BEAUFORT REGIONAL ENVIRONMENTAL ASSESSMENT

Seasonal Changes in the Full-thickness Temperature of Multi-year Ice

Canada

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Final Progress Report for:

Seasonal Changes in the Full-thickness Temperature of Multi-year Ice

Objective of this Progress Report

Ice temperature is believed to provide the single best proxy for quantifying the strength of old ice over its full thickness [1]. This progress report documents the efforts that have been made over the past year, to more fully document old ice temperatures. Old ice includes both second-year ice and multi-year ice. *In situ* temperature chains provide the most common source of full thickness temperature measurements on multi-year ice more than 6m thick[1]. This is largely because extracting multi-year ice cores at depths below 6m is extremely challenging, requires specialized equipment and is labour intensive.

Summary of Past Project Results

Thousands of measurements of old ice floes across the Arctic have been used to produce updated distributions for the temperature, salinity and borehole strength of old ice [1]. In that study, two approaches were used to characterize properties over the full ice thickness (i.e. bulk ice properties) for every month of the year. The first approach averaged all measurements made on old ice in any given month, regardless of the sampling depth and geographic region. The second approach was based upon calculating the average based on measurements made in the same borehole. The sample population associated with the first approach is much larger than for the second approach (n = 4161 versus n = 938 depths respectively). Considering that multi-year ice with thicknesses of 20m or more has been shown to occur in all parts of the Arctic [2], using measurements made in the uppermost 6m of ice to evaluate the properties of old ice over its full thickness will have its limitations, as shown further below.

The temperature and borehole strength of old ice are highly dependent upon the time of year, but the mean salinity of old ice is not [1]. Figure 1 shows the general trends in the depth-averaged ice temperature and depth-averaged ice borehole strength. The trends are mirror images of one another. There is a general tendency for ice strength to decrease from winter to late summer, and increase again in the fall. The opposite trend is seen in ice temperature. Note however, that the temperature and strength of old ice is highly variable at any time of year. That is to be expected, given the highly non-uniform nature of multi-year ice and, to a lesser extent, second-year ice. In addition to natural variations due to differing ice properties, the figure also contains variations due to the (in)completeness of data from individual boreholes: most data were obtained in the uppermost several metres of multi-year ice, rather than through the full ice thickness. Therefore, data in the figure are biased towards colder, stronger ice (in winter) and warmer, weaker ice (in summer).

[1] For example, ~20% (n=849) of temperatures in the Johnston and Frederking compilation were obtained from extracted ice cores, whereas ~80% of the temperatures were obtained from temperature chains. Most of the extracted cores represent only the uppermost 6m of old ice.

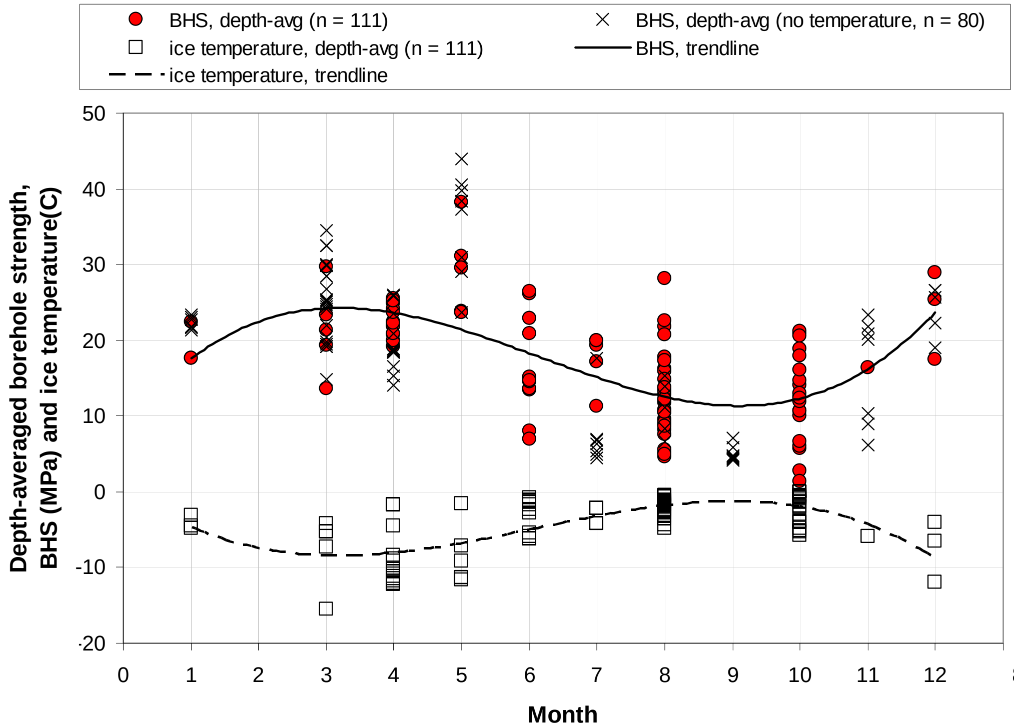

Figure 1 Depth-averages of borehole strength (BHS, circles & crosses) and ice temperature (squares) for individual boreholes, after [1]

Preliminary Project Results: Year 4

The temperature chain data used in this updated analysis were derived from two sources: the Cold Regions Engineering Laboratory (CRREL) and the National Research Council (NRC). Typically, sensors in the *in situ* temperature chains are positioned to capture the temperature of air, snow, ice and seawater. The spacing of individual sensors ranges from 0.10m to 0.50m. The sensor spacing is usually governed by the ice thickness and the duration for which the temperature chain is expected to operate (more sensors require greater battery capacity). Sensors should be more closely space towards the top and bottom ice surfaces, to confirm or deduce ice ablation rates. A sampling interval of once per hour provides a sufficiently detailed record of temperature changes occurring at the various ice depths. It is important that the sensors surrounded ice are differentiated from the sensors in air, snow and water since failing to do so will skew the data.

Results here expand upon the data examined in [1], which merged temperatures measured on partial/full thickness cores from old ice floes with the *in situ* temperatures from 9 old ice floes. Four of those floes were instrumented with Ice Mass Balance Buoys (IMBs) during the 1997/98 SHEBA program [3]. Based upon IMB data from the SHEBA CD-ROM, the analysis in [1] presented the monthly bulk ice temperature of different floes based upon the *in situ* temperatures recorded by each sensor at mid-month (either at early morning or midnight). In comparison, here, the mean monthly temperature for the instrumented floes is calculated using all of the *in situ* data logged by sensors (surrounded by ice), in any given month.[2]

[2] Comparison showed that the mid-month ice temperature is a reasonable representation of the monthly average obtained from the whole month of ice temperatures.

The floes in the data compilation in [1] included a mature multi-year ridge (3.1m thick), thick multi-year ice (3.1m thick), thin multi-year ice (0.9m thick) and undeformed multi-year ice (2.8m thick). This updated analysis includes only two floes from the 1997/98 SHEBA program (3.1m thick ice at 1997A and 8.0m unconsolidated ridge at 1997B). The analysis also includes 5 other old ice floes on which IMBs were installed (1993A, 2005F, 2007E, 2007H, and 2007J). All of the data for this updated analysis were downloaded from the CRREL website[3]. Many more floes have been equipped with IMBs, but those data have not been included in this analysis because (a) either the floes were thinner than 3m or (b) the data have not yet been posted. Most of the 7 floes that were included in this analysis were about 3m thick and were located in the Beaufort Sea or the Arctic Ocean (see Table 1). All 7 floes drifted far beyond their location after the equipment was deployed, as shown on the CRREL website. The IMB equipment ensemble provides information about the increase in ice thickness that occurs over IMBs operating period, as noted in the table.

Table 1. Temperature Chains that Extend through the Full Thickness of Old Ice Floes

Floe ID	Deployment location (latitude)	Period of Operation	Initial ice thickness (m)	Max ice thickness (m)
1993A*	Beaufort Sea (75°N)	Sep '93 – Dec '94	2.13	2.65
1997A*	Beaufort Sea (75°N)	Oct '97 – Sep '98	3.10	3.30
1997B*	Beaufort Sea (75°N)	Oct '97 – Sep '98	8.00	8.00
2005F*	Arctic Ocean (86°N)	Aug '05 – Mar '07	2.58	3.10
2007E*	Arctic Ocean (78°N)	Aug '07 – Oct '08	3.05	3.12
2007H*	Arctic Ocean (85°N)	Sep '07 – Mar '08	2.92	3.25
2007J*	Arctic Ocean (83°N)	Sep '07 – Oct '09	2.80	3.07
2008-R02	CAA (75°N)	May '08 – Jul '08	10.2	--
2008-R05	CAA (75°N)	May '08 – Aug '08	10.4	--
2009-L03	Eastern Arctic (78°N)	Aug '09 – Sep '09	12.4	--
2009-L08	Eastern Arctic (78°N)	Aug '09 – Aug '10	13.5**	--

* *CRREL data, see footnote below for link*
** *temperature chain extended to 11 m depth; ice from ~8m to 11m remained isothermal through winter [5]*

The four, very thick multi-year ice floes on which the author deployed temperature chains (R02, R05, L03, L08) are also included in the analysis. Three of these floes were sampled in the Canadian Arctic Archipelago (CAA) and one in the Canadian Eastern Arctic. All of these floes drifted far beyond their initial location. Ice thicknesses were measured along various transects using the drill-hole technique. Where possible, ice (core) temperatures, ice salinities and borehole strengths were also measured on the floes. The initial ice thickness on these four floes were obtained from drill-hole measurements (see Table

[3] see http://www.erdc.usace.army.mil/Media/FactSheets/FactSheetArticleView/tabid/9254/Article/553850/ice-mass-balance-imb-buoy-program.aspx

1), but instrumentation was not used to measure changes in ice thickness directly, largely because of the problems associated with conducting those kinds of measurements on such thick ice. It should be noted that the four floes included in Table 1 are the thickest multi-year floes on which temperature chains have been installed to date. The only other *in situ* temperatures of 10m thick multi-year ice were made in the southern Beaufort Sea in the spring of 1977 [4]. Although only a few temperature profiles are available from that study, they are in general agreement with *in situ* temperatures from the only other thick multi-year ice floe (10m+) for which *in situ* temperature profiles are available in spring (Floe L08).

January has been noted to produce the coldest temperature at any given ice depth (-34.3°C) in the Beaufort Sea [1]. The present analysis shows that clarification is needed: typically, January does produce the coldest monthly mean ice temperatures in the Arctic, but ice that is snow-free – which is usually the case for the crests of multi-year hummocks and sometimes level areas of multi-year floes – will have temperatures comparable to the coldest air temperatures (-40°C). Records from Floe L08 show that to be the case. The area where the temperature chain was installed on Floe L08 was snow-free, both when the instrumentation was deployed (August 2009) and when the floe was visited the following spring (May 2010). During the month of January[4], the top ice surface of Floe L08 experienced a minimum temperature of -39.4°C and a maximum temperature of -23.7°C. At the 2m depth, the minimum ice temperature was -20.1°C and the maximum temperature was -18.1°C. Clearly, the uppermost 2m of ice on Floe L08 was characterized by very cold temperatures in the deep of winter.

The temperature record of Floe L08 is interesting because data show that the bottom 3m of ice remained isothermal at -1.8°C throughout winter (8m to 11m depth). Drill-hole measurements revealed a large, sea-water filled cavity below a depth of 7.25m [5]. Due to the size of the cavity, the bottom ice of Floe L08 remained isothermal throughout winter. This is important because, including the isothermal layer of ice when calculating the bulk ice temperature produces a difference of 4°C: for the same period in January, the bulk ice temperature is -17.4°C (over 7.25m layer thickness) and -13.7°C (over the 11m thickness). Technically, the bulk ice temperature should be calculated over the full ice thickness, but when the floe exhibits an isothermal bottom layer in the deep of winter, it would be best to neglect the isothermal layer and calculate the bulk ice temperature over the cold ice portion only.

The bulk ice temperatures for the 11 instrumented old ice floes are listed in Table 2 and plotted in Figure 2, by month. In general, there is a systematic trend of increasing bulk ice temperature in spring and summer, and decreasing bulk ice temperature in fall and winter. The bulk ice temperature begins to increase in April, signaling the end of 'deep winter' (Jan, Feb, Mar). The highest bulk ice temperatures occur in July, August and September, hence those three months can be classified as 'summer'.

Note that, for any given month, the bulk ice temperature of the various old ice floes is highly variable. The variability is a function of elements such as the ice thickness, snow depth, air and water temperatures, drift speed of the floe and geographic location. Clearly, a single value for the bulk ice temperature cannot be used to describe old ice floes in the Arctic, for any given month. Rather than quoting the mean bulk ice temperature for each month, it would be preferable to have distributions of the bulk ice temperatures obtained from a wide number of floes, plotted by month.

[4] January data are available from 16 to 31 January 2009. Temperatures for the first two weeks of January were not logged, likely due to battery failure.

Table 2 Mean Temperature of Old Ice, by Month*

Month	Mean temp., all samples, after [1]	1993 A	1997 A	1997 B	2005 F	2007 E	2007 H	2007 J	2008-R02	2008-R05	2009-L03	2009-L08
Jan	-11.9	-8.8	-13.2	-6.3	-10.4	-10.6	-10.6	-9.3	--	--	--	-13.7
Feb	-14.3	-8.3	-12.2	-7.2	-10.5	-11.7	-10.5	-10.0	--	--	--	-13.9
Mar	-11.7	-10.2	-9.9	-7.3	-11.7	-11.6	--	-9.8	--	--	--	-14.6
Apr	-9.2	-8.0	-6.7	-6.6	-9.5	-9.3	--	-8.2	--	--	--	-11.4
May	-7.2	-5.2	-4.7	-5.8	-5.5	-6.0	--	-4.9	--	--	--	-7.1
Jun	-2.7	-2.5	-1.8	-3.1	-3.0	-2.7	--	-2.2	-6.3	-8.2	--	-4.6
Jul	-2.4	-1.5	-1.2	-2.3	-1.6	-1.2	--	-1.2	-4.1	-6.2	--	-2.2
Aug	-2.0	-0.9	--	-1.8	-1.2	-1.1	--	-1.0	--	-4.3	-2.9	-2.3
Sep	-1.9	-1.2	--	-1.7	-1.8	-2.0	-2.2	-1.3	--	--	-2.7	-2.5
Oct	-4.9	-3.0	-7.0	-2.8	-3.2	-2.5	-2.6	-1.8	--	--	--	-4.7
Nov	-6.6	-5.5	-7.4	-3.4	-7.2	-5.2	-5.4	-4.7	--	--	--	--
Dec	-12.0	-7.6	--	-5.0	-11.0	-7.3	-7.0	-6.8	--	--	--	--

* *temperatures quoted in °C*

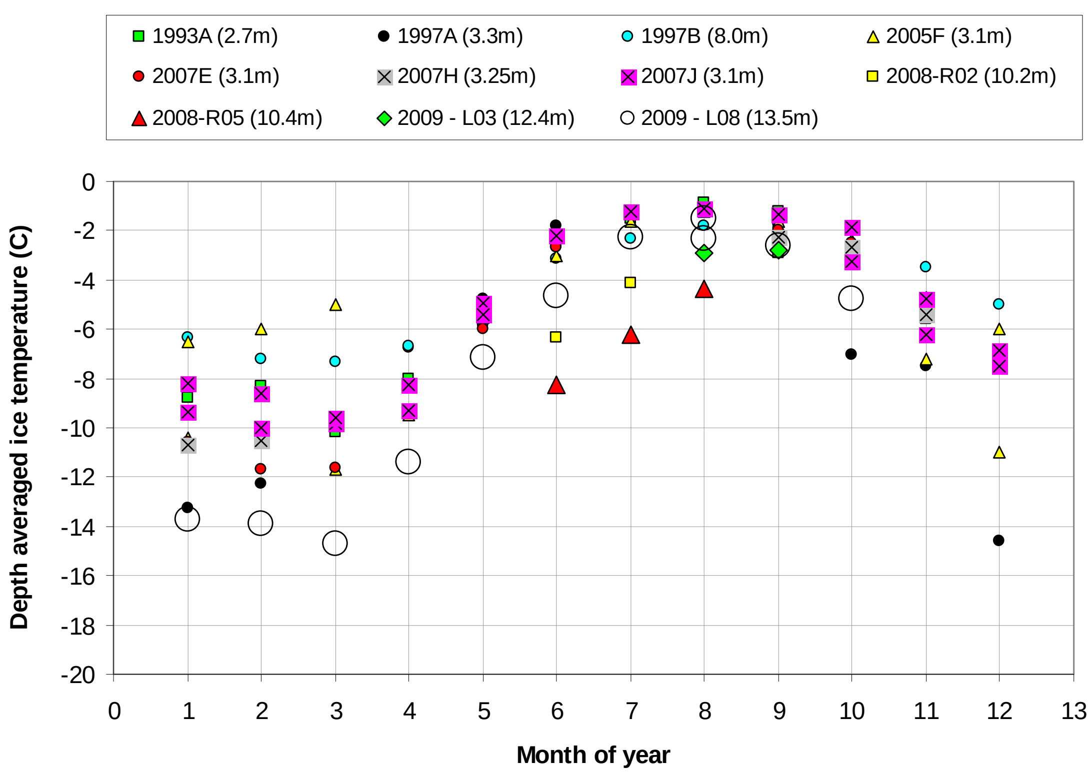

Figure 2 Seasonal change in bulk ice temperatures from instrumented old ice floes

Figure 3 compares the bulk ice temperatures for 11 instrumented old ice floes ('depth avg, select floes') to the results cited in [1] ('mean temp, all samples' and 'depth avg, cores from BHS studies'). The comparison is surprisingly good for most months. The exception being the sample population from the borehole strength studies ('depth avg, cores from BHS studies'), which produced unusually warm ice temperatures for January, February and March. This may have been because measurements were made on flooded multi-year sea ice during the drilling platform work in the CAA [6]. Note also that calculating the monthly mean from the entire sample population ('mean temp, all samples') produces colder temperatures from December to April than obtained the *in situ* temperatures from the 11 instrumented floes. Note that the three approaches produced similar mean, bulk ice temperatures for the months of May to October. That is reassuring if ice temperatures are to be used as a proxy for estimating the strength of old ice in summer/early fall – reassuring because most shipping activity in the Arctic occurs from July to October. That said, the objective of this study is to quantify the properties of extreme ice features – including cold, multi-year ice hummocks. Clearly, further research is needed to more fully describe the temperatures that can be expected in second-year and multi-year ice floes during the cold, winter months.

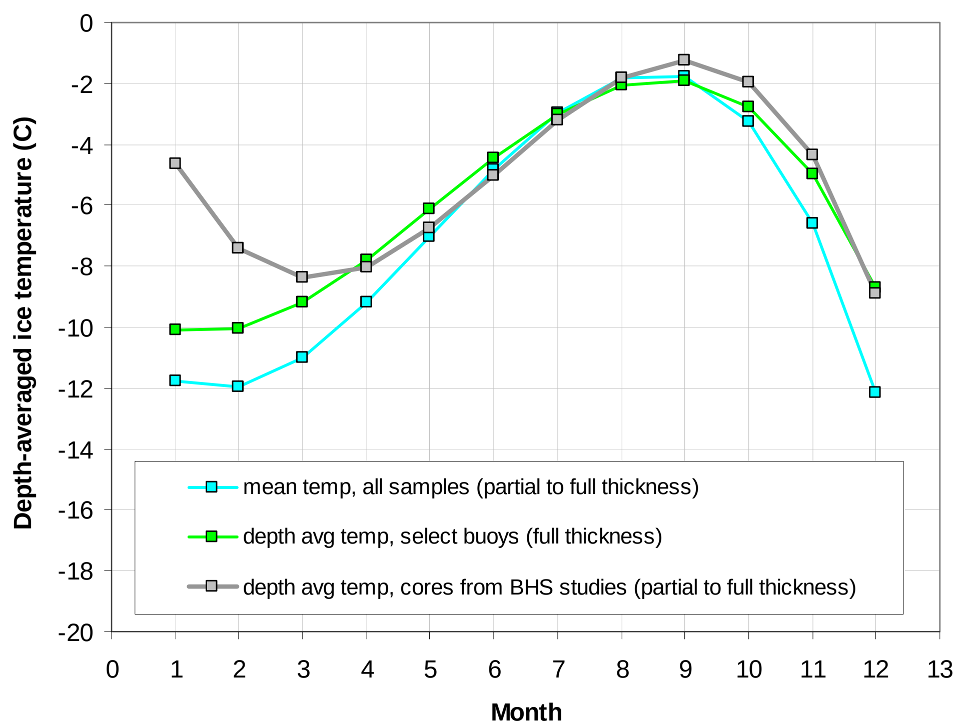

Figure 3 Comparison of results from three approaches for obtaining bulk ice temperatures

The results in Figure 2 and Figure 3 can be used to better interpret the relation between ice temperature and borehole strength. The relation is shown in Figure 4, based upon the borehole strengths from tests conducted at various depths in old ice and the corresponding temperatures that were measured at the various test depths (binned by 1°C increments). Data are shown for the range of ice temperatures from 0 to -20°C. Labels in the figure are used to indicate the number of strength tests that were included in each temperature bin. Considerably more strength tests have been made in warm multi-year ice than cold multi-year ice.

Despite the large standard deviations in the ice strength, Figure 4 shows a strong trend of increasing ice borehole strength with decreasing ice temperature. These results are consistent with a similar study [6], where ice temperature was shown to be the single largest factor influencing the borehole strength of multi-year ice. The inverse relation between ice strength and ice temperature is strongest in the temperature range from 0 to -12°C. It is less evident at temperatures colder than -12°C. That is largely because strength tests in cold ice are most often conducted near the top ice surface (30cm to 60cm). At those depths, fractures generated during the borehole indentation process easily propagate to the free surface, producing lower strengths. These so-called 'premature failures' [7] do characterize strength tests near the top ice surface, but not always. In fact, when the premature failures are removed from the strength data, there is solid evidence that the borehole strength continues increase over the ice temperature range -12 to -15°C [6].

The previous discussion confirmed that the temperature range from 0 to -20°C captures the bulk ice temperatures of old ice floes in all months – including the coldest months of winter. However, it was also shown that the top ice surface of snow-free multi-year ice can have temperatures approaching -40°C during the coldest months, and that temperatures at the 2m ice depth can approach -20°C. Figure 4 shows that too few strength tests have been conducted in multi-year ice at temperatures colder than about -15°C to draw meaningful conclusions about the strength of multi-year ice at those temperatures.

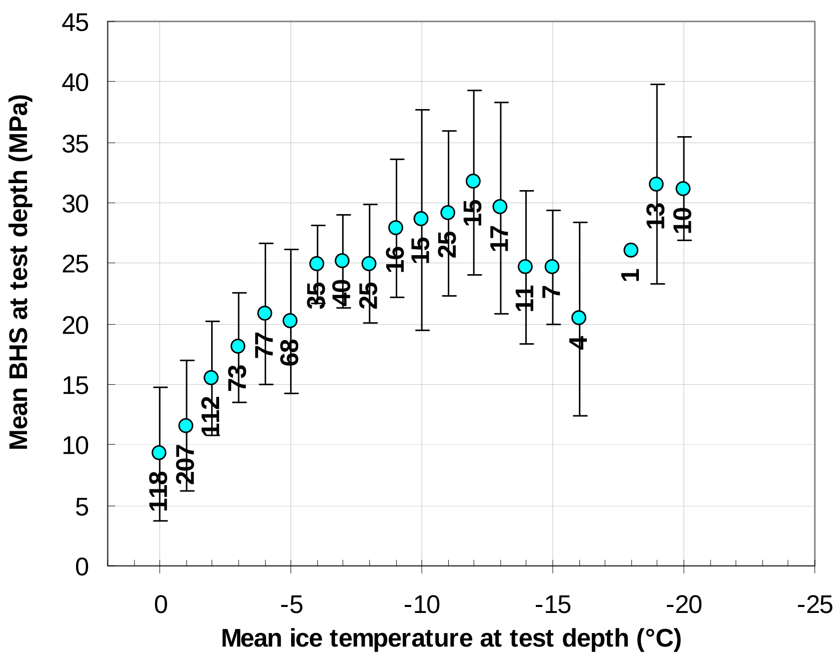

Figure 4 Mean and st. dev. of old ice borehole strength (BHS), binned by ice temperature, after [1]

Recommendations

It has been stated that the limited number of borehole strength tests conducted at ice temperatures colder than -15°C does not pose a serious impediment to quantifying strengths over the full thickness of ice [1]. That is correct. Yet, this preliminary investigation also showed data on the properties of cold, multi-year ice to be lacking. Too few data exist at present to satisfy the objective of this study: reducing uncertainties in the forces that cold, multi-year ice hummocks are capable of exerting on offshore structures. That is because first, only a limited number of strength measurements have been made on multi-year ice colder than about -15°C (uppermost layer of ice) and second, strength tests have been made through the full thickness of only one multi-year ice hummock. That hummock was sampled during Year-2 of this BREA project [8].

Suffice it to say that we have ‘scratched the surface’ of what we need to learn about multi-year ice hummocks. A larger sampling population is needed before reliable statistics can be developed for the temperature, salinity and strength of multi-year ice. The data that have been collected during this project, and will hopefully be collected in the future, also have direct bearing on determining whether climate-related effects are altering the properties of multi-year ice. Efforts in this important area of research should continue – to build upon advances made during this jointly sponsored BREA/PERD/Industry-funded study.

Acknowledgements

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R. Lanthier, C. Fillion and J. Amarualik deserve a huge thank you for participating in the spring 2012 program: through their skillful operation, the properties of a multi-year hummock were obtained, for the first time, from crest to keel. The experience and dedication of PCSP's M. Kristjanson and T. McCagherty were essential for safely transporting personnel and equipment offshore. Similarly, the work could not have been done without the Bell 206L helicopter pilot, G. Hartery – who had the skill to deliver on the program – and the Twin Otter pilots.

C. Fillion, K. Brett, T. Retieffe and J. Kuptana were responsible for delivering results during the 2013 program and – as importantly – for maintaining their enthusiasm and composure as the program took a turn for the worse. University of Manitoba's assistance during the 2013 field program is sincerely appreciated. In particular, Dr. K. Hochheim was instrumental in obtaining the scientific permit, sharing satellite imagery and permitting NRC to deploy satellite tracking beacons meant for his own work. Canadian Ice Service, in particular T. Wohlleben, provided essential support via satellite imagery and ice information for the 2012 and 2013 programs. A very special thanks to E. Hudson, Environment Canada, for extending the Greater Forecast Area (GFA) to include offshore Banks Island during our program.

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