don't make sense. Flag 1: hard ice for 10 flights, soft ice at 11 flight, pocket at 6th flight, we cuttings at 2nd flight. Thickness 10.59 m, freeboard 0.97 m (first reported ice thickness measurement of 5.2 m). Flag 3: hard ice for 12 flights, soft ice for 13th flight, wet cuttings at 7th flight, pocket at 6, 9 and 13th flights; ice thickness 12.7 m, freeboard 1.23 m (first reported ice thickness measurement of 6.25 m). Flag 5: hard ice for 9 flights, soft ice at 10 and 11th flights, hard ice again at 12th flight; pocket and wet cuttings at 8th flight; ice thickness 13.23 m, freeboard 1.66 m (first reported ice thickness measurement of 8.55 m). Flag 6: hard ice for 7 flights; pocket & soft ice/drilling really tough at 7th flight and below; wet cuttings at 5th flight; ice thickness 9.16 m, freeboard 0.56 m (first reported ice thickness measurement of 7.32 m). Having watched enough, and falling behind on the EM-34 measurements, I begin taking EM readings again. At 4:00 we take break – Richard asks me how many more holes I want drilled. I ask him if he is up for drilling four more along the orange line. He groans, and says he just doesn't have it in him. No problem. How about doing one more hole and taking us up to the blue line? He is find with that. The helicopter picks Richard and Carl up at 5:30; and then returns for Izzy and me about 15 minutes later. We do a fly around for aerial photos and then fly across the floe to gauge the floe diameter (with the odometer on the GPS). A total of 22 holes were drilled on Floe L07 (3 re-drills). Later that night, Richard told me later that he was bothered by short notice. I tried to explain to him that I only know about 2 minutes before he finds out – if he wants to get a better handle on what is going on, I told him to go up the bridge so he will find out first hand how quickly decisions are made. I also explained that the final decision to fly comes at the very last minute – the call for "flight deck ops" means be ready. This is how it is: it is called "fieldwork". Drilling a few of these monster floes has been very difficult, so it is important to have easier days (thinner floe) in between the more strenuous days (thick floes).

Thurs 20 Aug 2009
We are headed back up the Petermann Fjord so that Humfrey's team can do CTDs along the front of the glacier and also visit the two sets of camera-pairs that Jason Box (Ohio State University) installed on the cliffs in early July to document ice shelf calving. Open water permits our transiting right into the Fjord without any trouble at all. Linda, one of Humfrey's team, notes that "where has all the ice gone since we last visited this area two days ago (Tuesday)?" We are all amazed that it is so easy to get to the ice sheet front. They spend the day flying here and there and using the FRC to run CTD lines across the Fjord. Salinity of the surface water (1 to 2 m deep) is 29 ppt. Richard, Carl and I meet to discuss how best to deploy the ice buoy (if the day ever comes). We talk about how many loads would be needed, what if the pilot can't set the buoy into the legs embedded in the ice, who would be involved, the steps required for installation in either case. At about 19:00 the FRC is recovered and we start out of the Fjord. I overhear the Captain give Shannon instructions to head out between the headland and Joe Island – the ASAR image is showing that as quite clear – much open water to be had – so going south to Hans Island should not be a problem. They start out and then, about 21:30 I stop working in my room to go up to the bridge – the ship is reversing. On the bridge, the Captain has control – must be the Joe Island transit didn't work out. I can't see how he will get through all this ice – it is nothing like the ASAR image shows. Through the binoculars I can see ice all around and no open leads. Well, for the next four hours, the Captain tries to negotiate his way through the ice – rebounding off massive floes, forcing him right into another. He says that the ice conditions changed really fast – compared to what the satellite image (noon-time) showed. What ice had been north, allowing us to transit into the Fjord unfettered, had moved clear over the mouth of the Fjord – blocking every which way. The only way out now was to use brute force – which he did until 2 a.m. By 1 a.m. all was quiet – the only people on the bridge were the Captain, Bernard (Mate), helmsman and me. Then at about 1:15, I hear the door to the bridge open and in walks Richard – he can't sleep with all the commotion. About 10 minutes later, the door opens again, and in walks Carl! Captain then says to me "jeeze, you give them a day off and they don't even sleep – and you, why you never sleep!". Pretty funny. Well, by 2:00, I decide to call it a night – figuring that this would take us well into morning. Shortly after that, the Captain reaches a place where he is comfortable and decides to call it a night. All is quiet.

Fri 21 Aug 2009
I awake at 06:30 to ice impacts – must be we are on the move again. I don't think we will head out on the ice today – but one never knows, so I better not be up too late. I walk up to the bridge to see open water along the Greenland coast. The Captain sends the helicopter up to take a look – they come back, confirming that open water conditions are not far, and that the transit to Hans Island will be in mostly open water. So, we just need to get through this. Mostly, that will require transiting the one very large floe in front of us. At 09:30, he calls for three engines We begin to back and ram to get through this large ridged floe – that overturned pieces suggest is about 4 m thick. It takes one hour to make our way through this floe – a total of at least 9 rams at 8 kts to penetrate the floe. After about the 7^{th} ram, the bridge is populated with scientists and the Captain calls out "is this one going to do it?". Well, it doesn't. Matter of fact, two of the rams result in about a 4 to 5° roll to starboard. It is pretty much all over by 10:30, as we penetrate the floe and enter into open water along the Greenland side. The idea is to make it to Franklin Island so that Humfrey can deploy his final four moorings. Then, the objective will be to leave Kane Basin, transit south through Jones Sound and into Cardigan Strait (where Humfrey has more work to do). En route, it would be great to revisit Floe L03 on which the CALIB beacon was installed, run a few more ice thickness transects (to see how much the ice thickness has changed) and if all still looks good, deploy the ice buoy. Humfrey is agreeable to this (thankfully). I have been lining up the RADARSAT images and tracking different sorts of floes, to get a general idea of ice movement in Kane

Basin and in Norwegian Bay. If Floe L03 no longer looks promising the ice buoys will need to be deployed in Norwegian Bay, where I hope the ice floes will be thicker. Recall that the four floes we sampled last year in Wellington Channel all had an average thickness of about 8 m.

Sat 22 Aug 2009

Continue transit south to Smith Sound area, where Humfrey plans to install a weather station, has plans for CTDs and hopes to recover tide gauge at Foulke Fjord. Spend day doing oceanographic work. Foulke Fjord is looking like it won't happen because it would take too much time to transit to the Greenland side, launch the FRC and recover the gauge. MJ spends the day examining imagery for Kane Basin and Norwegian Bay, using it to track floes. Floe L03, in particular, is of interest, as the CALIB beacon was deployed on it and we have been tracking it ever since. The idea is to re-visit the floe to recover the beacon, assess its viability as a home for the ice buoy and (if it still looks good) deploy the ice buoy. Weather is calling for high winds (30 kts), which will severely limit the distance (and possibly the option) of slinging the buoy for installation. At this point, the only way to install the buoy is to sling it – as it has already been sealed permanently. We could install system 'B' which has not been sealed up yet, but that would require taking it out component-by-component in the helicopter. We measure the cargo space of the helicopter – the base of the buoy is about ¾" too high (even though it had been designed to fit into the cargo space). This helicopter has rails (for a stretcher) that decreases the overall cargo height by about 1". Given that system 'B' will not fit inside the helicopter, we decide to complete the assembly of the system, should the possibility of deploying it arise.

Sun 23 Aug 2009

Download coordinates of system 'A'. It is about 26 n.mi. northeast of the ship. When the Captain hears that he asks "we passed it?!?". Yes, the floe is moving north. The question now is whether the ship (Humfrey) will be willing to allow us to re-visit the floe, and if it looks good, to install the buoy. We do a lot of waiting (out on the flight deck), until after lunch we are permitted to take a helicopter reconnaissance to the floe to recover the beacon and to assess whether we still want to deploy system 'A' on this floe. At 12:40 we depart the ship for the last known coordinates of the floe (now 60 km northeast of the ship). I start the trip odometer on the GPS to give an idea of when we should start looking out for Floe L03. At about 12:30, we pass over a floe that reminds me of "our floe" but it doesn't have any orange paint markings on it. I spot the linear ridging (characteristic features) of Floe L03 shortly after and announce "this is our floe". Everyone starts looking for the paint markings, which the helicopter pilot first spots on a ridge. We land on the floe at 12:40, Richard, Izzy and I get out to recover the beacon (which has fallen out of its hole on the ridge) and is now resting at the foot of the ridge. It also makes me wonder if the "fate" of the many floes we have instrumented with CALIB beacons has been for this very reason. The paint marking the transect holes is well worn, but still visible (from 13 Aug). The fresher paint on the ridge itself (left when we installed the beacon 14 Aug) stands out more. We return to the ship with the beacon – even though the floe still looks really good, I had recovered it because it might not be possible to re-visit the floe, it being more than a 4 hour steam northeast of the ship. We return to the ship to report that, ideally, we would like to re-visit Floe L03, deploy the ice buoy and re-drill a few of the holes to compare thickness now to the thicknesses measured about 10 days ago. Humfrey is approached, and all three of us consult to determine whether the transit south could be interrupted so that we can venture north to visit Floe L03. It is agreed that we can head north on the detour. We are all happy about that – even the Chief Officer says that installing the buoy is priority, since the crew really want to see "R2-D2" deployed, all the more since there are now two of them sitting on the back deck. The floe is too far for the Captain to allow us to go right now (the steam to us would be too far, should something happen), but he says that after dinner we should be within range of the floe. The weather station team returns to the ship at about 15:00, after which we begin our steam north. The ship makes excellent time, since there is plenty of open water. At 17:48 we are in the helicopter ready to depart for the floe, which is less than about 1 hour steam away. At 18:05 we land on the floe. The first item of business is to find a suitable location for the ice buoy, someplace where the ice is thick and level enough to make the installation smooth (especially if the slinging doesn't work and the buoy has to be man-handled into place). Ice thickness at the first two holes we drill, each about 10 m from each other, is more than 14 m thick (the limit of the auger brought out this time round). I settle upon a third spot (even though we didn't drill for thickness) because it is another relatively "flat" spot about 20 m away, giving us a bit more distance from the floe edge. Having found a suitable location for the buoy, we start drilling the 3 m holes for the buoy legs, and leveling them so that the buoy can be slung and set down into its legs. At about 20:45 we call for the first load of back-up people (the helicopter engineer and two students from U. of Alberta). Once they arrive, we call for the buoy itself. The helicopter engineer directs Bob, the pilot, as he is coming in with the load. As requested, I have painted lines extending from the four corners of the legs, to help the pilot see where the buoy needs to be. We can see the buoy as it is lifted from the ship's deck, then out it comes, directly overhead – the 250 kg buoy being slung on a 120 ft long rope – until it smacks into the sides of two of the PVC pipes. We all thought everything was lost then. The engineer radios the pilot to pull up and within 60 seconds four of us have lifted the legs of the buoy up to its own "stubby legs" and the buoy is set down in place. All this in about 2 minutes, or less. Richard and Carl then set to drilling the hole for the actual temperature chain. The hole is about 2 ft from the buoy itself. They certainly have a hard time drilling and clearing the hole – and finding the bottom of the ice using the ice thickness tape. They arrive at a thickness of about 12 m for the temperature chain. A 3 m long PVC pipe is installed in the ice, and then the thermistor chains are sent down the hole using a weighted fishing line. While Richard and Carl drill the hole for the temperature chain, Izzy and I fill the holes for the 4" PVC legs with melt pond water. The installation is complete by about 21:30, Richard and Carl move on to the other side of the ridge to re-drill a few of the holes that I marked earlier. I go see how Richard and Carl are doing. They drill four holes, then it is 10:30 and we call for pick-up, realizing the helicopter pilot has had a very long day. As it turns out, the pilot was on the bridge asking if we had called in. The Captain replied "give them five more minutes", then our call came in about "ready for pickup".

Mon 24 Aug 2009

Transit south for Cardigan Strait. We pass some worthwhile floes in Smith Sound – they appear to be holding together quite well, given the swell and relatively warm ocean water. It bodes well for Floe L03, which thankfully, is still headed north into colder waters. No new imagery for Norwegian Bay. There are many complaints about the imagery for Nares Strait not being available or not being delivered in a timely manner. We are hoping for better results in Norwegian Bay. I try to dial Arctic 'A' at 16:00, but can't get through. I try using only the handset, and get a busy signal. So, must be they are calling from Ottawa. I find out later that was the case, and they forward me the data. Everything looks good.

Tues 25 Aug 2009

We are in Cardigan Strait. The RADARSAT imagery is showing some monster floes in Norwegian Bay, but we really can't tell whether they are substantial multi-year floes or landfast ice from the Bay itself that fragmented into individual floes and decayed. I select three floes from the image to check out during an aerial reconnaissance. One of the U. of Alberta students (EM bird) and myself depart in the helicopter to see about the ice in the Bay. We leave at 12:37. The floes I had selected from the imagery, one of which was 12 km across, are huge, uniformly ponded landfast ice floes that are severely decayed and rotten (melt holes penetrating through full thickness of ice). Likely, it is second-year ice judging by the uniformity of the ponds, the hummock shapes and the overall thickness. Having eliminated the three pre-selected floes, I note 8 other, smaller floes that look more substantial. That is a relative term, because all of the floes in this area are severely ponded – and many look like they are just barely hanging together. I take photographs of the floes. We return to the ship at 13:36 and I report to the Captain about the rotten ice and the coordinates of the floes that I saw during the reconnaissance. He says that the ship will venture into Norwegian Bay once Humfrey is completed his work in Cardigan Strait. Since the floes are about 25 to 50 miles north of the ship, he does not feel comfortable with our working on them before the ship is within range. We wait.

Wed 26 Aug 2009

Humfrey will finish his work in Cardigan Strait by noon – the Captain says it will be early afternoon before the work is done. Then, we will transit to the floes of interest and we can sample. Starting in late afternoon is not ideal, because much of the day has been already spent, it requires overtime for the ship's Crew, cleaning the equipment takes time upon returning all of which make an early start and full day difficult the day after. I think my preference would be to transit as far north as possible to see if the Captain is comfortable transiting through Belcher Channel to Penny Strait – see what the ice conditions are like. We certainly should find suitable floes there and, if not, we can always come back and sample the few floes I have seen in southern Norwegian Bay. We will wait and see how Humfrey and the Captain want to play it. So far, the Captain is not committing to the Penny Strait transit – which is to be expected – until he finds out what the ice is like. Every day that goes by, we can see the ice changing – hardening – new ice if forming overnight, but the days are still long. We should start to see some significant changes in the next week or so. Still, we are due to disembark the ship by 1 September. Take another reconnaissance of Norwegian Bay after dinner. Captain limits radius of reconnaissance to 50 miles. I expect the point is to re-examine the floes we saw yesterday, to settle upon a floe that could be a home for buoy 'B'. Truth is, none of the floes I saw yesterday were worthwhile for system 'B' – they were decently ridged but appear to be barely holding together. I would prefer the ship venture further north, and for us to find a floe there that is suitable for the ice buoy. We return to the ship after about one hour of seeing what amounts to the same area of ice as seen yesterday. I select one of the floes as decent for thickness measurements, but confirm that none are suitable for the buoy. The Captain says the ship will head to the location that I gave yesterday (seven floes in the same approximate area); if I decide to sample the buoy in the south part of Norwegian Bay, then we can always fly back. If I do an aerial reconnaissance to the north (once the ship arrives on station) and the ice looks good, then we will sample in that area.

Thur 27 Aug 2009

We prepare for a helicopter reconnaissance just after breakfast. The idea is to fly northwest out to Crescent Island at the westernmost point of the Grinnell Peninsula to see what the ice conditions are like (1) to see how easily a transit through Queen's Channel down to Penny Strait could be made and (2) find a home for the ice buoy. The reconnaissance last a little over 1 hour. We fly behind Table Island where I see many decent multi-year floes and many remnants of ice islands (or are they landfast multi-year ice?). These remnants clearly are not like conventional smooth or hummocked multi-year ice. Some of them have a very low freeboard, but appear to be quite thick because they are wholly intact – very little ridging. Their drainage features are extremely uniform (parallel rivulets), as is the top ice surface, which is also a different hue than traditional multi-year ice. I would love to land on this type of ice to see just how thick it is. After flying behind Table Island out to Crescent Island, we see that conditions in Queen's Channel are quite congested, confirming what we see in RADARSAT imagery. We are not dealing with decayed second-year and first-year floes & relatively young multi-year ice, as much of the ice in Nares Strait was this year. Rather the multi-year floes look quite solid – and menacing for a ship trying to transit the area. There are open leads and areas of open water, but I don't think there are enough to make it comfortably through the area (judging by how challenging the transit through Hall Basin/out of Petermann Fjord was). We turn back at Crescent Island and return north of Table Island, through Belcher Channel. There I see many ridged, solid multi-year floes; one in particular was massively ridged and would make a nice home for the buoy (although it would probably be too thick). About 10 miles to the east, we see another very attractive multi-year floe, about 2 km in diameter. It is extensively ponded, but also has extremely rugged topography. Since it is only about 30 miles from the ship and it appears to be relatively easily accessed, I decide that is the floe that I will recommend we sample today.

We return to the ship at about 10:30 and I report to the Captain and Humfrey about the ice conditions. I convey my thoughts about transiting Queen's Channel, mention the "easy access floe" and the other, heavier feature further on. We settle upon the more easily accessed floe, and it is decided that the ship will make their way towards us during the day. We pack equipment and then Richard, Izzy and I prepare to fly to take another look at the rugged floe and then circle back to the floe in closer proximity to the ship. We land at about 11:30 and the helicopter takes off for the 2nd load. Then, I notice that whoever packed the helicopter did not put in the right equipment to get us going. We wait about 20 minutes for the helicopter to return (he refueled when he landed for the 2nd load). Out comes Carl and more equipment. The pilot signals me to put on the head set. I hear that Yvonne won't be coming because if weather were to come down, transporting five people would require a 3rd trip. I understand that. Next, he tells me that we are out of range of the VHF radio. I mention that we have an Iridium phone and that I will try it to make sure we can call the ship at the pre-set time. He asks when we will be ready for the buoy, and I reply 19:00 hours. He says o.k. and then departs. We start working to map out transects along the level part of the floe and one of the ridged areas of ice (blue line and orange line). We continue drilling and the EM measurements until 17:10 and then I mention to Richard and Carl that we should start prepping the legs for the ice buoy because Coast Guard may surprise us with an early visit (although 19:00 was agreed upon). The legs for system 'B' go in easier than system 'A', probably because we have been through it once already. Richard and Carl use the level and transit to survey the legs so that they are level when the 250 kg buoy is set down onto/into them. We finish by 18:15 and Izzy radios the ship to send the helicopter engineer out so that he can direct Bob about where the buoy needs to go and use hand signals/radio communication to advise Bob about his altitude. The radio works this time, and we hear Bob come across the radio to say that Guy will not be coming out –that Bob is on deck and is ready to transport the buoy (about 30 minutes early). Apparently, the weather/fog is coming down at the ship's location, but we have clear skies on the floe. We have enough time before he arrives to drill the thickness at Flag 1 on the blue line, which was a ridge about 2.5 m high. I had asked Richard and Carl to begin with the level ice at Flag 2, 10 m away, so that they started out easy. That was no sooner done than we heard the helicopter - out the buoy comes, with Bob leaning out of his cockpit (door off) so that he can see down to plant the buoy where we need it. It goes very smoothly, to his credit. Then, off the sling comes and he lands, ready to take one person and equipment back to the ship before the "weather closes". Carl goes (with a good portion of the equipment – the pilot pointing and waving at us to bring more) leaving Richard, Izzy and I to finish the buoy. I tell the pilot we need at least 30 minutes to finish installation. Away he goes, we get busy on drilling the 2" hole for the temperature chain. The ice turns out to be about 13 m thick, which is thicker than we had hoped for (11 m temperature chain), but there is no time to look for a more suitable location – we must leave the floe in 20 minutes. Thirty minutes later, to the mark, we hear the helicopter. Thankfully, all went well and the assembly was straightforward. We have the gear packed up and ready to go when he arrives. In the helicopter, Bob says that we have time for one go round (for photos) and then need to hurry back to the ship. He does the circuit too low, so I ask him to go a little higher – then he replies, "just this one and then we must go". I got a few shots, but not enough, and could not get a measure of the floe diameter using the GPS. We return to the ship and the Captain asks how it went. 'Great floe' I reply. He says we were lucky because he almost called us back twice: once when the VHF radio wouldn't work and second, when the weather started to come down at 18:00 hours. Turns out, the open water I had seen in the helicopter (prompting me to describe the floe as "easy access", was over shoals – and there was a several km diameter multi-year floe between the ship and us – so the ship could not get to us without backing and ramming its way through that floe). I told the Captain I sincerely appreciated his allowing us to finish out on the floe. We drilled 18 holes in the ice, installed ice buoy 'B' and did EM measurements along both transects. Now, we were headed for south – the Captain had decided that he would not be going to Penny Strait via Queen's Channel.

Fri 28 Aug 2009

Transit south into Jones Sound. By dinner we are rounding the eastern portion of Devon Island en route to Resolute, via Lancaster Sound. The intention is to head up to Penny Strait through McDougall Sound or Wellington Channel. I have yet to ask the Captain how far into Penny Strait we will go – likely that question will be met with the standard reply "depends upon the ice conditions". It is possible that I may be able to sample some of the landfast multi-year sea ice that we saw in Belcher Channel via the south side of Penny Strait. Or the intention may be thoroughly characterize a multi-year ice ridge by drilling along its crest and shoulders. Since the ice in this area continues to move, it looks like it will not be possible to install the system temperature chain 'C' (20 m long) in a landfast ridge – or one that will soon be landfast. That may have to wait until the spring. We will have to play it by ear – once we know when we will arrive, we can see who can cover off what. One more day of sampling would be super. And that will be all we have, since we won't arrive until Sunday afternoon and we have to be in Resolute on Tuesday.

Sat 29 Aug 2009

Transit through Lancaster Sound (making great time) and up Wellington Channel towards Penny Strait. It might not seem like it, but circumnavigating Devon Island in open water was preferred to transiting 200 km of congested ice to exit Belcher Channel towards Penny Strait. Granted, there were some areas with open leads and less congested areas of ice in the region, but after struggling to get out of Petermann Fjord, I think that no one on the bridge looked forward to navigating another area of congested multi-year ice. And fuel-wise, it was much more economical to circumnavigate a longer distance in open water (on one engine) than to make our way through multi-year ice (on three engines, like Hall Basin/Petermann Fjord). Estimates are something like $30k/day to transit open water on one engine vs. $100k+/day to transit ice on three engines. Heading north up Wellington Channel, there is no ice to be seen. Not until we reached the north end of Cornwallis Island did we start encountering ice. There were many ice island fragments, with freeboards of at least 2 to 5 m.

Sun 30 Aug 2009

After breakfast, I talk to the Captain on the bridge, who says that we should prepare for an aerial reconnaissance to see if there is a suitable floe in the vicinity. He says that the floe should be within a 10 mile radius of the ship because he likely will not get too far given the way the ice looks. Humfrey will have to settle for a mooring location that is south of where he wanted. I ask if this is just a reconnaissance, or will we also be permitted to take equipment? He and the pilot agree that we can carry three passengers and some equipment. I take a copy of the most recent RADARSAT image and then leave for the flight deck. We are in the helicopter warming up at 9:07, and by 9:24 we have selected a floe for sampling. Most of the floes in the area are pretty rotten, with thaw holes in the ponds that extend throughout the full thickness of ice. The floe we selected was a rugged looking floe closer to the coast of Bathurst Island. We fly around it, again and again – trying to find a decent place to land the helicopter. At last, Bob the pilot decides on a place that is acceptable – and tells to be careful exiting because of the uneven slope, plus the drainage feature in front of us, and a small melt pond on one side of the helicopter. Richard, Izzy and I unload the gear, as Bob returns for Carl and the remaining equipment. While they are gone, I look around and see that, definitely, this is the roughest floe that we have ever sampled (even more so than Floe L08 in Belcher Channel). The peaks on the ridges are steep, most of which have a knifelike crest, with melt ponds extending along either side. Clearly you will need to be part mountain goat to feel totally comfortable walking all over this floe. The weather is pretty miserable, light drizzle that turns into rain in the afternoon. Soon after we start working on the floe, I see that the ship is sailing on past us. I cry out to the rest, "hey they are passing us". As it turns out, the ice conditions weren't as bad as the Captain had suspected – partly because winds from the southwest had pushed the ice offshore, forming an open lead. By mid-day, we can all see that the winds have died down and fog is starting to close in around us. We continue working. By the end of the day, the fieldbook is sopping wet, as are all four of us, and the surface of the ice has become like an ice rink. We sample the floe all day, until about 18:00 hours, since that is the time I had told Captain Vanthiel we would finish. Right around 17:00 hours we see the ship in the distance, through the fog. At about 17:30 they call for an updated position, as the helicopter prepares to come pick us up. The ship pulls close to the floe and in comes the helicopter – he takes Richard and Carl first and then he returns for Izzy and me. We do one circuit around the floe (not high enough for a good picture, because of the fog) and then we return to the ship. Over the course of the day, we drilled 20 holes, for a maximum thickness of 21.1 m. During the day, Floe L09 drifted northeast and then reversed direction and drifted south, for a total drift of about 8 km.

Mon 31 Aug 2009

I hold out on giving the word to pack up until after lunch, hoping that the fog would lift long enough for us to reach a 10^{th} floe. It does not, so the ship heads for Resolute (via Crozier Strait) and we decide to start packing the equipment. We finish with the gear after supper, move it to the hold and then supply the Chief Officer with a list of the goods to be shipped upon the ship's arrival in St. John's. I need to send him dangerous goods documentation for the two batteries that we did not deploy (system C). We did not deploy that system because, unlike the other two floating systems, it was housed in a wooden box – which required deploying it in landfast ice, so that we could be absolutely sure that we could reach it in the spring 2010, as planned. Since there was no landfast ice, that system was not deployed. With all the equipment attended to, we start packing our personal gear. The ETA for Resolute is about 5 a.m. on the morning of 1 September.

Tues 1 Sep 2009

We arrive in Allen Bay and prepare for transporting gear and people to Polar Continental Shelf Project (PCSP). Humfrey has about 4 flights required for slinging the anchors and chains he will use to deploy his mooring in the spring of 2010, the EM bird needs to be slung to PCSP, all of our luggage and about 16 people. This takes all morning – the last flight ferry is about 12:30 ship time, arriving at PCSP just before lunch (11:30, since they are one hour difference from EST). We have lunch, unpack a few things and then I walk over to talk to Tim about how things at PCSP are and get his feedback about a possible land-based field program in Byam Martin Channel for spring 2010 and about recovery of the ice buoys next spring, if need be. I also asked about the people in the community that we have worked with in the past. He suggests we drive into town to see who is around. Walking out of the PCSP office we bump into the Chief Officer, Bob the pilot and Kenny the ship's storekeeper. They have been down at the RCMP station asking about what is required of the military people on the two Danish frigates that will be arriving tomorrow (for a search and rescue SAR exercise with the CCGS *Henry Larsen*). That is the reason why Humfrey could not purchase another day for science operations in this area – the SAR exercise was already planned.

Wed 2 Sep 2009

Spend the day in the community, talking to people and seeing people we have worked with in the past.

Thur 3 Sep 2009

Flight out at 06:30. Arrive in Ottawa at 17:00.

END OF REPORT