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Quantifying the Properties of Hummocked Multi-year Ice: Two Measurement Seasons

M. Johnston
Ocean, Coastal and River Engineering
National Research Council of Canada
Montreal Road
Ottawa, Ontario K1A 0R6

FINAL REPORT

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Abstract

The purpose of this four-year research project, which spans from March 2011 to March 2015, is to document the thickness and strength of hummocked multi-year ice. The first two years of the project are reported upon here. Year 1 involved designing and manufacturing customized equipment to measure the temperature, salinity and strength of 12m thick multi-year ice and using the equipment to sample a multi-year ice hummock from crest to keel. The first season of measurements was conducted in the spring 2012, on landfast multi-year ice 120km northwest of Resolute, Nunavut. Year 2 of the program was taken to plan, prepare and conduct a field program on drifting multi-year ice in the Beaufort Sea in the spring of 2013. Background is given about the three main options for accessing multi-year ice (ship-based access, community-based access and remote camps) in order to more fully appreciate the challenges and data collected during the 2012 and 2013 field seasons. Outcomes from the 2012 field program, conducted from 3 May to 20 May from Resolute, Nunavut, include: (1) field testing equipment by collecting data on the thickness, temperature and borehole strength of 1.75m thick first-year ice, (2) measuring the thicknesses at 19 holes on a hummocked multi-year ice floe that had an average thickness of 8.6 ± 1.0m, (3) measuring the temperature, salinity and strength through its full thickness of 10.8m thick ice on the shoulder of a multi-year ice hummock, (4) measuring the partial temperature and salinity profile of a hummock crest and conducting borehole strength tests through the full thickness of the 12.4m thick ice. The 2013 field program, conducted from 18 March to 7 April from Sachs Harbour, NWT, was prematurely terminated due to health and safety concerns. As a result, the program's primary objective – measuring the strength of hummocked multi-year ice – could not be met. Nevertheless, outcomes from the 2013 field program include (1) equipment being field-tested on 1.65m thick cold, first-year ice to collect data on its temperature, salinity and borehole strength, (2) satellite tracking beacons were deployed on four, hummocked multi-year ice floes, (3) the two floes on which at least ten thickness measurements were made had an average thickness of 2.7 ± 2.2m (first-year ice) and 5.6 ± 2.5m (multi-year ice) and (4) photographic documentation of numerous substantial, deformed multi-year ice floes 150km west of Sachs Harbour. The drift trajectories of the two, hummocked multi-year ice floes on which drift trajectories are available for a period of five months clearly illustrate that some of the more significant floes encountered during the 2013 field study pose a very real hazard for structures in the southern Beaufort Sea, including the relatively near-shore Amauligak site.

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1.0 Introduction

The purpose of this four-year research project, which spans from March 2011 to March 2015, is to document the thickness and strength of hummocked multi-year ice. Funding for the project comes from the Program of Energy Research and Development (PERD), Aboriginal Affairs and Northern Development Canada (AANDC) through the Beaufort Regional Environmental Assessment (BREA) program and Industry. The BREA funding is directed towards the collaborative efforts of the NRC, University of Manitoba and York University to better quantify the engineering properties of extreme ice features and validation of those features in satellite imagery, on-ice electromagnetic surveys (by University of Manitoba) and airborne electromagnetic induction (EMI) soundings (by York University).

The first two years of the project are reported upon here. Year 1 involved designing and manufacturing customized equipment to measure the temperature, salinity and strength of 12m thick multi-year ice and then traveling to the Arctic to prove that the equipment could be used to sample a multi-year ice hummock from crest to keel, successfully. That first season of measurements was conducted in the spring 2012, on landfast multi-year ice 120km northwest of Resolute, Nunavut. Year 2 of the program was taken to plan, prepare and conduct a field program on drifting multi-year ice in the Beaufort Sea in the spring of 2013. Thus far, Year 3 of the project has involved providing a state-of-the-art review of the borehole strength of multi-year ice (Johnston, 2014) and exploring what will be needed to safely conduct a spring 2014 program from Sachs Harbour or Resolute.

This report is a companion report to “Probing the Depths of Hummocked Multi-year Ice in the Beaufort Sea” (Johnston, 2013) that was issued to the Oil and Gas Industry. The companion report describes only Year-2 of the study, since Industry did not contribute to Year-1. That report has been classified as ‘restricted confidential’, as requested by the Client.

2.0 Summary of Results

The 2012 field program was conducted from 3 May to 20 May 2012. The members of the field team were M. Johnston, R. Lanthier, C. Fillion and J. Amarualik. The total cost of the 2012 program was $350,000, including the expense of designing and fabricating key pieces of equipment to probe the depths of multi-year ice. Background information about preparations for the 2012 field program are included in Appendix A. Results from the field program can be summarized as follows:

- Equipment was tested on level first-year ice to ensure that it functioned properly, prior to transporting it offshore. Tests provided information about the thickness, temperature and borehole strength of cold, first-year ice .
- Snow thickness, ice thickness and freeboard were measured at 19 holes on a hummocked multi-year ice floe by mechanically drilling or steaming through the full thickness of ice.
- Temperature, salinity and strength of 10.8m thick ice on the shoulder of a multi-year hummock was measured through its full thickness.
- The temperature and salinity of a 12.4m thick multi-year hummock crest was measured to a depth of 5m; strength tests were conducted through the full thickness of the 12.4m thick borehole.
- The new equipment worked flawlessly proving, for the first time, that measurements on a thick multi-year ice hummock can be measured from crest to keel.

The 2013 field program was conducted from 18 March to 7 April[1] for a cost of approximately $1M. The field program was prematurely terminated due to helicopter-related safety concerns, as discussed in Appendix A. Although the program's primary objective – measuring the strength of hummocked multi-year ice – could not be met, the four flights offshore provided important information about ice conditions in the Beaufort Sea. Results of the 2013 field program can be summarized as follows:

- the temperature, salinity and strength of cold, level, first-year ice was measured
- a total of 39 drill hole and steam hole thickness measurements were made during the program
- the two floes on which at least ten thickness measurements were made had an average thickness and standard deviation of 2.7 ± 2.2m (first-year ice) and 5.6 ± 2.5m (multi-year ice)
- tracking beacons were deployed on four old ice floes
- very substantial, deformed multi-year ice floes were identified 150km from Sachs Harbour

[1] Although the helicopter operations terminated on 28 March, it was not possible for the 5 members of the NRC field team to depart earlier than planned because Aklak Air could not provide a DC-3 prior to the scheduled date.

3.0 Background

On 12 April 1986, the most significant impact yet documented on a full-scale structure occurred when an 8 to 12m thick multi-year ice hummock advanced towards the Molikpaq at the Amauligak I-65 site in the southern Beaufort Sea. The event generated high enough loads and structural vibrations to warrant a full-scale evacuation of the structure, essential personnel excepted. Our knowledge of multi-year ice has improved somewhat since then, but not enough to settle questions about the magnitude of ice forces generated by the April 12 event (Frederking and Sudom, 2006) and, more importantly, the forces that multi-year ice in excess of 12m thick can exert on offshore structures. In the engineering community, hummocked multi-year ice is still considered to be the most hazardous type of sea ice in the Arctic and the least known, in terms of its thickness and strength. Realizing that these questions likely will not be addressed by obtaining more full-scale data – until another exploration or production structure is deployed in the Arctic, that is – this research is meant to provide new information about the properties of thick multi-year ice needed to engineer well-designed structures for the Arctic offshore environment.

The past ten years of field programs on multi-year ice have made significant contributions, as discussed in Johnston (2014a), but have also raised very important questions about the consolidation of multi-year ice and its keel strength, both of which relate to calculating ice loads on offshore structures. Quantifying the strength of consolidated, hummocked multi-year ice is essential for understanding and interpreting the forces generated on the Molikpaq during the widely discussed “April 12 event” and it is a fundamental component of using equations such as those in ISO 19906 (ISO, 2010) to calculate ice forces. The data collected during this project are relevant to the next round of improvements to ISO19906 which, in turn, is necessary for ensuring that offshore structures are well-engineered for the environment in which they operate.

4.0 Logistics of Accessing Multi-year ice in the Beaufort Sea

This section and the material in Appendix A discuss some of the complexities involved in sampling multi-year ice. When considered from this perspective, it is not surprising that so little is known about the engineering properties of multi-year ice. That is not because multi-year ice is rare, since multi-year floes can be easily found throughout the Arctic, rather it relates to the difficulty of accessing multi-year ice and measuring its properties at depths below the uppermost few metres. Communities in the Arctic are few (Figure 1), infrastructure is limited and weather can be problematic – all of which make for costly operations. The three main options for accessing multi-year ice are discussed below. It should be noted that, regardless of which option is selected, the objectives of this research project require safely transporting personnel and nearly 1500kg of equipment to thick, heavily deformed multi-year ice floes. In reviewing the three options below, the reader should bear in mind that compromises will have to be made, in the interest of striking a balance between the program objectives, the proximity of multi-year ice, the quality of the floes sampled and the cost of conducting the work. That said, safety is a key factor in any operation.

Ship-based field programs: Ships provide a reasonably reliable means of accessing multi-year ice but only during the shipping season. Ships venture into the Arctic in mid-July (at the earliest) and depart by mid-November (at the latest), which poses two disadvantages for accessing multi-year ice from a ship: (1) measurements will be biased because the ice may have undergone extensive degradation during the summer months and (2) since most icebreaking ships prefer not to operate in high concentrations of multi-year ice, operations may be limited to isolated floes drifting at the margin of the polar pack. As a result, ship-based programs do not generally capture information about the most hazardous multi-year ice floes. The relatively limited shipping season also makes for fierce competition onboard Canadian Coast Guard (CCGS) ships – particularly when the program requires the Crew's assistance (i.e. crane operations, helicopter operations, etc.). Chartering a ship for the sole purpose of conducting a field program is an option – but a very expensive one, since a CCGS icebreaker can cost upwards of $100,000 per day. Transferring personnel and equipment to the ice can be done directly from the ship, sometimes with deleterious results (Johnston, 2011a), or with the ship's helicopter. When accessing the floe directly from the ship, on-ice measurements likely will be relegated to the perimeter of the floe, since traveling to the interior of a ponded, multi-year ice floe by snow machine is not recommended, for safety reasons. A helicopter may be the only safe means of conducting measurements towards the interior of the floe – where the ice may be thicker and, therefore colder.

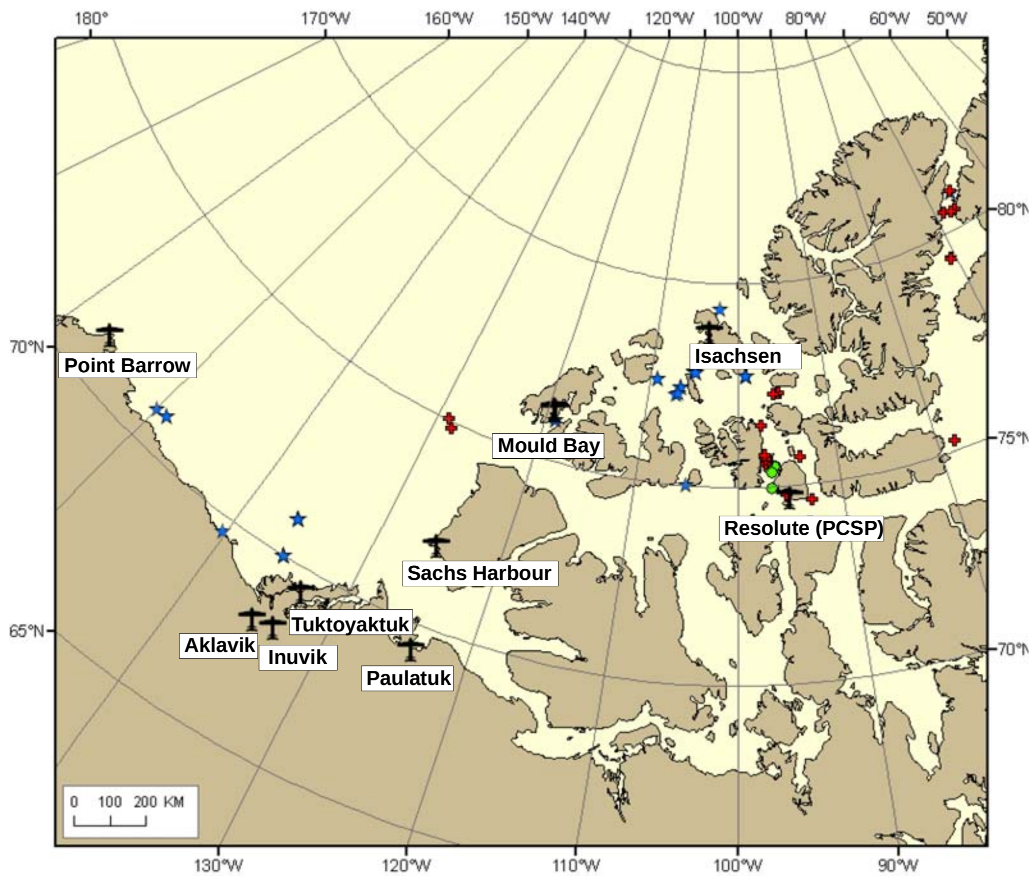

Figure 1 Communities and weather stations that can be used as a base for sampling multi-year ice. Mould Bay and Isachsen are formerly manned weather stations having some infrastructure. Also shown are strength measurements made by author on multi-year ice floes (red crosses), second-year ice floes (green circles) and by others on old ice floes (blue stars).

Community-based field programs: Although multi-year ice is often within reach of many Arctic communities in winter, the polar night and extreme cold prevent conducting measurements at that time. Accessing multi-year ice from communities in late summer can also be problematic because of weather (cloud/fog related to open-water) and ice conditions (generally, multi-year ice in the Beaufort Sea retreats far north in the summer). As a result, community-based field programs are most often conducted in spring. An investigation of the distance of multi-year ice from several communities along the Beaufort Sea rim was used to determine the most reliable location for conducting a field program on multi-year ice[2]. Regional Ice Charts issued by the Canadian Ice Service over a six-year period, from March to August, were used to obtain the distance of multi-year ice concentrations (1/10ths or greater), from different communities and weather stations (Figure 2). Each location showed a significant amount of variability; depending upon the particular year, multi-year ice could be more than 150km offshore, making measurements on multi-year ice extremely difficult, as illustrated later in this report. The unmanned weather station at Mould Bay, NWT is the most reliable location for encountering relatively high concentrations of multi-year ice within 150km of shore. Sachs Harbour is a relatively reliable site for accessing multi-year ice, provided the field program is conducted in spring. Given the 150km range of the helicopter, working from Point Barrow, Alaska offers marginal access to multi-year ice in most years, over the six year period examined; conditions are not much improved, even in spring. Tuktoyaktuk and Inuvik, NWT were the least attractive communities from which to sample multi-year ice, over the six year period examined.

The logistics of sampling landfast multi-year ice is much more straightforward than drifting multi-year ice. When the ice is landfast, a fixed wing aircraft (Twin Otter) can be used to transport the equipment to level, thick first-year ice in the vicinity of the multi-year floe of interest, and then a snow machine or helicopter can be used to transfer the equipment from the flat ice to the deformed floe of interest. That approach was used in the spring of 2010 to sample landfast multi-year ice in the central Canadian Arctic (Johnston, 2011b) and in the spring of 2012 to sample hummocked multi-year ice, as described later in this report. This option is not recommended for the Beaufort Sea because dynamic, snow covered ice makes it extremely difficult to determine where the ice is thick enough, over a sufficient area, to make a safe landing strip. Twin Otters cannot land directly on multi-year ice because even small undulations on the ice surface can damage landing gear. This is not a problem for helicopters because (a) they do not require a strip of ice to land on and (b) the helicopter skid gear can be used to gauge whether the ice is of adequate thickness, after which a person can exit the helicopter and drill through the ice, before shutting down the helicopter. A helicopter was used to access drifting, multi-year ice from Sachs Harbour in spring 2013, since that was the safest, most viable means of accessing floes offshore.

Transporting personnel and equipment to multi-year ice becomes much more complicated if refueling operations are not permitted on the ice, as is normally specified in the scientific permit (due to environmental concerns). Having a fuel cache in the vicinity of a sampling area allows the helicopter to refuel prior to making the return trip, as was done during the spring 2012 program. Refueling the helicopter prior to returning to base camp provides added security should adverse weather be encountered on the return route, forcing a deviation from the flight path or a place of refuge to be found. When the sampling area is 150km offshore in the Arctic Basin – and re-fuelling is not possible – it is imperative that enough fuel be taken for the outbound and return trips, along with the standard amount of reserve fuel. Carrying such a large quantity of fuel makes it extremely challenging to transport enough

[2] The preliminary study was conducted in preparation for a meeting with Industry to examine the pros and cons of ship-based vs. land-based field programs, November 2008.

personnel and equipment to conduct meaningful measurements on thick, multi-year ice with one helicopter – even one as large as a Bell 212 (useful load: 4000lbs (1814kg) fuel, personnel and cargo). Experience from the 2013 field program showed that, for logistics and safety reasons, two helicopters (flying in tandem) should be used while operating in the Beaufort Sea. Specific attention should also be paid to ensure that the survival gear is appropriate for the given conditions.

Remote ice camps: The third – and most expensive – option is to establish a remote camp in a location that provides excellent and reliable access to the ice. Possible options for sampling multi-year ice from remote camps include Mould Bay and Isachsen (Figure 1). Since both locations are formerly manned weather stations, they have limited infrastructure for camping and gravel runways needed to airlift enough gear to establish camp. The cost of operating from a remote camp depends on its size and the number (and type) of aircraft which, in turn, determines the amount of fuel required. Barging is the cheapest method of transporting fuel to camp, but barging is not an option for locations north of Sachs Harbour, so the fuel would need to be transported by air – at roughly two to three times the cost. Scientific permits would have to be obtained for temporary storage of fuel, accessing water sources for personal use, refuse disposal and potential wildlife disturbance. On-ice camps were once an option, and still are in some parts of the Arctic, but the permits needed to establish an on-ice camp in the Canadian Arctic pose a significant impediment to this option. In any event, the unpredictable dynamics in the Beaufort Sea make an on-ice camp an unreliable and unsafe option for accessing multi-year ice.

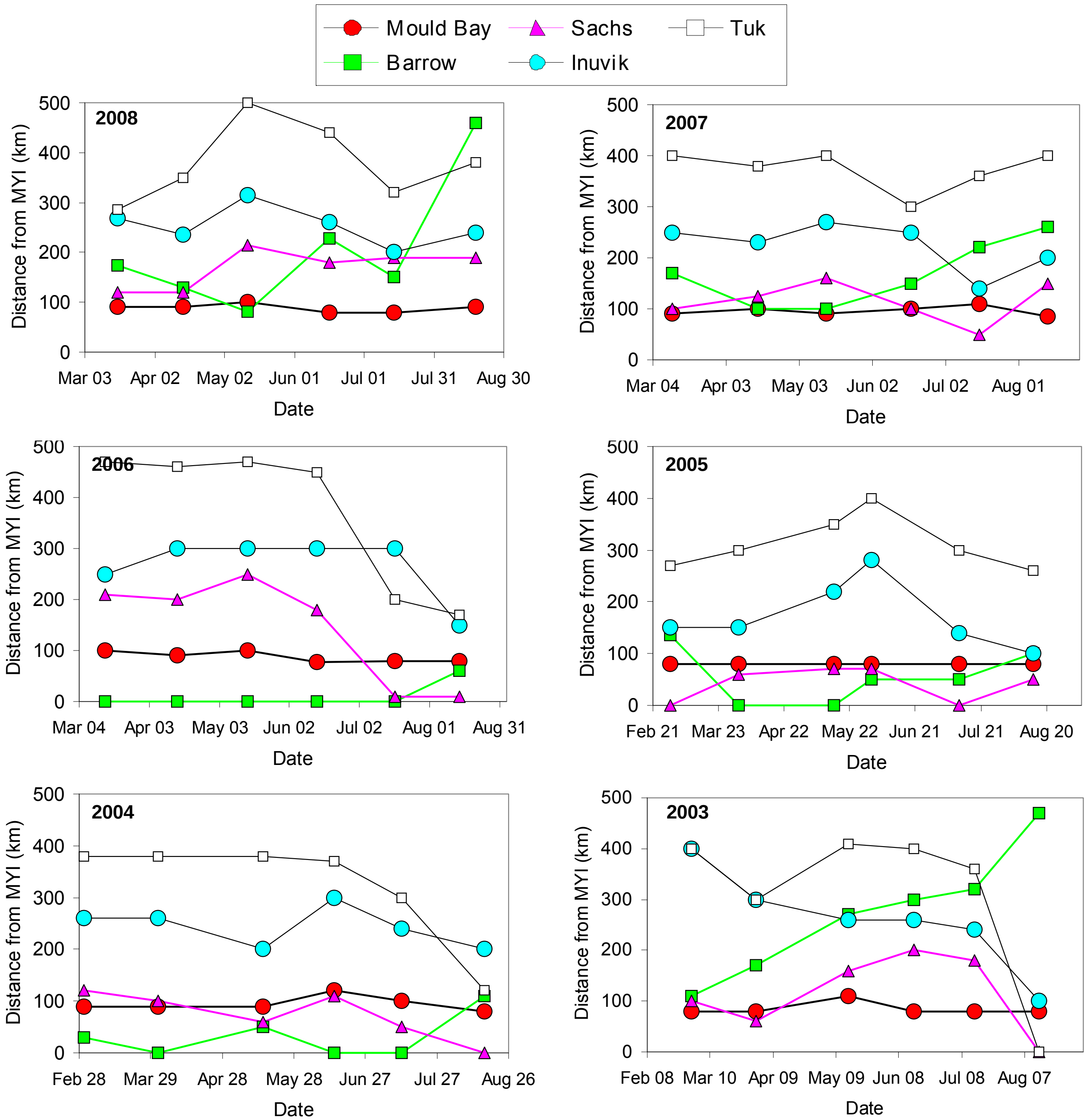

Figure 2 Distance of five communities from multi-year ice in the Beaufort Sea from 2003 to 2008.

5.0 Data Collected during 2012 Program

The objective of the 2012 field program was to test the newly developed equipment under Arctic conditions, make the necessary modifications to the equipment and use it to sample a single hummocked multi-year ice floe as a 'proof of concept'. The field team arrived in Resolute on 3 May, under clear skies. The first week of the program was set aside to unpack the equipment, test it on first-year ice near Resolute and arrange logistics to transport it offshore. Good weather held for about a week, permitting the equipment to be tested on first-year ice before the helicopter was scheduled to arrive on 7 May. Although the weather was favorable in Resolute, poor weather had caused helicopter-based science programs elsewhere to fall behind schedule. As a result, the helicopter arrived in Resolute several days late and, with it, came weather problems. Almost every one of the four trips made offshore from 10 to 16 May involved either a late (morning or afternoon) departure from Resolute, or a premature return. In many cases, the field team was grounded because the low hanging cloud around Resolute did not permit a safe departure, although the weather further offshore was favorable. Figure 3 shows the hourly air temperatures and wind chill during the three-week field program.

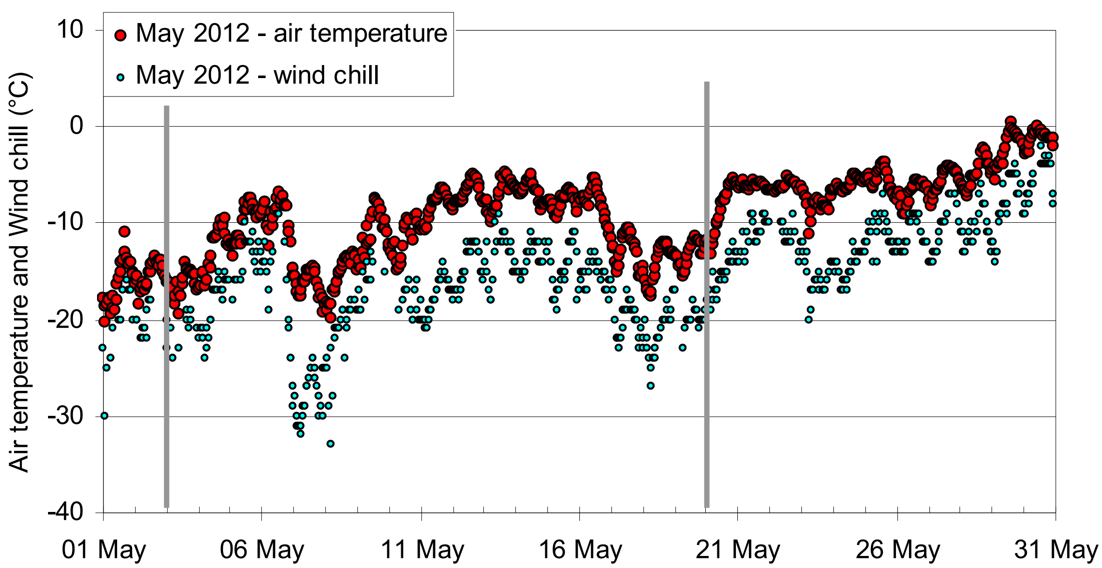

Figure 3 Hourly air temperatures at the Resolute airport during the 3 to 20 May 2012 field program (courtesy of Environment Canada). Grey bars show the start/end date of the field program.

5.1 Testing Equipment on First-year ice

It was initially thought that the equipment could be tested on level first-year ice in Allen Bay – just 1km from Resolute, which normally is possible – but prior to arriving in the field, it was learned that the moratorium on science activities in Allen Bay prevented sampling ice in that area. The only viable alternative (not requiring helicopter support) was to travel to first-year ice in Becher Bay, 20km west of Resolute. Two snow machines and two komatiks were used to transport equipment and personnel to Becher Bay on 5 and 6 May. The trip took about 2 hours each way and, as such, a considerable amount of time was spent traveling to and from the site. More importantly, the two hour ride over drifted, hard-packed snow caused excessive wear on the equipment and customized shipping crates: wires on sensitive instruments frayed or came loose and customized shipping crates were damaged. The trips were necessary, but the long journeys proved troublesome when later sampling multi-year ice offshore: quite likely, the trips explain why one of the LVDTs in the borehole indentor malfunctioned during the strength tests on multi-year ice.

The first trip to Becher Bay was made on 5 May, in clear weather. The air temperature was about -6°C, which is unusually warm for Resolute in early May. Measurement were made on level first-year ice 1.75m thick, with a 14cm thick snow cover and an ice freeboard of 7cm. The new 7" (17.8cm) diameter core barrel was used to extract cores from the full thickness of ice. The temperature of the cores was measured, after which the new borehole indentor system was used to conduct strength tests in the borehole, at 30cm depth intervals. After coring operations and strength measurements were complete, a new steam machine was used to measure the ice thickness at several holes and compare the measurements to ice thicknesses from the drill hole technique (Appendix B). On 6 May, the snow machines and sleds were loaded in preparation for the second trip to Becher Bay. The day brought overcast skies and poor visibility in the morning, with conditions deteriorating to blowing snow by afternoon. Upon reaching the same area of ice in Becher Bay, equipment was unpacked, as efforts were directed towards clearing an area for the drill frame. The snow cover in this area of ice was considerably thicker (30cm vs. 14cm the previous day) so, naturally, more time was needed to clear an area for the drill frame. After the drill frame had been erected, a 6.25" (15.9cm) diameter auger was used to prepare a borehole for strength testing (Figure 4). Note that the 5 May borehole was made with a 7" (17.8cm) diameter coring device and the 6 May borehole was made with a 6.25" (15.9cm) diameter auger in order to evaluate the effect that borehole preparation (and diameter) had on strength tests.

Figure 4 Testing equipment on first-year ice in Becher Bay, near Resolute.

The vertical profiles in Figure 5 show that the full thickness of ice in Becher Bay was characterized by a linear temperature profile: the ice was coldest at the top ice surface (-9.9°C) and warmest at the bottom ice surface (-2.0°C). Results from the borehole strength tests showed a consistent trend of decreasing strength[3] with increasing temperature. The ice was strongest at the top ice surface (25.2 and 25.9MPa) and weakest at the bottom ice surface (14.4 to 15.2MPa), although 'weak' is used here in a relative sense. The good agreement in the vertical strength profiles from the two boreholes shows that sufficiently smooth-walled boreholes can be prepared with either a coring device or an auger. Results show that the technique that is used to prepare the borehole has little effect on the strength tests, provided the borehole is made with sufficiently sharp cutting teeth and the proper engine rpm is used. The marginal variations in strength observed at equivalent depths in different boreholes demonstrates how uniform the strength of first-year ice can be.

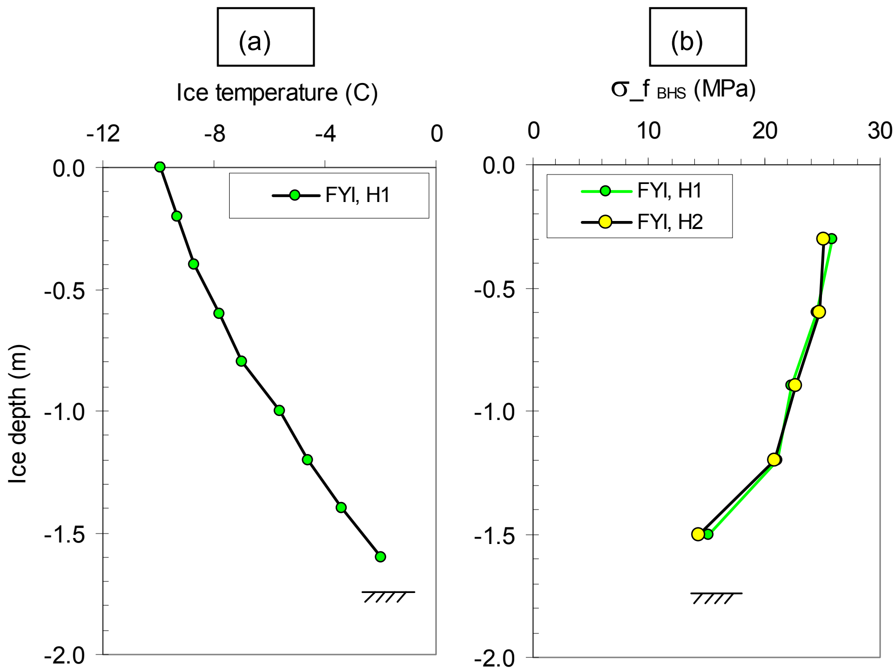

Figure 5 Vertical profiles of (a) temperature and (b) ice failure stress, σ_f_{BHS} for boreholes made on level first-year ice. Measurements referenced to the top surface of ice. Cross hatches show ice thickness.

5.2 Nanook Floe (75°46'N, 97°16'W)

The helicopter arrived in Resolute on the evening of 9 May and the next morning good weather permitted the first flight offshore. The field team departed Resolute at 09:00 hrs, having provided the PCSP office, helicopter pilot and Twin Otter pilots with the coordinates of several floes that had been identified from satellite imagery. The approach that PCSP suggested for delivering personnel and equipment to multi-year ice, 120km distant from Resolute, required Twin Otter and helicopter support. Most of the 2000lbs (1000kg) of equipment would be transported by Twin Otter, along with the helicopter engineer, allowing the aircraft to remain within its 2100lbs limit. A Bell 206L helicopter would transport the field team (4 persons) and remaining equipment to the ice. Four trips were made offshore from 10 to 16 May. On the first trip, personnel were transported to a sufficiently thick, hummocked floe of interest embedded in the

[3] Appendix B describes the procedure for determining the ice failure stress (σ_f_{BHS}).

landfast ice of Queens Channel (75°46'N, 97°16'W). The 2km diameter 'Nanook' floe was contained within an aggregate floe of first-year/second-year ice, about 5km in diameter overall. Since the Nanook floe contained several prominent hummocks, a considerable amount of information could be obtained without taking the time (and money) to ferry equipment to other floes. In addition, repeat visits could be made to the floe without too much difficulty because it was only 120km from Resolute. Incidentally, the floe was called 'Nanook' not because of its size, but because the number of bear tracks on the ice increased each time the floe was visited.

After arriving on the floe, a few thickness measurements were made to confirm that the hummocked ice was of adequate thickness to meet the project objectives. Then, PCSP in Resolute was radioed to request the Twin Otter deliver the remaining equipment to the flat area of ice (less than 1 km from the floe's edge) that had been suggested as a landing site from satellite imagery. At 10:45 hrs, the Twin Otter could be heard circling the area, looking for flat ice on which to land. The Twin Otter pilots examined the site that had been pre-determined from satellite imagery, found it too rough, and instead delivered the equipment to the nearest flat ice deemed acceptable: level first-year ice off Black Point, about 11km southwest of the Nanook floe (Figure 6). At 11:00 hrs, the helicopter and one member of the field team flew to where the Twin Otter had landed to begin slinging the equipment to the Nanook floe (Figure 7). Three trips were needed to sling the equipment from the flat ice to the Nanook floe. By 12:15 hrs, all of the equipment had been delivered to the floe (Figure 8), after which the helicopter pilot and one member of the field team flew to the fuel cache at Polar Bear Pass to replenish the helicopter fuel (Figure 6). The helicopter returned to the Nanook floe at 13:30 hrs. Meanwhile, the three members of the field team spent several hours distributing flags along a thickness transect and preparing a site for coring and strength tests.

Ice thicknesses along the flagged transect were not actually measured until the fourth trip to the floe, but that information is discussed first, to describe the overall characteristics of the Nanook floe. A total of 19 thicknesses were measured at 10m intervals, along a 200m long thickness transect (Figure 9). Working in teams of two, field personnel used the drill hole technique and the steam machine to measure snow and ice thicknesses at each flag. Thicknesses along the transect ranged from 4.4 to 12.7m, for an average ice thickness of 8.6 ± 1.0m. The average snow depth along the transect was 0.40 ± 0.26m. Aerial photographs, along with supporting information about the ice thickness, suggest that the transect spanned two, distinctly different multi-year ice floes: ice at the far end of the transect was considerably thicker (8 to 13m) than ice at the near end of the transect (4 to 5m), as shown in Figure 9. The profile view of snow and ice thicknesses along the transect is presented in Figure 10.

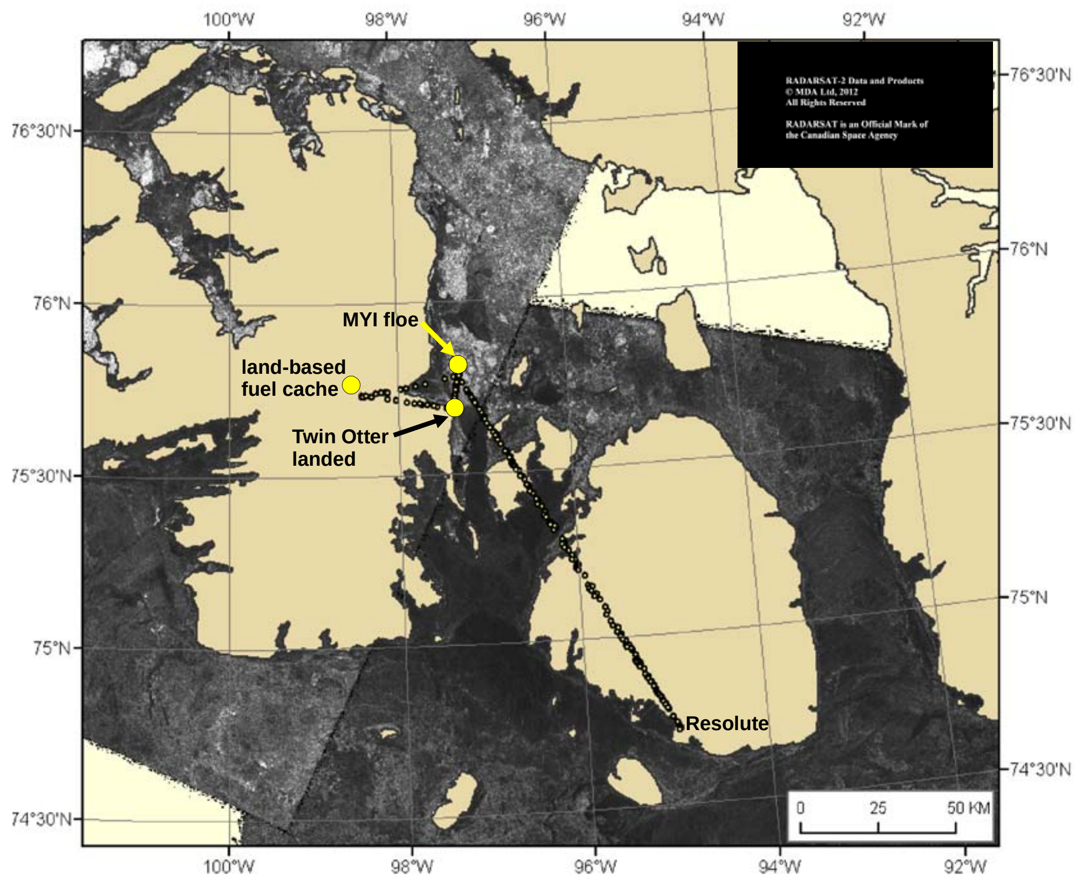

Figure 6 Flight path taken on 10 May from (a) Resolute to multi-year floe, (b) ice where Twin Otter deposited equipment and (c) fuel cache visited after 3 trips of ferrying equipment from flat ice.

Figure 7 Twin Otter on level, first-year ice waiting for helicopter to sling the equipment to Nanook floe.

Figure 8 Two bundles of equipment delivered to Nanook floe from flat ice.

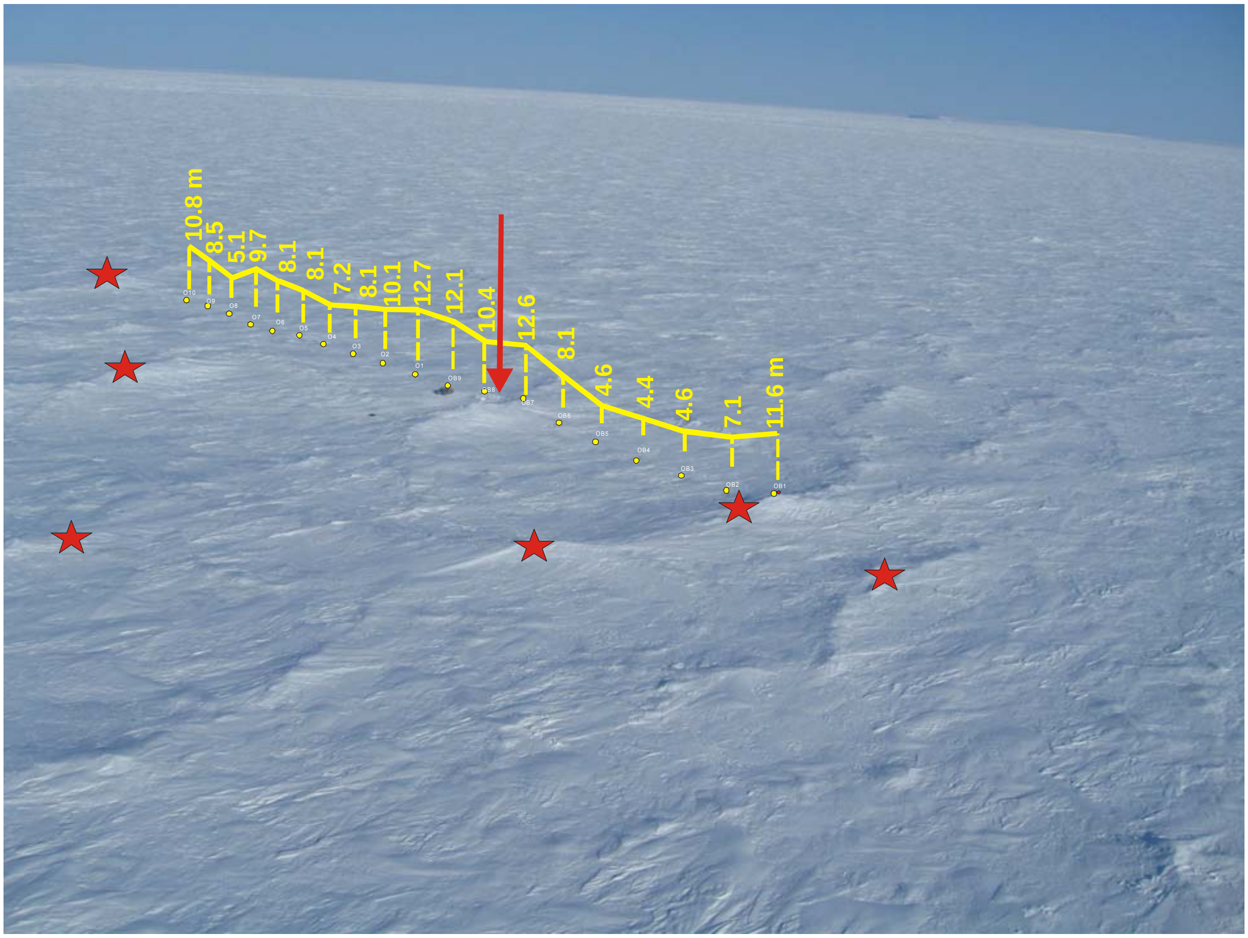

Figure 9 Ice thickness transect made on the Nanook floe.
Vertical bars show variations in thickness across the floe. The red arrow shows the hummock that was sampled. Stars indicate other hummocks that could have been sampled, had time permitted.

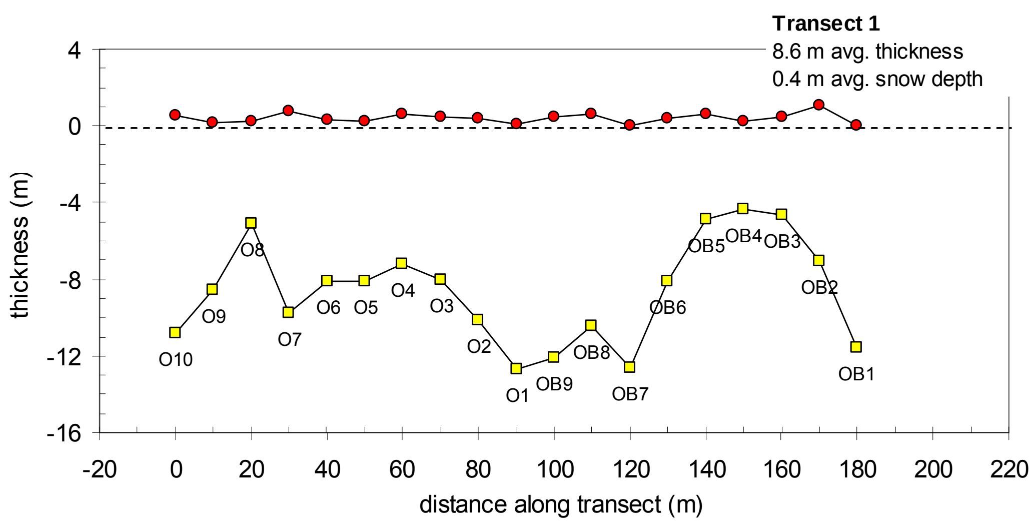

Figure 10 Ice thicknesses and snow depths along the Nanook floe transect.

The shoulder of the 3m high hummock, where the ice sloped down to a level area, was the area chosen for the first series of borehole strength tests. Nearly two hours were spent clearing the extremely hard-packed snow (60cm thick) from a large enough area to secure the drill frame to the top ice surface and operate it comfortably (1.5m by 1.5m). Leveling the ice surface was not required because the drill frame had been designed to be installed on a sloping surface. By 14:30 hrs, the drill frame had been erected and the field team began making a borehole with the 6.25" (15.9cm) auger, as shown in Figure 11. It took just under one hour to auger a borehole through the 10.8m thick ice (H1), where the ice freeboard was 0.92m. That accomplished, the next hour was spent performing borehole strength tests through the full thickness of ice. At 16:30 hrs, the field team started packing equipment to depart the floe in time to arrive in Resolute at the scheduled time. The equipment was carefully bundled and securely strapped all round so that it could be left on the ice overnight. At 18:00 hrs the field team departed for Resolute, content with accomplishments made on the first day sampling the Nanook floe. The day had been glorious: the air temperature was -8°C, skies clear, minimal wind and the equipment had worked flawlessly.

Poor weather prevented flights offshore on 11 and 12 May, so another trip to the Nanook floe could not be made until 13 May. The field team departed Resolute at 11:30 hrs, by which time the low stratus cloud in the local area had dissipated. The helicopter landed on the Nanook floe at 12:10 hrs, under clear skies and an air temperature of -8.5°C. The first order of business was to inspect the equipment for signs of "interest" from polar bears and foxes. There had been a considerable amount of bear traffic around the equipment over past few days but, thankfully, nothing was touched. The equipment was unpacked and the drill frame was set up in the same area of ice that had been cleared on 10 May in order to complete what could not be achieved during the first visit: extracting ice cores to document the temperature and salinity of the ice. Ideally, the temperature and salinity of the ice should be measured as close as possible to where strength tests are performed (to be representative) but that posed a problem in this case: the area around H1 had been exposed for several days and, therefore, the ice would have been altered by ambient air temperatures, yet installing the drill frame in adjacent (snow-covered) area would require another several hours of site preparation. The issue was resolved by extracting full thickness cores from a borehole (H2) close to H1 where strength tests had been conducted and then, to compensate for the altered condition of the snow-free ice in H2, cores were extracted from snow-covered borehole (H3) where the snow was 54cm deep (Figure 12). The ice at H2 was 10.4m thick and had a freeboard of 1.5m; the ice thickness and freeboard were not measured for H3. Cores from H3 were extracted to a depth of 1.5m, since it was thought that removing the snow cover at H2 would not have altered temperatures below that depth. Compared to H3, the top ice surface of H2 had warmed by 5.8°C but only by 2.1°C at a depth of 1.4m (Figure 13). Comparison of the curvature of temperature profiles from the boreholes H2 and H3 suggests that several days exposure (at H2) had warmed the ice to a depth of about 2.5m, but that cannot be confirmed since cores were only obtained to a depth of 1.5m. Coring operations were complete by 17:40 hrs, after which the equipment was packed and strapped together for another night on the floe. The field team departed the Nanook floe at 18:30 hrs, to arrive in Resolute at the scheduled time.

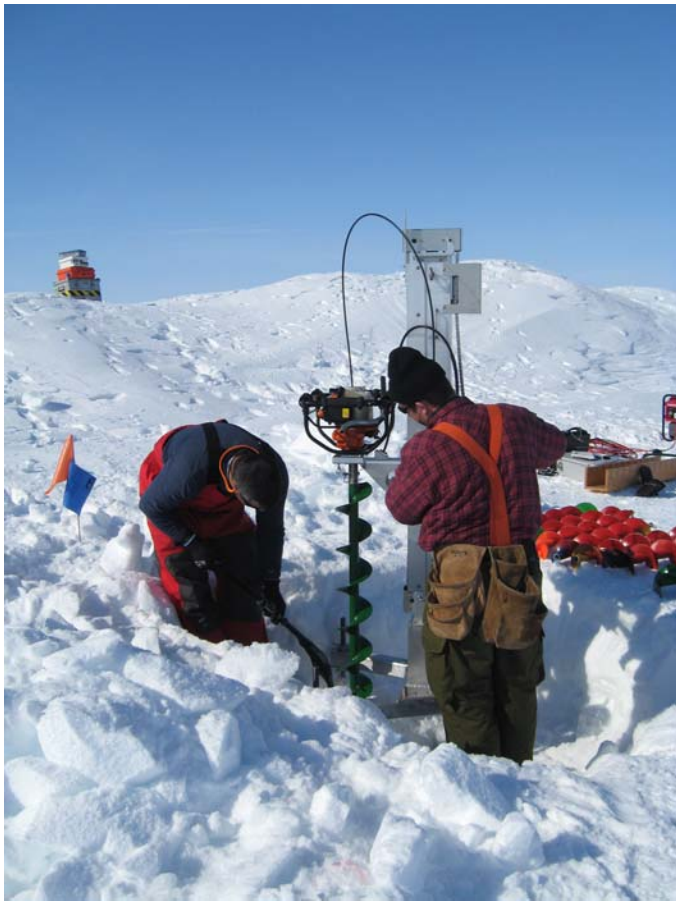

Figure 11 Preparing a borehole on the hummock's shoulder.

The third trip to the Nanook floe was made on 15 May, weather having prevented flying offshore the previous day. By 10:40 hrs, the low lying stratus at Resolute had cleared, permitting the field team to depart for the Nanook floe. At 11:40 hrs, the field team arrived on the floe under clear skies and a brisk wind. Having already documented the ice properties on the hummock's shoulder, focus turned to conducting a full set of measurements on the hummock's crest. The drill frame was erected on the crest, about 10m from where strength tests had been conducted on the shoulder (Figure 12). Securing the drill frame to the hummock was considerably easier than it had been on the shoulder because the crest was devoid of snow. The drill frame was erected without leveling the ice surface, after which coring operations proceeded in the fourth borehole (H4). At 15:00 hrs, after having processed cores from the uppermost 5m of ice only, it became obvious that time would not permit coring through the full ice thickness at H4 (12.4m). To expedite the process, the 6.25" (15.9cm) auger was used to prepare the borehole from depths 5.0 to 12.4m, realizing that the full thickness temperature profile for H4 could be later constructed by combining temperatures already acquired in H4 with temperatures from the full thickness of ice at H2 on the hummock's shoulder (accounting for differences in ice thickness). The same cannot be said of the salinity profile because ice salinity is unique for each borehole. By 15:40 hrs, a borehole had been prepared and by 17:00 hrs strength tests through the full thickness of ice on the crest had been conducted. The helicopter pilot then informed the field team that incoming weather would require an early departure from the floe. The equipment was packed reasonably quickly, strapped together and secured to the ice. The field team departed the floe at 18:00 hrs.

The temperatures, salinities and strengths obtained from boreholes made on the hummock are shown in Figure 13. Temperature and salinity profiles for the shoulder ice were obtained from cores extracted through the full ice thickness at H2 (10.4m) and partial cores obtained from H3. The ice from H2 was coldest at the 1.2m depth (-12.1°C), below which temperatures increased in a linear fashion to the ice bottom. In comparison, the unaltered ice from H3 was coldest at the 0.4m depth (-14.7°C). The curvature in the uppermost portion of the temperature profiles suggests that the 54 to 60cm thick snow cover at H2 and H3 prevented the ice from warming below depths of 0.4 to 0.8m, whereas the snow-free hummock crest (H4) had warmed to a depth of 2.2m. Ice salinities in H2 ranged from 0.1‰ (top surface) to 3.7‰ (5.2m depth), there being no apparent correlation between ice salinity and ice depth. The shoulder ice (H1) was strongest at a depth of 2.7m (32.3MPa), below which the borehole strength decreased in a gradual, but relatively steady fashion to the bottom ice (15.8MPa). It is noteworthy that seven of the ten strength tests conducted in the uppermost 2.5m of ice in H1 produced some degree of ice fracturing. Ice on the hummock's crest (H4) had strengths comparable to the shoulder ice (H1), but more variable with depth, including two weak layers that were not evident in H1 (depths 3.3m and 5.4m, Figure 13). Had time permitted, the properties and thicknesses of several more hummocks on the Nanook floe could have been documented but, having been weathered for several days already, the fourth and final visit to the floe needed to be used to measure ice thicknesses along the transect (as previously discussed).

Figure 12 Strength tests being conducted on the hummock crest (H4). H1 to H3 also shown.

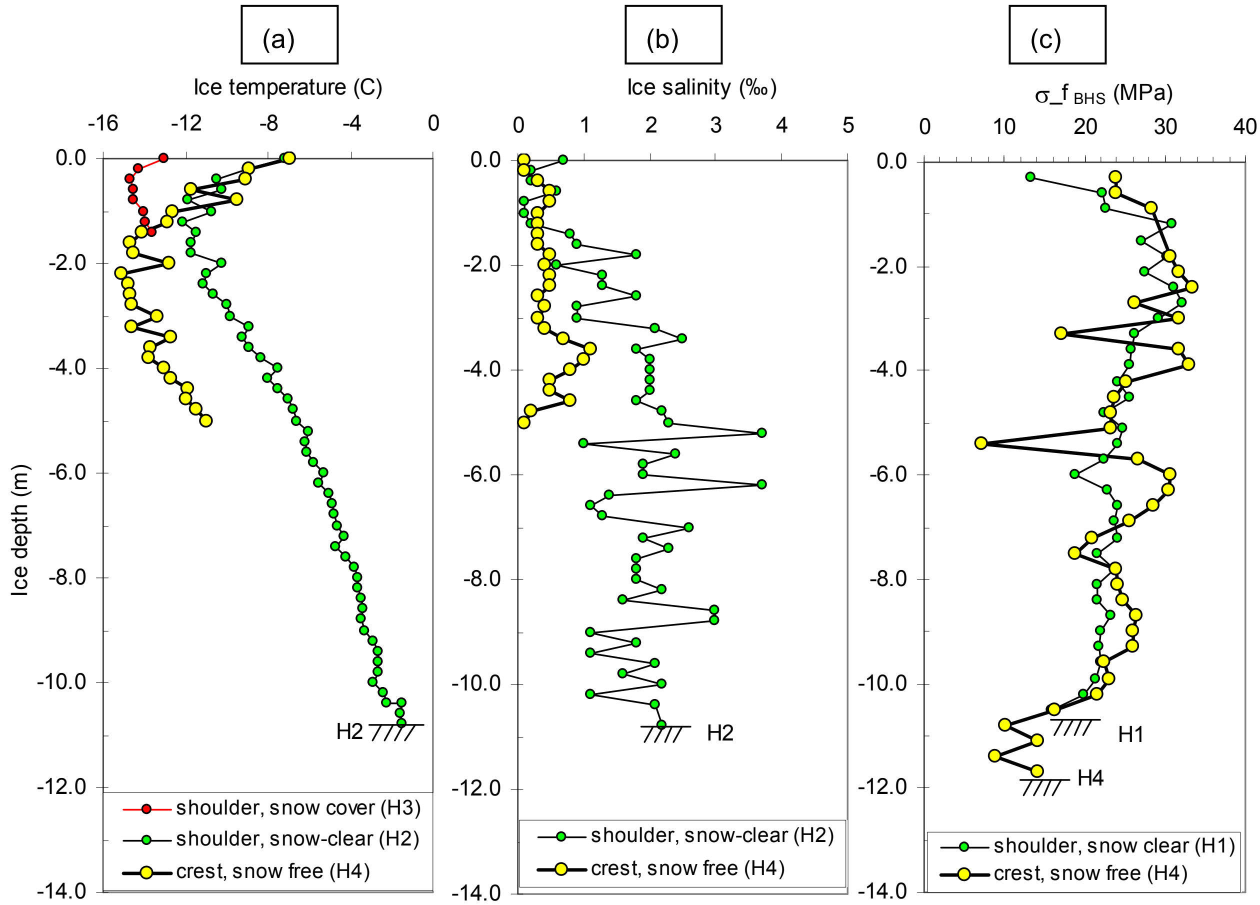

Figure 13 Vertical profiles of (a) temperature, (b) ice salinity and (c) ice failure stress, σ_f_{BHS} for boreholes made on multi-year ice hummock. Measurements are referenced to the top surface of ice. Since the ice thickness at H1 and H4 differ, the test depths in those boreholes do not coincide.

6.0 Data Collected during 2013 Program

The objective of the 2013 field program was to conduct detailed thickness measurements on up to six hummocked multi-year ice floes and to characterize the temperature, salinity and strength through the full thickness of one or more hummocks on each floe. The author was extremely eager to do this because it would provide the first concrete evidence of whether the properties of multi-year ice floes in the Beaufort Sea are, in fact, somehow different than elsewhere in the Arctic. The changing ice conditions in the Beaufort Sea have garnered much attention, but this section will show evidence that extremely hummocked multi-year ice floes in the Beaufort Sea are not rare – and therefore, still pose a very real hazard for offshore structures.

The spring 2013 field program from Sachs Harbour extended from 18 March to 10 April. During that time, the weather was generally good – clear, but cold and windy, as illustrated by the hourly air temperatures and wind chill from the Sachs Harbour airport (Figure 14). After arriving in Sachs Harbour on 18 March, the first few days were taken to organize the equipment, test it on first-year ice and familiarize the two, new members of the field team with the techniques of measuring ice thickness, ice coring and conducting strength tests. Since level first-year ice is, at most 2.0m thick, it can provide only a limited introduction to the skill needed to penetrate thick multi-year ice. Therefore, inquiries were made about sampling ridged ice near Sachs Harbour. Locating ridged first-year ice was not as simple as one might expect – but not because it didn't exist. The SHHTO was consulted about working on level and ridged first-year ice: conducting measurements on the level first-year ice just south of the community was acceptable, but working in the heavily rubbled, landfast ice near Cape Kellett[4] was not, because that was an active hunting area for community members. Instead Jeff Kuptana, our wildlife monitor, led us to a first-year ice ridge about 7km southwest of Sachs Harbour, where residents would not be disturbed. After spending three days working on level and ridged first-year ice, the field team prepared to fly offshore to the multi-year ice.

The helicopter arrived in Sachs Harbour late in the afternoon on 22 March. Four trips were made offshore from 23 to 28 March, as the ice drifted further west by the day. The ice conditions, combined with the inability to refuel offshore, meant that the helicopter had to operate at the margin of its endurance during every flight, that only a limited amount of cargo could be carried on each trip and that very little time could be spent identifying prospective floes. Those factors made it extremely difficult to conduct meaningful measurements on thick, multi-year ice, but the field team did their best to deliver the promised results. The data collected during the program are discussed below.

[4] Satellite imagery indicated that the rubbled ice off Cape Kellett had formed in the fall and, as such, was the most likely region to yield thick, ridged, relatively consolidated first-year ice to develop the expertise needed for coring thick ice.

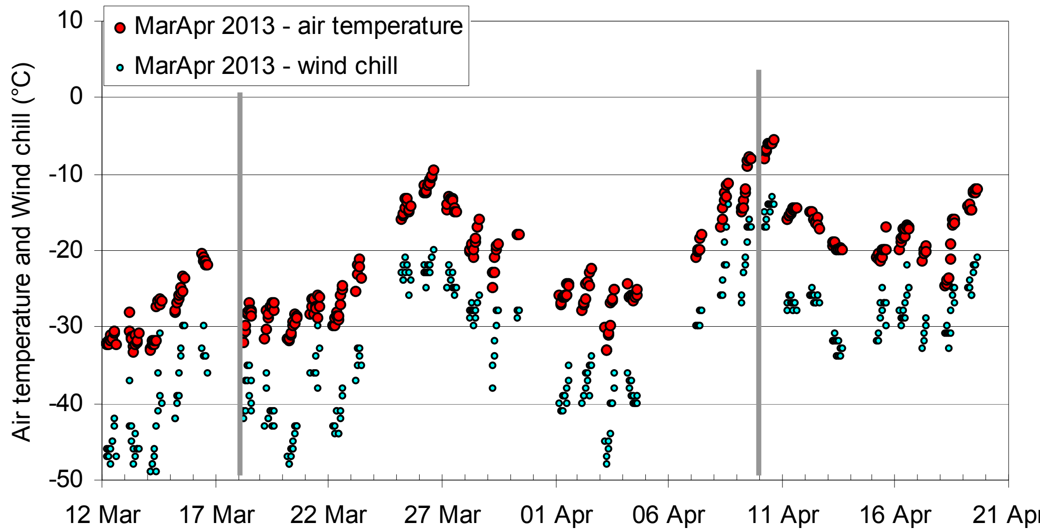

Figure 14 Hourly air temperatures at the Sachs Harbour airport during the 18 March to 10 April 2013 field program (courtesy of Environment Canada). Grey bars indicate the start/end of field program.

6.1 Testing Equipment on First-year ice

The morning of the first day on the ice was used to measure the thickness of level, first-year ice about 2km southwest of Sachs Harbour. The objective of the exercise was for the field team to gain experience with the drilling and steaming techniques under very cold, windy conditions and to be aware of equipment-related problems that might be encountered (and solved) before flying offshore. Three snow machines and two komatiks were taken to the ice and by 09:30 hrs, the two teams were conducting thickness measurements independently of one another. The problems that arose with the drill-hole technique had been encountered before: the gas-powered engine was finicky in the cold, the metal push-buttons connecting the 1m long flights of stainless steel auger froze quickly once wet, and wearing gloves or mittens made attaching/disconnecting the auger flights very difficult. Problems were also encountered with the steam machine (Figure 15), which was not entirely unexpected: lighting the propane burner was problematic in cold-windy conditions, water froze in the stainless steel wand and its 15m long hose when steam was not flowing, care had to be taken to monitor the pressure gauge (to ensure that pressure remained at an acceptable level) as well as the water level (so that the machine could be filled with water before it ran out). In terms of the overall speed at which measurements could be conducted, the drill hole technique and the steam machine were about the same, after taking into account the time to set-up the steam machine and haul the approximately 150kg (300lb) machine around on a sled. The drill-hole technique is much preferred when the intent is to transport a minimum amount of equipment offshore: a well-seasoned, two man team can penetrate to a depth of 20m in roughly 20 minutes without the assistance of a drill frame. If weight is not a consideration, the steam machine provides a less labour-intensive approach to measuring ice thickness, but it is thirsty at cold temperatures (enough fresh water needs to be transported to re-fill it, repeatedly) and man-hauling it around on a sled can be problematic, particularly when the objective is to measure the thickness of heavily deformed multi-year ice.

The snow plus ice thicknesses were comparable from drilling and steaming through level first-year ice at ten stations, allowing for differences in the snow thickness at each station (Figure 16). The comparison is not overly robust, but experience showed the drill-hole technique to be a more accurate approach for measuring ice thickness, provided a weighted tape is used to locate the bottom of the ice after drilling the hole. The weighted tape is also useful for determining the depth (and size) of sea-water filled cavities in the ice, when present. The hole made by the steam machine is about half the diameter of the 2” auger and, therefore, the weighted tape measure that was devised for the steam hole was not sensitive enough to locate the ice bottom. Therefore, ice thicknesses had to be determined from the (marked) length of hose consumed by the ice, which was not as accurate as using the weighted tape measure. Similarly, reading off the hose length made determining the location (and size) of cavities in the ice less accurate. Measurements were complete by 14:00 hrs, at which point the field team returned to the Lodge for lunch.

In the afternoon, the field team traveled to a first-year ice ridge about 7km southwest of Sachs Harbour to perform the same comparison. Working in teams of two, drill-hole measurements were made at two holes and steam holes were made at three stations. Each measurements was done in a different area of the ridge. Ice at the three locations where steam holes were made, ranged from 3.0 to 3.5m thick and snow depths from 6 to 44cm. The two holes where ice thickness was measured using the drill hole technique returned thicknesses of 4m and 13m and snow depths of 0cm and 100cm. Unfortunately, results from the two techniques could not be compared because once the steam machine was empty (after three holes), it could not be re-filled[5]. At 16:00 hrs, the equipment was packed and the team returned to Sachs Harbour. The air temperature was -29°C and the wind chill was -38°C (not accounting for the speed of the snow machine).

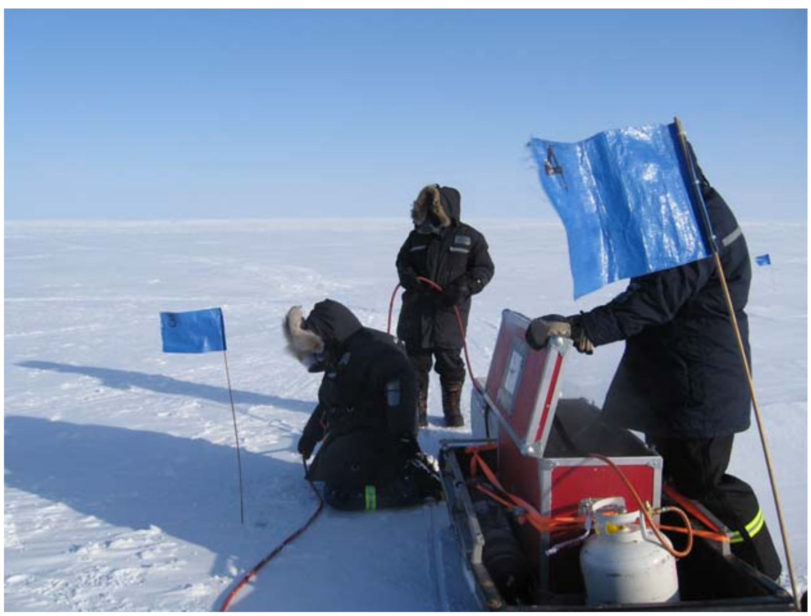

Figure 15 Steaming holes to measure the thickness of first-year ice near Sachs Harbour

[5] The manual pump to draw water into the system had broken in the cold, which left the fill tube as the only means of adding water to the steam machine. However, the steam machine could not be re-filled because the wrench for removing the fill-tube cap had not been taken. That, in and of itself, was an excellent lesson for the field technicians because it showed that trivial, seemingly insignificant items can limit the amount (and quality) of data collected.

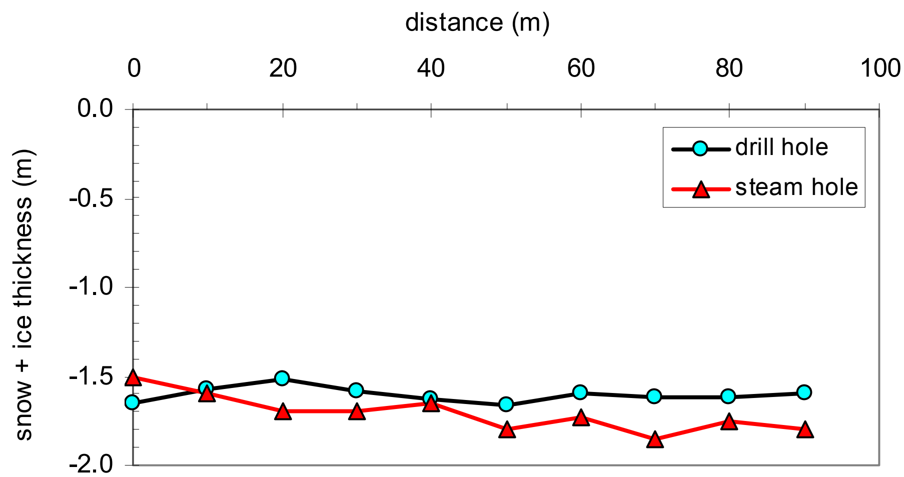

Figure 16 Comparison of thicknesses measured along transect on level first-year ice near Sachs Harbour using (a) drill hole technique and (b) steam hole technique. Snow thicknesses not measured.

Day 2 on the first-year ice near Sachs Harbour was used to prepare four boreholes for strength tests (Figure 17). The four boreholes were made in the same area, each separated by a distance of about 1m. Two boreholes were made with the 7” (17.8cm) corer and two boreholes were made with the 7” (17.8cm) auger. Strength tests in two holes were performed with the deep borehole system (15m long hoses) whereas the other two holes were tested with the shallow borehole system (6m long hoses). The two NRC borehole systems are essentially the same, apart from having different hose lengths (Johnston, 2014). The purpose of measuring strengths with the two systems was to examine whether the length of hydraulic hoses had a measurable effect on test results.

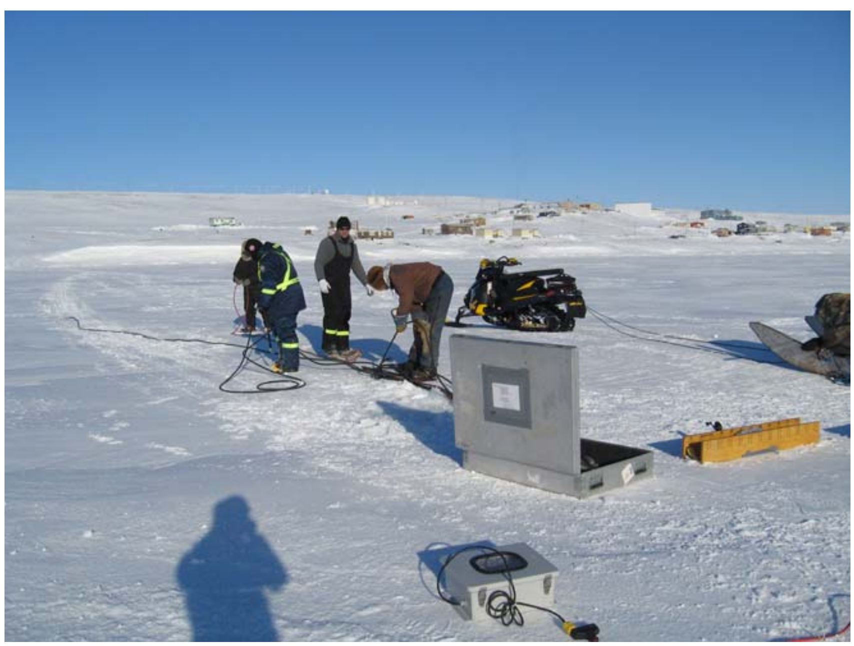

Figure 17 Packing equipment after measuring the temperature, salinity and strength of first-year ice near Sachs Harbour.

The vertical profiles in Figure 18 show the ice temperature and salinity from the first borehole (H1) and the ice failure stress (σ_f_{BHS}) from strength tests conducted in all four boreholes. The temperature profile shows that the 1.65m thick first-year ice was characterized by a linear profile, extending from the top ice surface, where temperatures were coldest (-21.4°C) to the bottom ice surface, where temperatures were warmest (-2.2°C). The ice salinity was highest at the top ice surface (10.2‰) but ranged from 3 to 4.4‰ below that depth. Strengths were comparable in the four boreholes: the ice was strongest at the cold, top ice surface (30.8 to 34.2MPa) and the lowest towards the warm bottom ice (3.7 to 8.8MPa). The standard deviation in strength for the different depths ranged from 1.2 to 2.3MPa, with the 60cm and 150cm test depths displaying the most variability. The pressure-time histories for those test depths (not shown) reveal that the ice responded differently to the penetrating indentors – and, in some cases, fractured prior to yield (see Appendix C). Since ice strength is determined by how the ice responds to loading (i.e. indentor penetration), the ice response directly relates to its properties. For example, of the four boreholes, H4 had the lowest strength measured at the 60cm depth (27.3MPa) because the ice fractured and failed prematurely, causing a substantial reduction in pressure (Failure type 2-d, Appendix C).

Tests in H1 and H2 were conducted with the 15m long deep borehole system and tests in H3 and H4 were performed with the 6m deep borehole system. Strengths from the four boreholes confirm that the hydraulic hose length has little effect on the test results, provided the borehole indentor system has been sufficiently “exercised” prior to conducting the tests (to decrease the viscosity of the oil).

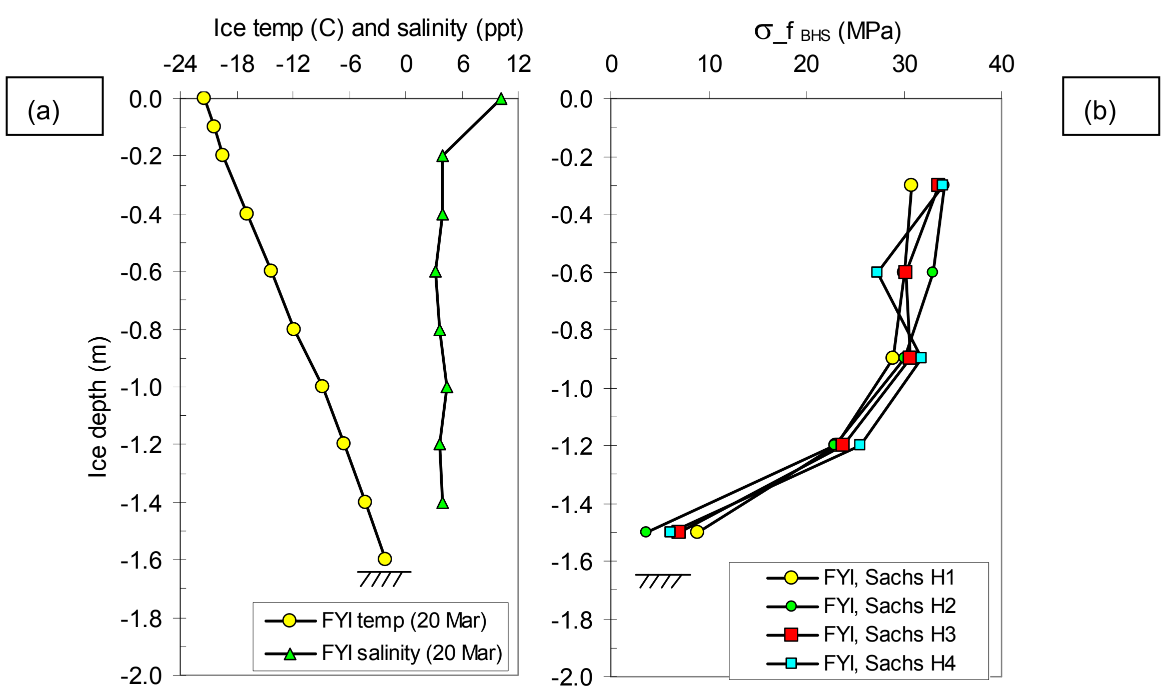

Figure 18 Vertical profiles of (a) temperature, salinity of H1 and (b) ice failure stress, σ_f_{BHS} for four boreholes in first-year ice near Sachs Harbour. Measurements referenced to the top surface of ice.

6.2 Ice Conditions Offshore

The winter of 2013 brought very dramatic – and unusual – changes to the Beaufort Sea. In fact, the changes were so unusual that they generated numerous media reports: Trudy Wohlleben, senior ice forecaster at the Canadian Ice Service, stated that the rapid ice drift began "in the southwest section of the Beaufort Sea around Feb. 20, initiating the first fractures in that area, then quickly spread eastward to encompass the entire Beaufort Sea by the end of February" (http://news.nationalpost.com/2013/04/02). What had been stable ice off the coast of Banks Island in early February, changed radically by month's end. Over the next few weeks, the ice offshore Banks Island continued to drift west, leaving open water and drifting, recently refrozen, thin ice in its wake. The 10 March satellite image in Figure 19 clearly shows the magnitude of the Basin-wide fracture pattern, as well as the lead that formed along the coast of Banks Island. The ice fractures extended 1500km north of Sachs Harbour and 900km west of Sachs Harbour, to the coast of Alaska. Ice dynamics continued into late March (see the Regional Ice Chart in Figure 20) and on into April, so the NRC field program was conducted in that extremely challenging environment, as would have the University of Manitoba's field program, had the offshore component occurred.

On 31 March, the field program was officially terminated by the author, due to helicopter-related concerns about health and safety of the field team. A detailed description of the reasons leading up to the termination is given elsewhere (Johnston, 2014b). The two primary reasons for terminating the program include (1) the Bell 212 helicopter arrived onsite on 22 March with skid gear only (no floatation), contravening what had been previously agreed to during a conference call between the helicopter company, Industry and NRC and (2) on 29 March, after spending a night on the ice, the pilots could not articulate an emergency plan should landing on thin ice be required, which was cause for serious concern, considering the distance that needed to be traveled over open water/broken ice to reach the multi-year ice offshore. On 1 April, the University of Manitoba cancelled the offshore component of their field program, which was scheduled to begin on 7 April 2013. University of Manitoba planned to use the same helicopter company, and the same helicopter, to access multi-year ice from Sachs Harbour.

Four flights were made to the multi-year ice from 23 to 28 March[6]. The first flight offshore, on 23 March, yielded first-hand information about ice dynamics in the Beaufort Sea. The flight traversed landfast ice, open water and ice types ranging from grey ice (10 to 15cm thick) to thick first-year ice (<2.0m thick). The field team crossed the landfast ice attached to Banks Island, which was comprised of rubbled ice and flat pans of thick first-year ice. Beyond the landfast zone, a large area of open water and broken, thin ice was encountered (Figure 21) which, by 25 March, extended up to 40km wide in some areas (Figure 20). Having crossed the active lead, the helicopter encountered 9+/10ths concentration of first-year ice mixed with second-year and multi-year ice. Freshly formed ridges were frequently observed where the ice concentrations were higher, as were fractures and open water leads. The helicopter had a maximum range of 200km provided minimal equipment and only 3 passengers were taken, which allowed the field team could approach the 131°W meridian. By 25 March, 131°W was at the very edge of where the higher concentrations of multi-year ice existed (5 to 8/10ths concentrations of old ice in brown regions "DD" and "T", Figure 20). The ice continued to drift west during the field program.

[6] An additional flight was made on 27 March, but that flight was aborted upon reaching the open water/broken thin ice along Banks Island because weather prevented the pilots from seeing across the lead.

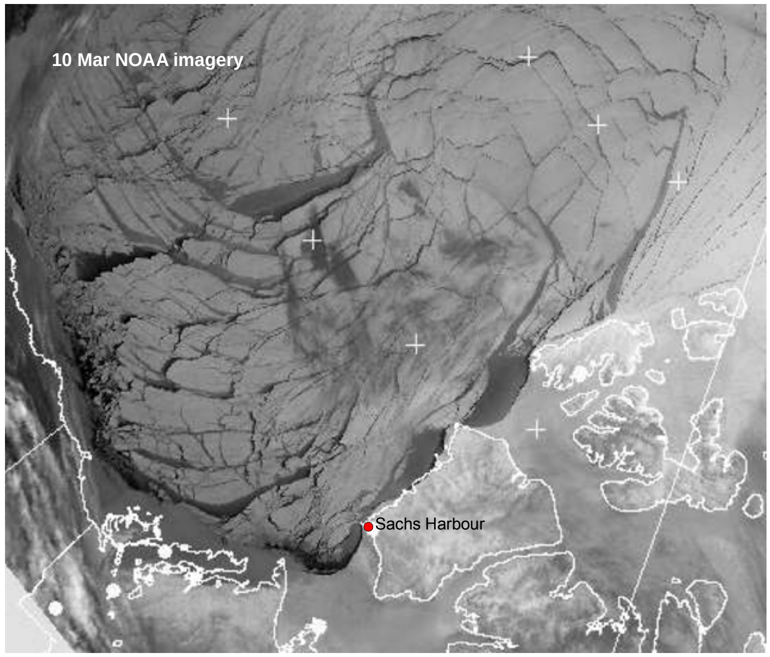

Figure 19 Fractured ice in the Arctic Basin, spring 2013. Dark is open water/thin ice; grey is thicker ice.

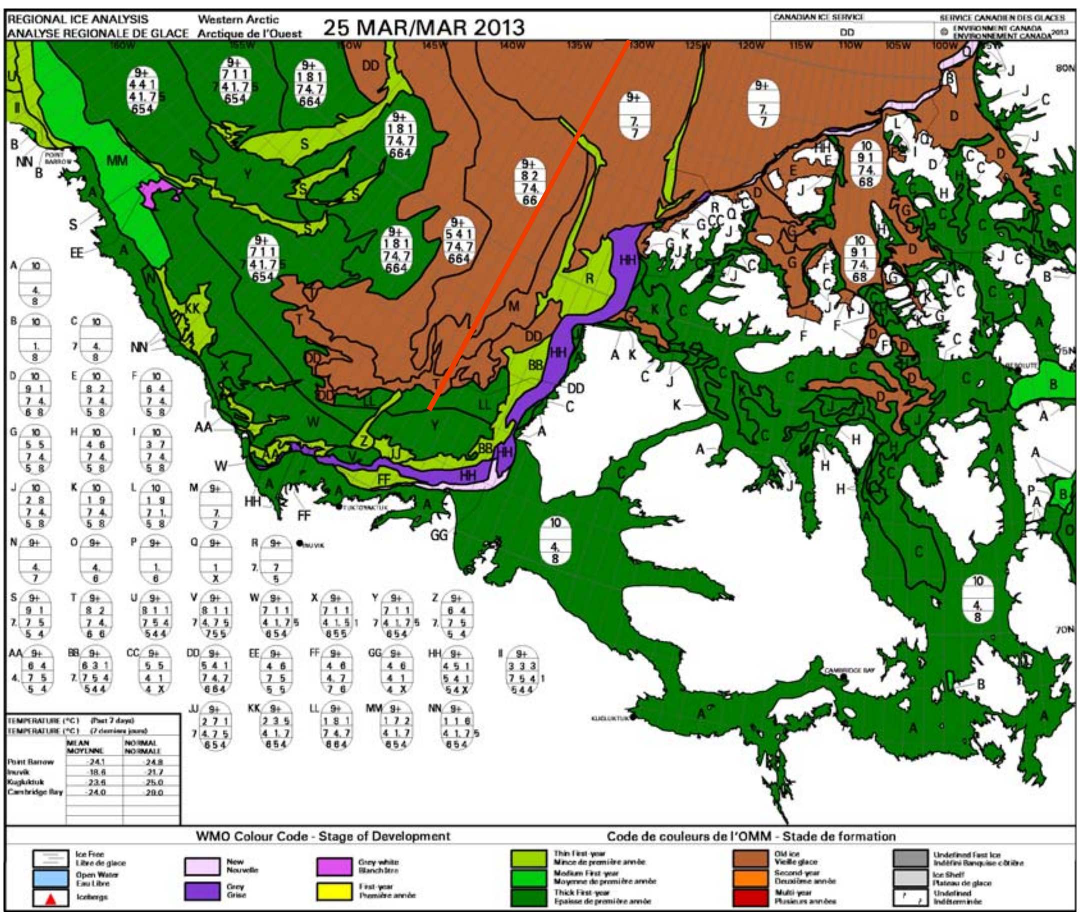

Figure 20 Regional Ice Chart for 25 March 2013 showing stage of development, courtesy of CIS. Predominant concentrations of grey ice shown as purple, thin first-year ice as light green, thick first-year ice as dark green and old ice as brown. The red line shows 131°N, the maximum extent of helicopter range on the lightest days.

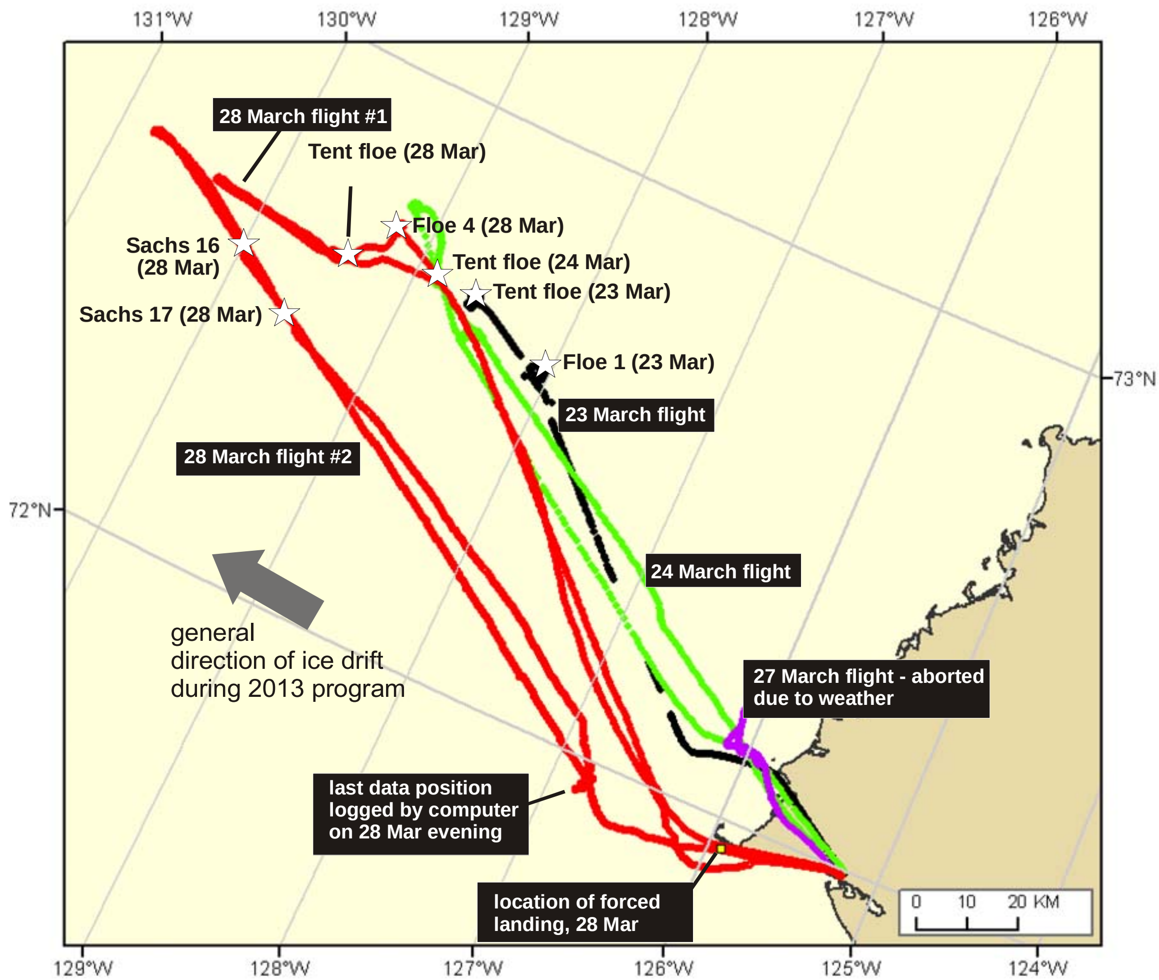

Figure 21 Floes visited during flights offshore from 23 to 28 March 2013.

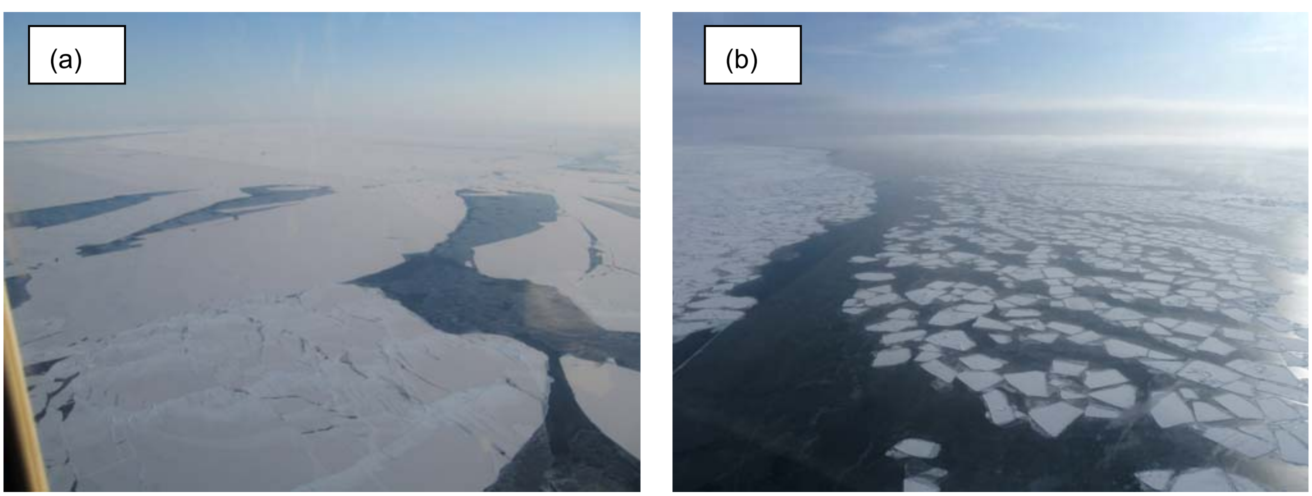

Figure 22 Active lead of thin, broken ice and open water spanning the length of Banks Island. Photographs taken on (a) outbound flight on 23 March and (b) return flight to Sachs Harbour on early-afternoon of 28 March.

A total of five old ice floes was visited during the program (Figure 21). Two floes were visited on the 23 March (Floe 1 and the 'Tent' floe). On 24 March, the Tent floe was again located, but flat light conditions prevented the helicopter from landing. On 28 March, a flight was made to the Tent floe and Floe 4 in the morning, and another flight offshore was made to floes Sachs 16 and Sachs 17 in the early afternoon. Ice thicknesses were measured at a total of 39 drill-hole/steam-holes during the program and satellite tracking beacons were installed on four floes. Two of the beacons were supplied by the University of Manitoba and two beacons were supplied by Industry (as replacements for the Environment Canada beacons that did not arrive). The flights offshore are discussed below.

6.3 Floe 1 (72°35.8'N, 128°03.7'W)

All five members of the field team departed Sachs Harbour on 23 March at 10:20 hrs, with enough equipment to allow two teams, working in parallel, to measure ice thicknesses using the drill hole and steam hole techniques. None of the beacons shipped by Environment Canada and Canatec had yet arrived, which made it nearly impossible to re-locate drifting floes that merited more than one visit. After traversing first-year ice for about one hour, the helicopter reached an area of ice that recent satellite imagery suggested could be old ice about 115km northwest of Sachs Harbour. The ice looked more like thick, first-year ice than old ice, however. Having consumed a considerable amount of fuel already, it was decided to call this Floe 1 (72°35.8'N, 128°03.7'W). At the very least, the field team could work together to develop an approach for measuring ice thicknesses efficiently using the drill-hole and steam-hole techniques before moving further west to, what was hoped, would be multi-year ice floes that were thicker and more deformed. The helicopter landed on Floe 1 at 11:10 hrs.

A flagged transect was laid out to mark the stations where snow and ice thicknesses were to be measured. The transect started at the helicopter and ended about 100m away, on a ridge estimated to be 2m high – the only moderately sized ridge on the floe (Figure 23, Figure 24). The field team worked together to measure thicknesses along the transect using the steam machine because the gas engine needed for the drill-hole technique failed to start at the cold temperatures (-26°C). Snow plus ice thicknesses along the transect ranged from 1.6m in the level ice to 8.75m towards the ridged ice (Figure 25), resulting in an average thickness of 2.7 ± 2.2m. The modest thickness of Floe 1, combined with its very level surface, suggested that the floe was first-year ice or perhaps thin second-year ice but that could only be confirmed by conducting ice property measurements (salinity, strength). By 13:15 hrs thickness measurements had been completed along the transect, the equipment was packed and the field team departed the floe. During the two hours spent on the ice, Floe 1 drifted about 600m west (72°35.9'N, 128°04.7'W) at approximately 300m/hr.

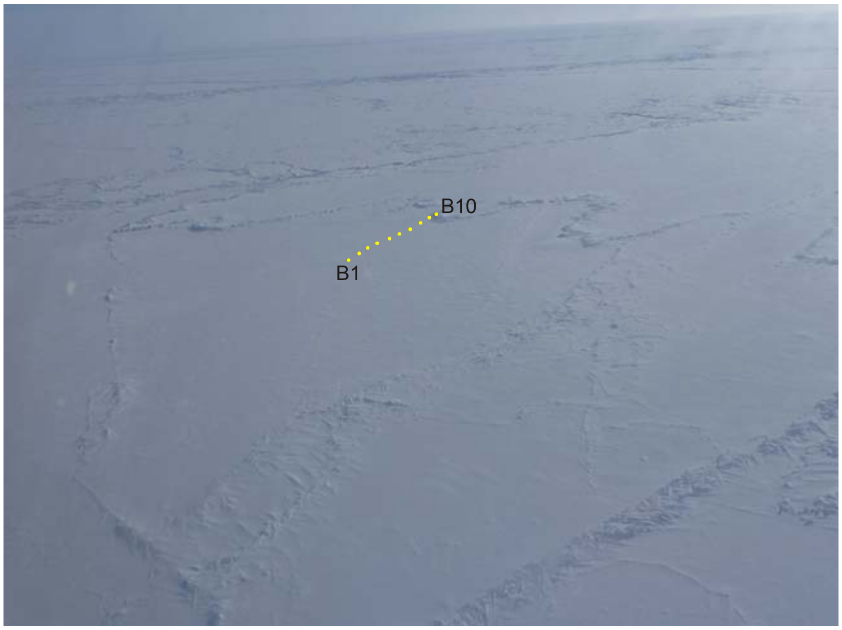

Figure 23 Transect B made on Floe 1 which was likely was first-year ice rather than old ice. What had been identified as old ice in the satellite imagery had drifted further west since the date of the satellite overpass.

Figure 24 Surface view of Floe 1, sampled on 23 March

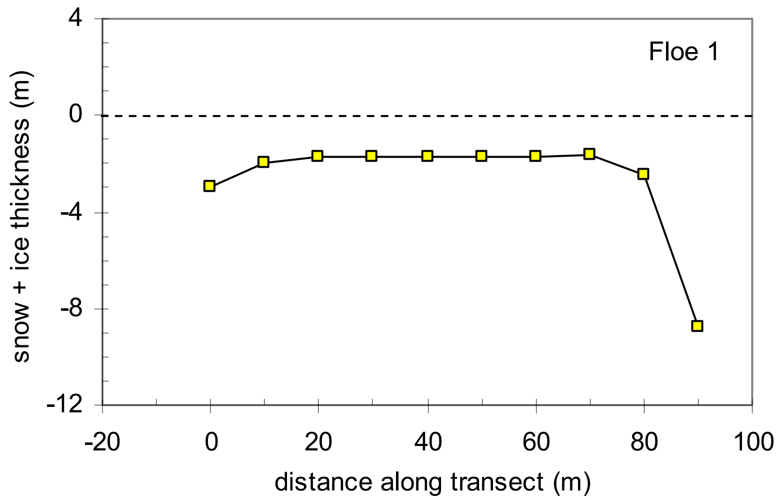

Figure 25 Ice thicknesses measured on Floe 1

6.4 Tent floe (72°39.48'N, 128°36.22'W)

About 20km northwest of Floe 1 the helicopter flew over a pair of similar looking floes, with several well defined hummocks (Figure 26). The floe that was selected for measurements was approximately 250m across – although it would have been equally acceptable to sample the adjacent floe, which was somewhat larger (~500m). At 13:35 hrs, the helicopter landed on a level area of what became known as the 'Tent floe'. The first day on the floe was spent making two transects across the floe and measuring its thickness. Transect B extended away from the helicopter and terminated at the upturned ice along the floe edge whereas Transect OB extended along the crest of the hummock, as shown Figure 26. The steam machine was refilled in preparation for conducting thickness measurements. Over the next five hours, thicknesses were measured at 17 stations along the two transects. The on-ice photograph in Figure 27-a shows a few of the stations where ice thicknesses were measured: a blue flag on Transect B and, in the distance, several orange-blue flags along Transect OB. Having conducted thickness measurements on the floe, seven of the stations along the 2.5m high hummock crest, it was decided to erect a vertical tent on the top of the hummock before departing, to make the floe more recognizable from the air. This was done because there were no beacons to mark the floe and also to help identify the floe in high resolution satellite imagery. The tent was secured to the hummock (with ice screws) until it could be replaced with a tracking beacon. At 18:20 hrs, the field team departed the Tent floe (72°39.62'N, 128°39.18'W). The floe had drifted 1.7km to the northwest during the approximately five hours spent on the ice. The drift speed of the Tent floe (340m/hr) and Floe 1 (300m/hr) were comparable. Considering how quickly the floes drifted, it was not surprising that the ice encountered during the offshore flights did not match the targets identified from satellite imagery acquired several days prior. Clearly, out-of-date satellite imagery would be of little use targeting floes of interest – without accurate, real-time ice forecasting, that is. The helicopter landed in Sachs Harbour at 19:25 hrs, concluding the first trip offshore.

On the following day, 24 March, the field team left the Lodge for the garage at 07:40 hrs to deliver equipment to the airport. By 09:20 hrs, the field team was in the helicopter ready to depart for the second flight offshore. The temperature was -17°C, skies were cloudy, but visibility was sufficient to permit a flight offshore. At 10:18 hrs, quite unexpectedly, the helicopter passed over the Tent floe – which was recognizable from the surrounding ice, only because a tent had been installed on the floe. The helicopter attempted to land on the 500m diameter floe next to it, as requested (Figure 26). After making two attempts, the pilots were unable to land safely, so the helicopter departed the area to explore other floes nearby. By 11:10 hrs, the weather had deteriorated much faster than expected and the field team returned to Sachs Harbour. The helicopter landed in Sachs Harbour at 12:10 hrs.

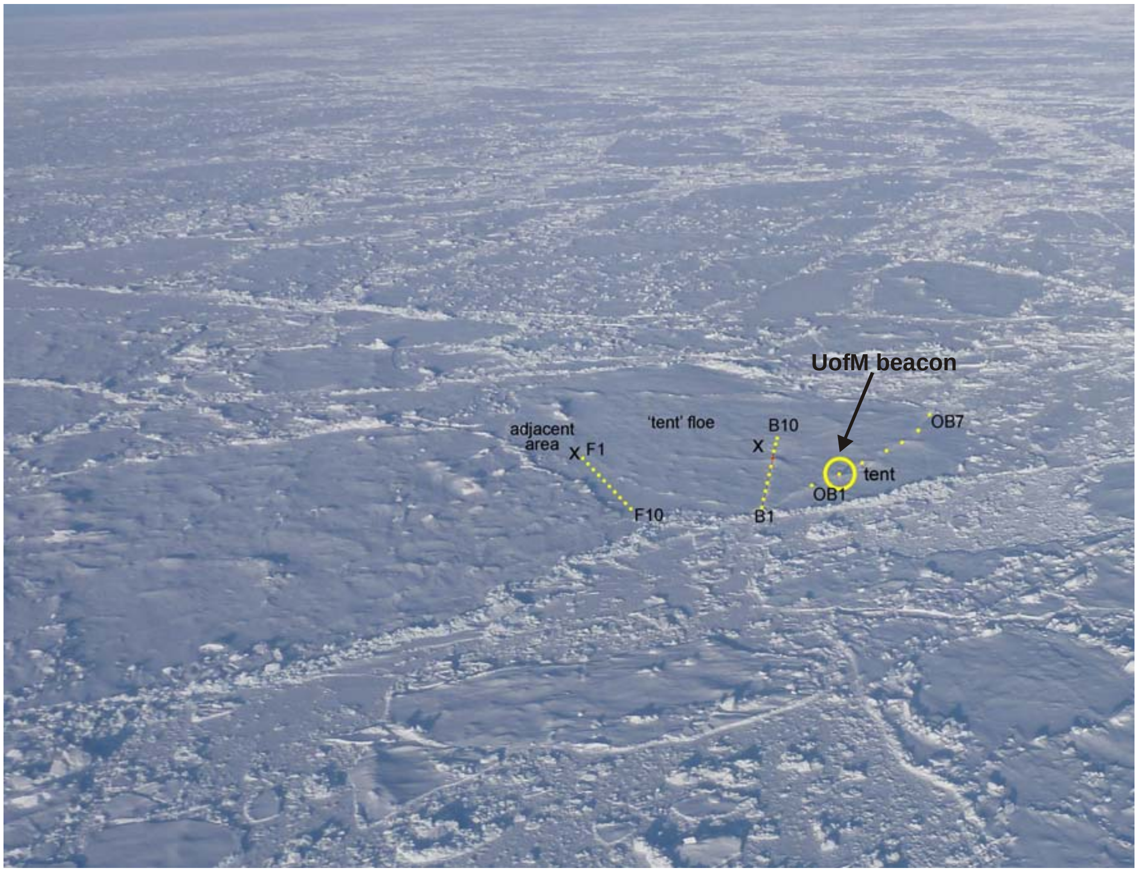

Figure 26 Tent floe that was visited during three of the flights offshore.
Three ice thickness transects shown, along with the tent used to mark the floe and the beacon that was eventually installed on the floe.

On 28 March another flight was made offshore, weather having prevented flying on the previous three days. Since the three tracking beacons from Environment Canada and Canatec still had not arrived, Dr. Klaus Hochheim generously allowed NRC to borrow two of University of Manitoba's beacons in the interim. Only minimal personnel (3 persons) and equipment could be carried that morning because the objective was to reach two floes that were 180km west of Sachs Harbour. The floes were especially attractive because satellite imagery indicated they had a rounded shape and that they appeared to be reasonably deformed. One of the floes was 8.8km across and the other, 7.0km across, was 25km to the southwest. The field team departed Sachs Harbour at 10:15 hrs. By 11:20 hrs, the helicopter had reached the Tent floe and had attempted to land to allow field personnel to properly install a tracking beacon on the ice. The weather cooperated this time, but the 'snow bowl effect' stirred up by the helicopter downwash prevented the pilots from landing. The Tent floe's position was entered into the GPS as a waypoint (72°37.62'N, 129°2.47'W) and the helicopter moved on to more distant floes. At 11:23 hrs, having traveled nearly 180km, with no evidence of either of the two targeted floes, the helicopter turned around and returned to the Tent floe for a second attempt at beacon deployment. It had been agreed that, if the helicopter could not land, the approximately 7kg (15lb) beacon would be tossed out of the helicopter after the pilot had given the signal – even though it risked damaging the electronics of the expensive instrument. Upon reaching the Tent floe, the helicopter hovered above the ice surface as the beacon was tossed out of the aircraft, then the helicopter landed on a very smooth, snow-covered area of ice. Unfortunately, the exact landing area on the floe could not be determined with any accuracy because the fogged up windows of the helicopter – which was a chronic problem on all of the flights – prevented aerial photographs from being taken. Rather, the location of ice that was sampled was determined from the photographs that were taken from the ice. It was later determined that the ten drill-hole measurements that were made on 28 March were not actually on the Tent floe 'proper', but on level (second-year ice?) between the Tent floe and the 500m diameter floe next to it (Transect F, Figure 26 and Figure 27-b).

Figure 28 shows the profile view of the snow and ice thicknesses that were measured along three transects made on the Tent floe and its adjacent ice during the different visits to the floe. Snow and ice thicknesses were measured along Transects B and F at a 10m spacing and along Transect OB roughly at a 25m spacing (to capture the peaks along the hummock). The ice along Transect B was from 2.0 to 6.5m thick, for an average thickness of 3.8 ± 1.4m. Snow depths along Transect B ranged from 7 to 40cm. Thicknesses of the (snow-free) hummock peaks along Transect OB ranged from 6.5 to 9.5m, for an average thickness of 8.1 ± 1.2m. Thinner ice was encountered along Transect F, where thicknesses from 2.5 to 3.0m were measured at the drill holes, producing an average thickness of 2.9 ± 0.2m. Having measured ten thicknesses along Transect F, the beacon that had been dropped from the helicopter was recovered and two members of the field team walked to the hummock to install the other UofM beacon on (next to the tent). At 13:15 hrs, the field team departed the Tent floe to find another floe nearby on which to deploy the beacon that had been dropped – there being no means of determining whether it had been damaged by the fall, or not.

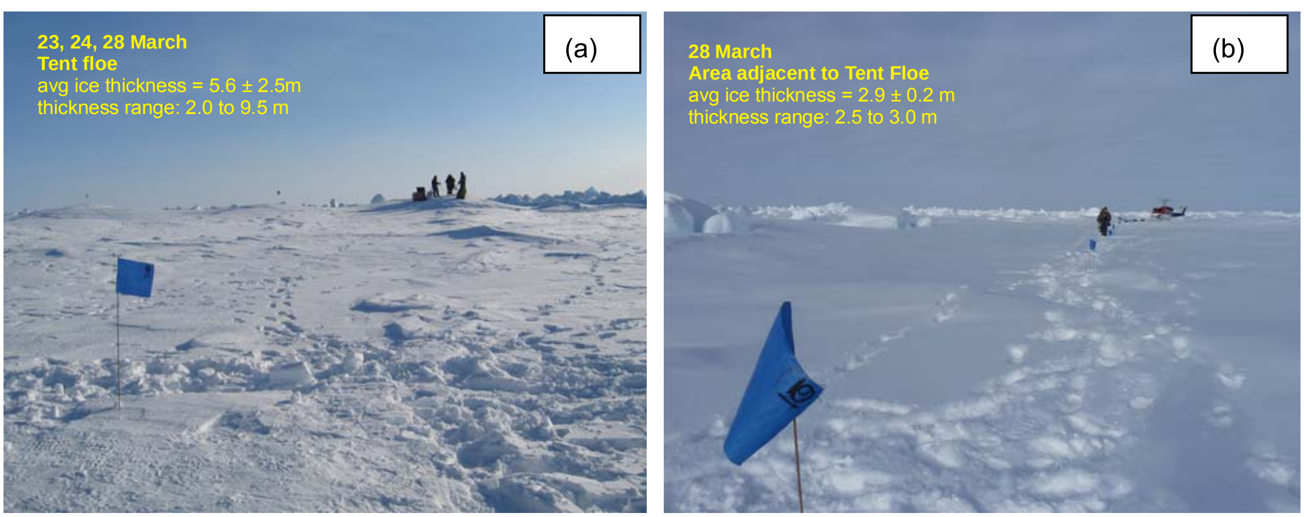

Figure 27 The 'Tent floe' on which a UofM beacon was placed and thicknesses measured along (a) Transects B and OB and (b) Transect F in an area of ice adjacent to floe.

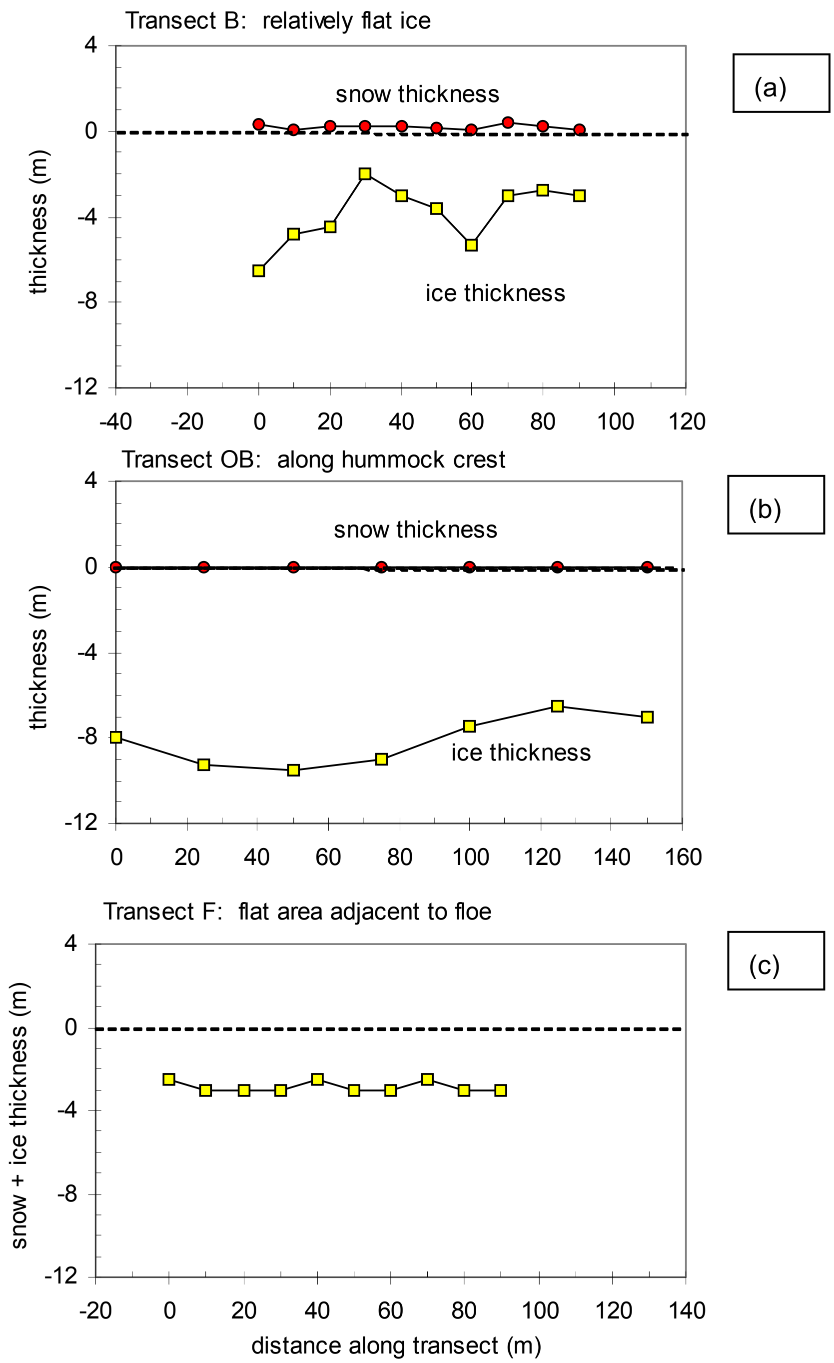

Figure 28 Snow plus ice thicknesses measured with the steam machine along (a) Transect B, (b) Transect OB on Tent floe and from drill holes along (c) transect F in an area adjacent to Tent floe.

6.5 *Floe 4 (72°43.53'N, 129°11.86'W)*

After the field team departed the Tent Floe on 28 March, they flew about 14km to the northeast, where several hummocked floes were encountered. The pilots were informed that the floe of choice was the "oval floe near the open water lead" (~750m across) but since communicating (and pointing to floes) was extremely difficult from the back of the helicopter, the pilots understood the instructions to mean that they should land on flat ice near an open water lead. Before shutting down, the pilots were informed that the target was actually "the smooth, hummocked ice on the other side of that ridge". The helicopter then moved to a floe that was considerably smaller (~250m across) and less hummocked than the floe that the author had intended to sample (~750m across, Figure 29). At 13:26 hrs the author decided that the landing site would have to suffice as Floe 4, since the intention was merely to deploy the beacon and measure one or two thicknesses. Ice thicknesses were measured at two locations on Floe 4 (72°43.53'N, 129°11.86'W). The first hole was drilled in a flat area of ice, about 10m from the helicopter, where the full thickness of ice 4m and the snow cover 6cm thick. The second drill hole was made on the crest of the 2.7m high hummock shown in Figure 30, where the ice was 8.0m thick and the snow was 5cm thick. The UofM beacon that had been recovered from the Tent floe was re-deployed, in hopes that a future visit to Floe 4 could be made – or, preferably, the 750m long floe nearby. The field team departed the floe at 14:20 hrs to return to Sachs Harbour to refuel, determine whether the beacons from Environment Canada and Canatec had arrived on the incoming commercial flight, and (hopefully) conduct a second flight offshore to identify additional floes that afternoon. The field team arrived in Sachs Harbour at 15:30 hrs to learn that the beacons had arrived.

Figure 29 Aerial photo of Floe 4 on which second UofM beacon was placed.

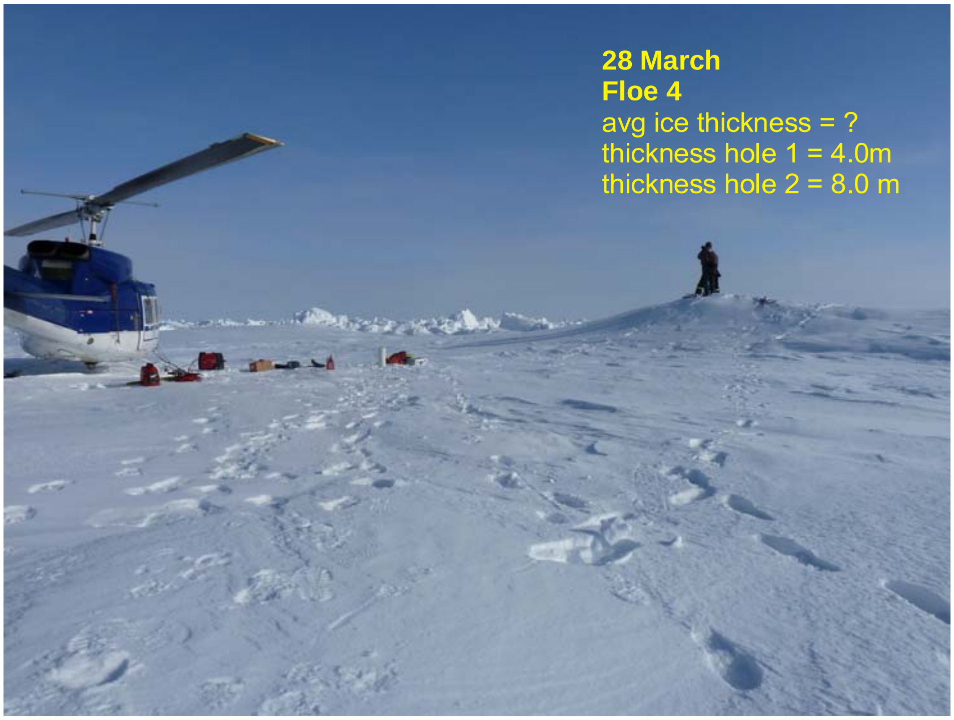

Figure 30 Thicknesses were 4.0 and 8.0 m at two drill holes on Floe 4 (~250 m across).

6.6 Sachs 16 (72°33.68'N, 129°57.55'W)

After landing in Sachs Harbour (15:30 hrs), the helicopter refueled and then the same three passengers boarded the helicopter for another trip offshore. Four beacons were taken (two Environment Canada and two from Canatec). The helicopter departed Sachs Harbour at 16:25 hrs, although the pilots noted that the weather would need to be watched, and that it might not be possible to reach the targeted floes 180km offshore. A more direct route was taken to the targeted floes during the second trip offshore (Figure 21), since it was not necessary to re-visit the Tent floe again that day, having equipped it with a beacon. The helicopter reached its maximum range approximately 200km west of Sachs Harbour, still without encountering either of the floes targeted from satellite imagery. At that point, the helicopter turned around so that beacons could be installed on two floes identified during outbound trip during the return trip to Sachs Harbour.

The first floe that was selected for one of the beacons was Sachs 16 (72°33.68'N, 129°57.55'W) about 170km northwest of Sachs Harbour. The floe's gently undulating surface topography, rounded shape and rubbled perimeter was characteristic of multi-year ice (Johnston and Timco, 2008). At 17:00 hrs the helicopter landed and, without shutting down (to conserve fuel), the First Officer and one of the field team exited the helicopter to deploy a Canatec beacon. The beacon, in its small Pelican case, was wedged into the snow to prevent it from blowing away. The First Officer and passenger then returned to the helicopter and departed Sachs 16 in search of a floe on which to deploy the other Canatec beacon.

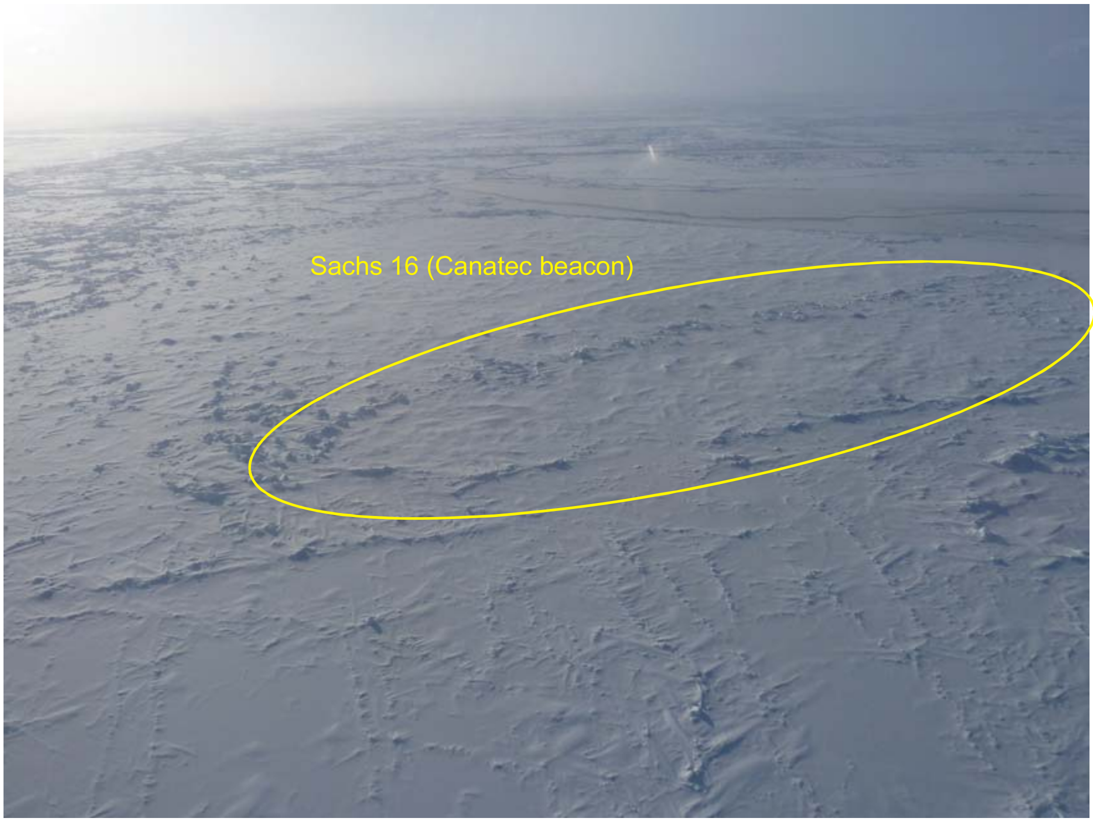

Figure 31 Sachs 16 on which one of the Canatec beacons was placed.

6.7 Sachs 17 (72°28.57'N, 129°28.98'W)

At 18:10 hrs, and 20km southeast of Sachs 16, the field team encountered a rugged looking floe roughly 150km northwest of Sachs Harbour, at 72°28.57'N, 129°28.98'W. Sachs 17 was a formidable ice feature: it was about 750m across and had several parallel lines of hummocks extending along its length. The substantial pile of rubble at one end of the floe (Figure 32) indicated that the floe was considerably thicker than the first-year ice around it. Similar floes have been sampled in Norwegian Bay, Nunavut, where ice thicknesses in excess of 15m were measured at sequential holes (Johnston, 2007). Once the second Canatec beacon had been deployed on Sachs 17, the field team returned to Sachs Harbour, having deployed four beacons that day. It was thought prudent to retain the two Environment Canada beacons for future deployments. Although the beacons from Canatec and Environment Canada had been activated before departing Sachs Harbour, none of them had been confirmed to be transmitting prior to departing because that could not be checked from the airport. As it turned out, the Sachs 16 beacon malfunctioned on 31 March and the Sachs 17 beacon malfunctioned on 29 March, likely because the beacons had been assembled at short notice (Canatec, personal communication), to replace the Environment Canada beacons. As for the two Environment Canada Compact Air Launch Beacons (CALIBs), the author was later informed that, due to a programming problem, the CALIBs were unserviceable when they arrived in Sachs Harbour. As a result, the two heavy-duty beacons from the UofM (also obtained from Canatec) were the only beacons for which detailed floe positions are available for an extended period.

Figure 32 Sachs 17 floe on which the second Canatec beacon was placed.

6.8 Drift Trajectories of Instrumented Floes

The UofM beacon on the Tent Floe transmitted the floe's position (at hourly intervals) from 28 March, when it was deployed, to 14 August[7]. The floe's trajectory was erratic during that time (Figure 33). Initially, the floe was at 129°30'W, then drifted southeast between 128°W and 129°W until it drifted closer to Sachs Harbour than when it was first visited on 28 March. From there, the Tent floe drifted as far west as 133°W before heading east again to 128°W, traveling north along that meridian in a spiral pattern.

The UofM beacon on Floe 4 transmitted from 28 March to 12 August[8]. The drift trajectories of Floe 4 and the Tent floe were nearly identical over much of the five month period. That should not be surprising because the two floes were just 14km apart when they were visited on 28 March and were surrounded by a high concentration of ice. As a result, the floes likely drifted in unison until, later in the season, they began to drift independently of one another. Notice that the floe trajectories diverge off the tip of the Tuktoyaktuk Peninsula: Floe 4 followed the coast as it drifted southeast into Franklin Bay and then moved north along 126°W, whereas the Tent floe drifted north along 129°W after reaching the

[7] The reason for the terminated data transmission cannot be attributed to the low voltage of the batteries because both the battery voltage (4.80V) and the modem voltage (4.31V) were still quite high compared to when the sensors were deployed (4.74V and 4.73V respectively). The transmission may have failed because the beacon was lost when the floe broke up or, possibly, because the beacon was submerged in a melt pond.

[8] The data transmission from Floe 4 is not expected to have terminated due to battery limitations because there was still reserve capacity in the batteries when the last signal was transmitted on 12 August.

Tuktoyaktuk Peninsula. By late summer, both floes exhibited the spiral-like trajectory that has been documented previously for multi-year ice floes in the Beaufort Sea (Johnston, 2011; Hochheim et al., 2012; Blunt et al., 2013; and others). So, although the Tent floe and Floe 4 had nearly identical drift patterns early in the season, when the ice concentrations were high, the floes began to drift independently of one another as lower concentrations of ice were experienced later in the summer. An in-depth discussion of the driving forces behind floe drift is beyond the scope of this project, but will be reported upon elsewhere (Hochheim et al., 2012). That said, the drift trajectories of the Tent floe and Floe 4 clearly illustrate that some of the more significant floes encountered during the 2013 field study could pose a very real hazard to structures in the southern Beaufort Sea, including the relatively near-shore Amauligak site (Figure 33). In the following section, evidence is given of four, much more hazardous ice features that were encountered during the flights offshore but were not sampled.

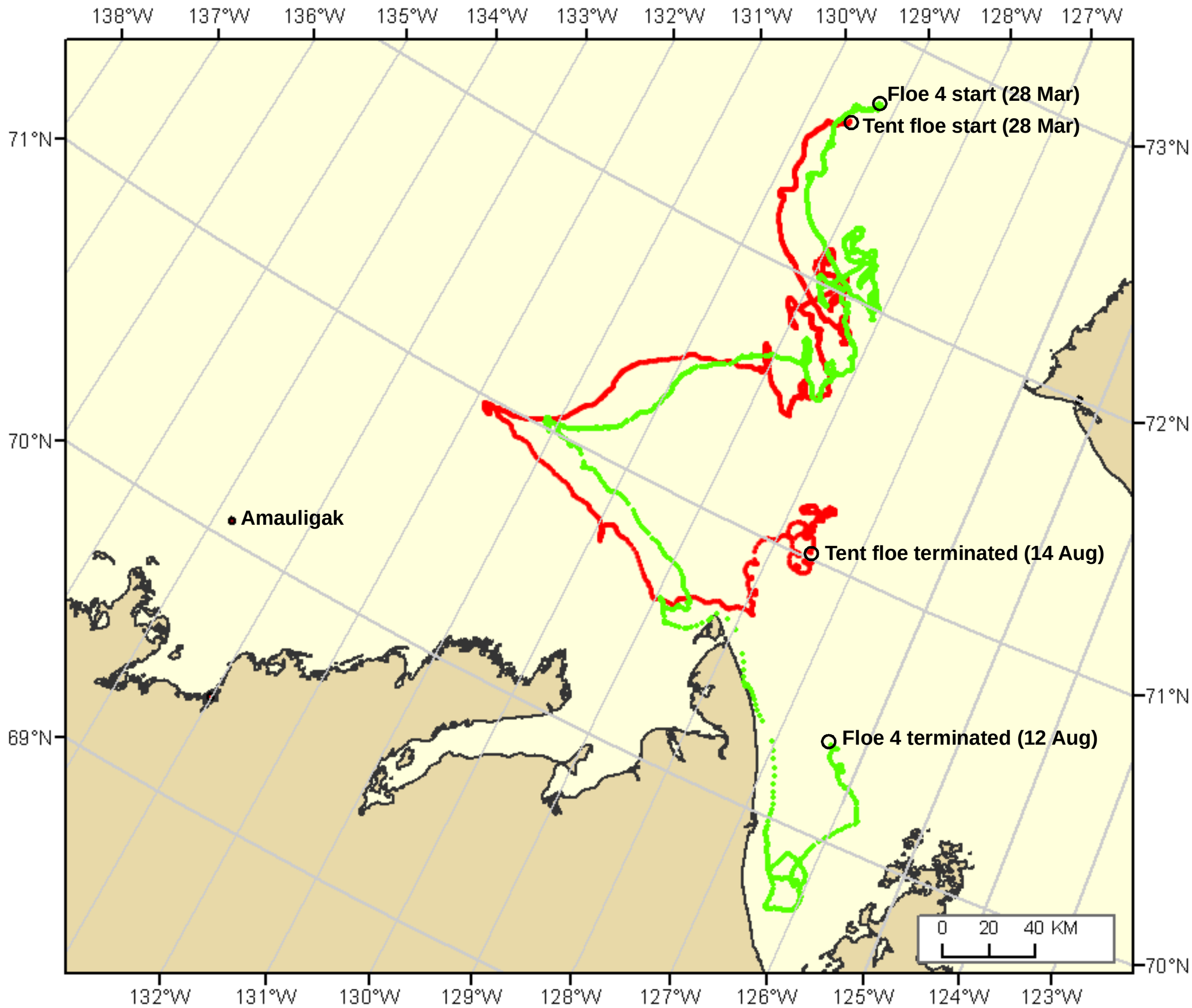

Figure 33 Trajectories of Tent floe and Floe 4 from March to August 2013.

6.9 Hazardous Floes whose Properties will Remain a Mystery

Had the field program continued for its full duration, it is fully expected that several of the more hazardous floes identified during the flights offshore could have been sampled. In addition to the floes discussed previously here, four additional floes are included, to further illustrate the types ice features that were encountered during the program. This discussion is by no means exhaustive because (a) it includes only a few of the features that were observed during the flights offshore and (b) each flight was made over the same general area of ice, as it drifted west. The floes discussed below were all identified about 150 to 200km northwest of Sachs Harbour.

On 23 March, during the first flight offshore, the First Officer pointed out an extensively hummocked floe as something that might be of interest to the field party. The author replied that the feature was of interest but that the floe presented too difficult of a challenge so early in the program. Figure 34 shows the floe that the First Officer was referring to. The extensively hummocked floe was encountered at 72°27.6'N, 129°22.4'W, 150km northwest of Sachs Harbour, and was estimated to be about 800m long. It was important for the pilots to slowly gain expertise while safely landing on deformed multi-year ice – which is not a trivial matter. In addition, it is prudent to step into the measurements slowly because the field team needs to familiarize themselves with operating the equipment, re-fresh their memory of (or learn about) the problems encountered while penetrating thick multi-year ice, and learn to work safely and efficiently to acquire measurements. First-hand knowledge has shown how fast equipment can freeze into the ice when an unpracticed field team samples sea ice of any thickness – thick, multi-year ice in particular. Losing equipment (or damaging it) on a formidable floe on the first day would put the entire field program in jeopardy.

Figure 35 shows a hummocked floe that was encountered on 28 March at 72°26'N, 129°17'W, also about 150km from Sachs Harbour. This particular floe was about 500m across and was similar to Sachs 17 in that hummocks were oriented in a linear fashion along its length.

Figure 36 shows a multi-year floe that has a hummocked interior but a relatively flat, level exterior. The floe was about 200m across and was observed at 72°26'N, 129°17'W, 148km northwest of Sachs Harbour.

Figure 37 shows a multi-year floe that is relatively level, apart from the prominent, serpentine hummock that extends along its full length. The floe was estimated to be about 500m long and was observed at 72°31'N, 129°43'W, about 165km northwest of Sachs Harbour.

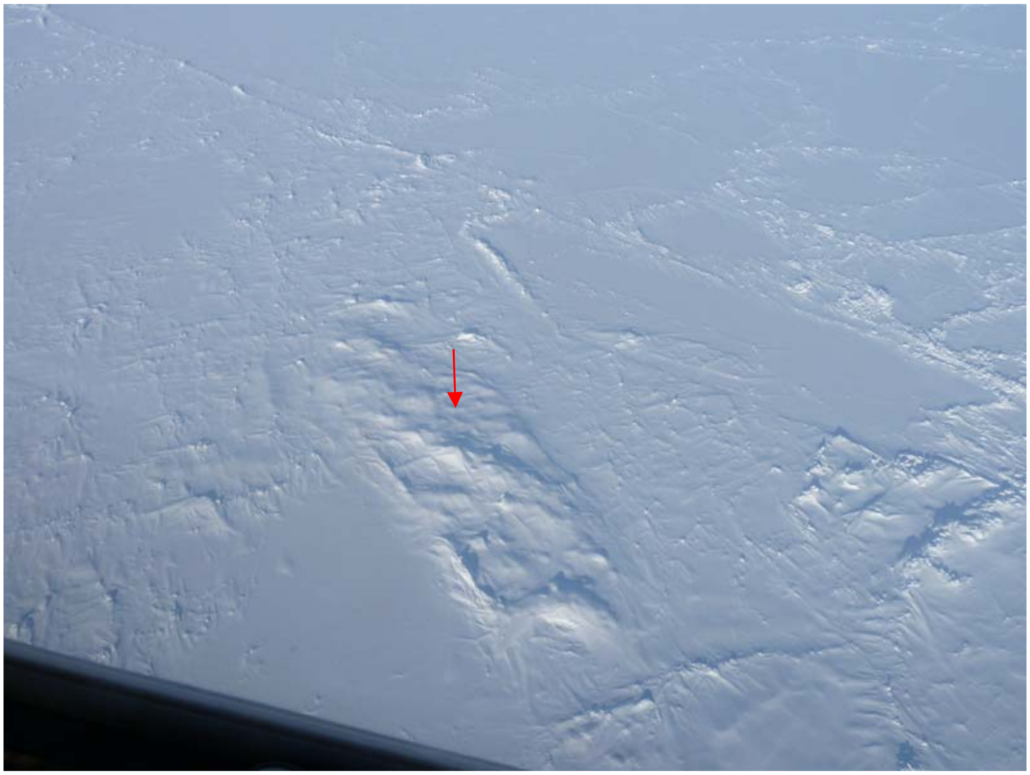

Figure 34 Extensively deformed multi-year ice floe with randomly oriented hummocks

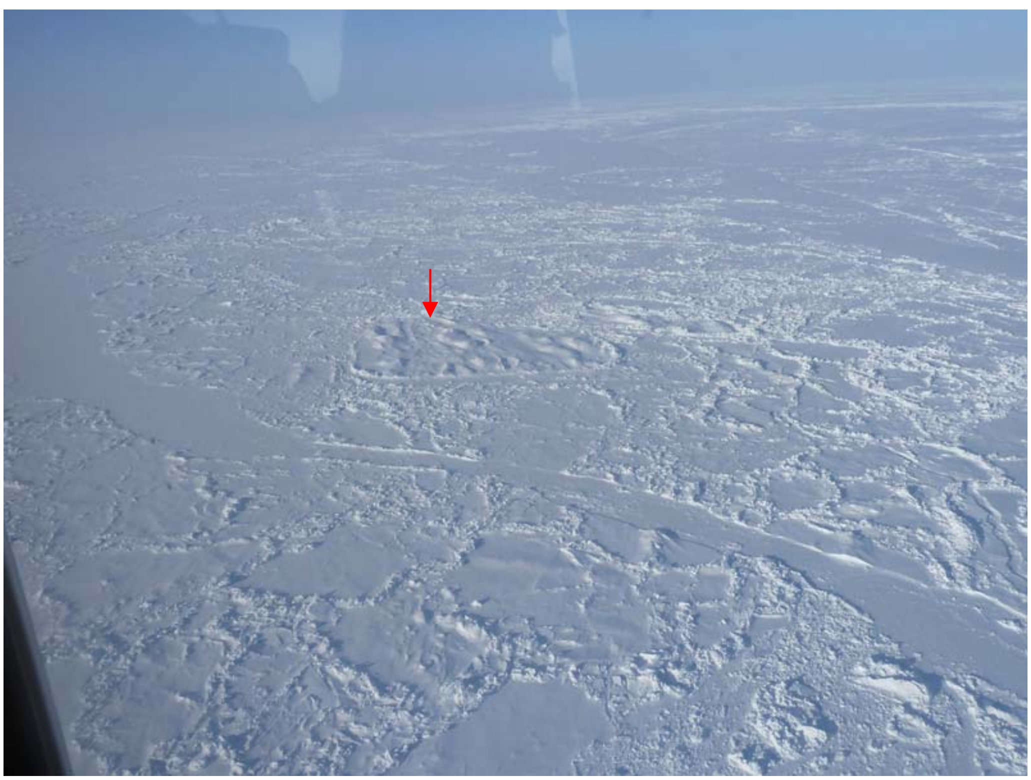

Figure 35 Multi-year ice floe with parallel, oriented hummocks

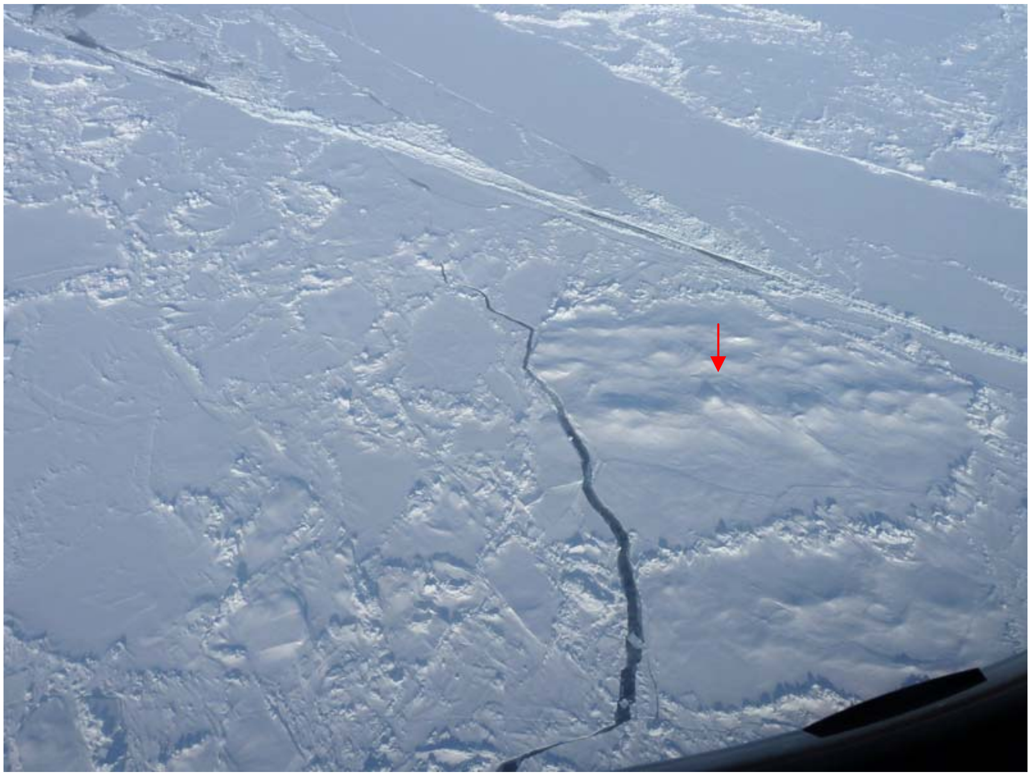

Figure 36 Multi-year floe with hummocked interior and relatively smooth exterior

Figure 37 Multi-year ice floe with sinuous hummocks extending along its full length

7.0 Summary and Conclusions

The 2012 and 2013 field programs were undertaken to provide information about extreme ice features, hummocked multi-year ice in particular. Having reported elsewhere about the intensive thickness measurements that have been made on multi-year ice floes over the past five years (Johnston et al., 2009) and the borehole strengths measured over the past decade (Johnston, 2014), the project sought to provide information about the strength of hummocked multi-year ice at the depths were none exists at present. In that, the 2012 field season was successful: for the first time, the borehole strength of multi-year ice below a depth of 10m was measured.

Results from the 2012 and 2013 field programs are summarized in Figure 38, along with borehole strength measurements made on multi-year ice over the past ten years by the author. The figure includes the temperatures and strengths measured on first-year ice in Becher Bay (Resolute, May 2012), first-year ice near Sachs Harbour (March 2013), and a hummock on the Nanook Floe (Resolute, May 2012). Results from approximately 600 borehole strength tests on multi-year ice floes sampled across the Arctic in spring, summer and fall are also included in the figure. The figure highlights some important points:

- Both first-year ice and multi-year ice exhibit a general trend of increasing strength with decreasing temperature. Multi-year ice shows a considerable amount of data scatter, whereas first-year ice does not. In terms of its strength: multi-year ice is far from uniform, whereas level first-year ice can be very uniform.
- Below a temperatures of -10°C, the borehole strength of first-year ice increases more gradually than the borehole strength of multi-year ice. As a result, the borehole strength of cold multi-year ice can be up to 50% higher than first-year ice, for a given temperature
- The borehole strength of first-year ice can be as high (or higher) than multi-year ice, for a given temperature, but that is not always the case, as noted above.
- First-year ice at near melting temperatures can be reliably determined to be weak, but multi-year ice can be either weak or strong at near melting temperatures.
- Data suggest different mechanisms control the temperature-strength relation for first-year ice (i.e. brine volume) versus multi-year ice (i.e. brine plus air volume), as discussed in Johnston (2014).

Having shown a direct relation between ice temperature and ice strength does not provide the complete solution to the questions posed at the beginning of this report: “how consolidated are multi-year ice hummocks” and “what is the keel strength of multi-year ice”. The fact that the vast majority of borehole strength tests on multi-year ice have been conducted above a depth of 6m (Figure 39) – which, in many cases, is not even half-way through the ice thickness – poses a significant challenge. Too few measurements have been conducted throughout the full thickness of multi-year ice to be able to confidently extrapolate past results to greater depths. That bears repeating: measurements conducted from crest to keel on a single multi-year ice hummock cannot be used to discuss the keel strength of multi-year ice, for a larger population sample, with any confidence. The objective of the 2013 field program was to document the thickness and strength of hummocked multi-year ice in the Beaufort Sea and compare those measurements to floes sampled elsewhere in the Arctic. Future field programs on multi-year ice will aim to satisfy that objective which, as yet, has not been fulfilled.

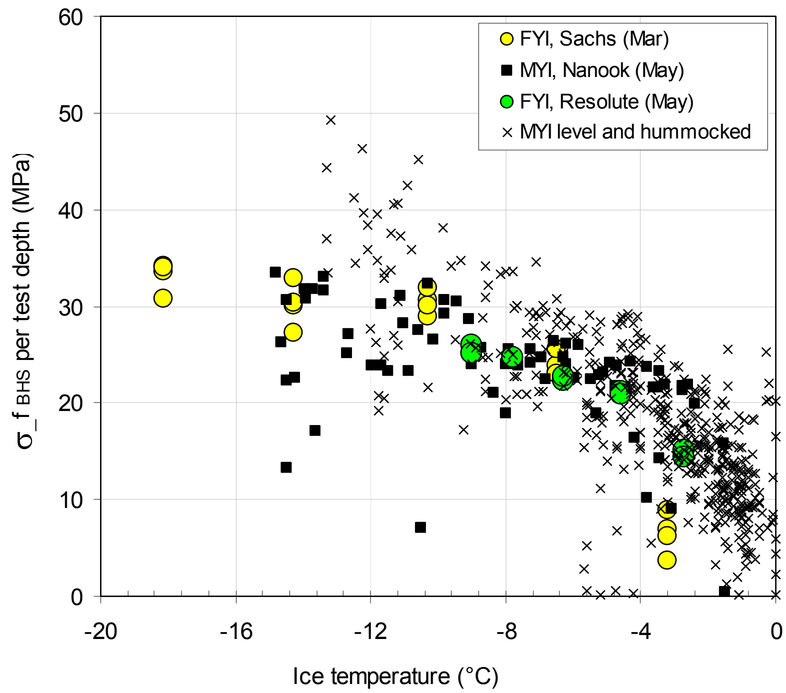

Figure 38 Ice failure stress, σ_f $_{BHS}$ versus ice temperature for level first year ice and multi-year ice. Strengths measured by NRC on level and hummocked multi-year floes over past decade also shown (after Johnston, 2014).

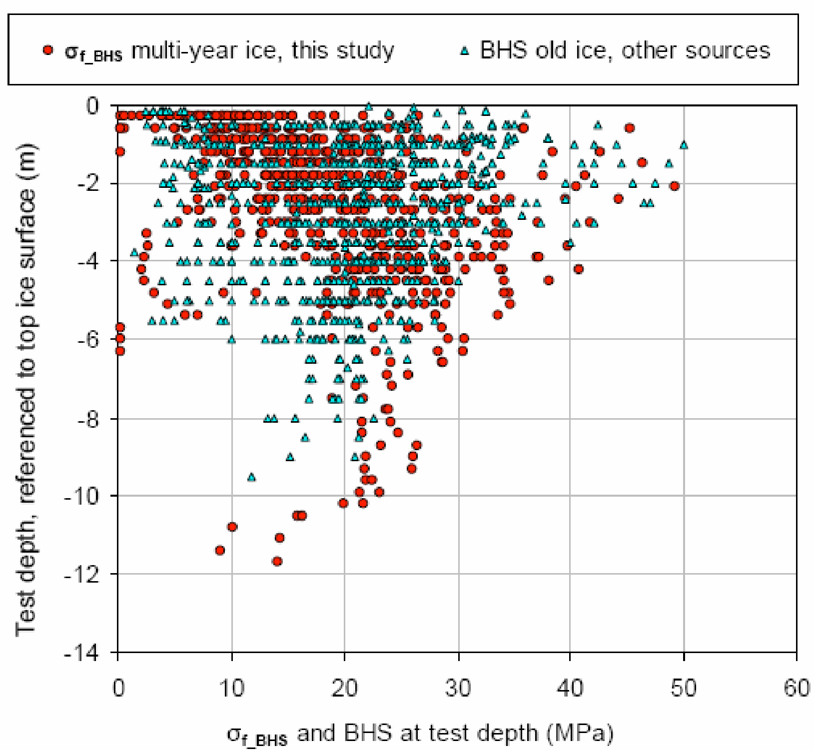

Figure 39 Results of borehole strengths for (1) old ice floes sampled from 1978 to 1991 and (2) multi-year ice floes sampled since 2002 (after Johnston, 2014).

8.0 Acknowledgments

This Joint Industry Project (JIP) was made possible through the financial support of the Program of Energy Research and Development (PERD), Aboriginal Affairs and Northern Development Canada (AANDC) via the Beaufort Regional Environmental Assessment (BREA), Polar Continental Shelf Program (PCSP), National Research Council Canada and the Oil and Gas Industry. The financial support that NRC provided for some of the key items needed in the first year is gratefully acknowledged, as is the enthusiastic involvement of OCRE's (formerly CHC) then-acting General Manager, E. Magel. 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. PERD and BREA also deserve credit because, without their support, this would not have been possible. 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 – who had the skill to deliver on the program – and the Twin Otter pilots. C. Fillion, K. Brett, T. Retieffe and J. Kuptana were the people 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. Klaus 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 Ed Hudson, Environment Canada, for extending the Greater Forecast Area (GFA) to include offshore Banks Island during our program. The ongoing support of the National Research Council's Design and Fabrication Services (DFS) is sincerely appreciated because they are the people who design and fabricate much of the first-class, customized equipment needed to tackle multi-year ice. The Nunavut Research Institute and the Aurora Research Institute also deserve credit for the programs because, through them, communities are contacted and scientific permits awarded. R. Frederking has also been an important contributor to the project through his review of the report but, more importantly, for his assistance in organizing the 2013 field program. My apologies are extended in advance to the many other persons who helped with both field programs, but are not mentioned here.

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Appendix A: Logistical Challenges met with during 2012 and 2013 Programs

Logistical Challenges met with during 2012 and 2013 Programs

The Beaufort Sea is the area of interest for BREA and the Oil and Gas Industry. Due to perceived differences in the properties of the ice, sampling multi-year ice in regions outside the Beaufort Sea is frowned upon, because the ice may not be representative. That is not the opinion of the author, however. The compilation of drill hole thickness data from the past 50 years does not show substantial regional differences in the thickness of multi-year ice across the Arctic (Johnston et al., 2009). Similarly, one of NRC's past field programs on multi-year ice in the Beaufort Sea confirmed that multi-year hummocks, even in late summer, can be thick, cold and competent, making them comparable to multi-year floes sampled in the central and eastern high Arctic (Johnston, 2014). The 2012 and 2013 field programs were made in very different regions of the Arctic – one successful and the other unsuccessful – which suggests that delivering on the objectives of this research program, in the time-frame given, may require conducting the field program outside the Beaufort Sea, where the work can be performed safely, in a less risky environment, and in an area that is more assured to produce results, at lower cost. The subsequent discussion includes some important elements from both field programs that should be taken into account when objectively evaluating past and future work.

Spring 2012 program

Year 1 was about developing new equipment: designing, fabricating, testing and modifying the equipment as needed and then, over the course of a two or three-week field program, using it to sample as many multi-year hummocks as possible. NRC's Design and Fabrication Services (DFS), in consultation with the author, began designing and fabricating the equipment in April 2011. By October, a field program from Sachs Harbour in spring 2012 looked unlikely, for the reasons given below. The author contacted PERD and AANDC (BREA) to explore the possibility of relocating the field program to Resolute. Four of NRC's past field programs on multi-year ice (2002, 2008, 2010, 2012) have been conducted from Resolute – all of them produced results – largely because the experience and infrastructure of Polar Continental Shelf Program (PCSP) make Resolute an excellent and safe staging point for on-ice operations. Field programs can certainly be staged from other locations, but costs can be prohibitive and the success of operations less assured.

PERD was amenable to relocating the project to Resolute, but it was more challenging for AANDC to support the move, due to the site-specific nature of the BREA program. NRC conveyed to AANDC the following information, to allow them to be informed when approaching the BREA Regional Advisory Committee (RAC) about why a program from Resolute was needed, and whether it could be supported. AANDC was given the following rationale for relocating the program:

> **Shipping equipment to Sachs Harbour:** A field program from Sachs Harbour would require shipping equipment from Ottawa to Inuvik in late February. However, several new pieces of equipment would not be completed until January, leaving insufficient time to test the equipment and fabricate custom-made shipping boxes. Relocating the program to Resolute, and conducting it in May (rather than March/April), allowed the equipment to be shipped later, since commercial First Air flights could transport the over-sized equipment directly from Ottawa to Resolute. Shipping costs would also be considerably cheaper because it would not be necessary to truck the equipment (to Inuvik) and then charter aircraft (from Inuvik to Sachs Harbour).
>
> **Workspace in Sachs Harbour:** Facilities in Sachs are extremely limited. Problems with the new equipment were almost certain to occur in the field and, without some sort of machining facilities to

retool the equipment, it could not be adequately tested and proven under Arctic field conditions. The workshop and warehouse at PCSP provided the space and machining facilities to fix equipment, which is key to ensuring a successful program.

Cost of Sachs Harbour field program: Finances threatened to sabotage the 2012 field program if conducted from Sachs Harbour. When the author approached BREA in October about relocating the program, funding from BREA had been secured for the program but PERD had not formally announced support for the project. Industry funding would not be forthcoming for the field program because the equipment had not yet been proven. Given those parameters, the only option was to conduct a bare-bones program from Resolute using Government funding alone. The sum total of Government funding would cover only a portion of the costs of operating from Sachs Harbour.

Transporting equipment to the ice each day: Considerable time and effort had been spent from August to October determining how to transport the 1500kg of NRC equipment from Sachs Harbour to the multi-year ice each day, which would likely be 150km offshore. That was not a problem for our collaborators, the University of Manitoba/York University, because their measurements required transporting only about 150kg of equipment to the ice each day, and fewer people. Once it had been determined that Twin Otters could not provide a viable (or safe) option for transporting equipment and personnel offshore to dynamic ice in the Beaufort Sea, despite the assurances made by commercial aircraft companies, it was decided that helicopter support was the only option (with an attendant increase in cost). A Twin Otter/helicopter combination could be used to safely conduct the work from Resolute, however, since the ice would be landfast.

Demonstrating results: A field program conducted from Resolute had a much greater likelihood of successfully demonstrating that the strength of hummocked multi-year ice could be measured below a depth of 7m, where data are most needed. A successful 2012 field program was critical because the results could be used to attract Industry funding for a larger program from Banks Island the following year (spring 2013).

The matter was discussed at the fall meeting of the BREA Regional Advisory Committee (RAC). The RAC grappled with the question of funding a field program that would be conducted outside the Beaufort Sea Region. The decision was not an easy one for the members of the committee but, after considering the matter, the RAC decided to:

> "*support Johnston's relocation to Resolute for 2012-13 ONLY on condition of proof of support from PCSP or PERD and on condition of availability of aircraft to transport gear to multiyear ice*." *The decision is also contingent upon the 2013 field program being conducted in the Beaufort Sea.*

NRC received positive news from the RAC in late October. The official announcement of support from PERD was announced shortly after. NRC then contributed additional funds needed to make the project happen. Only then, with funding assured, was an application submitted to PCSP in time to meet their 1 November 2012 application deadline for the upcoming season. Several months later, PCSP issued an official email of support to applicants (4 April 2012), by which time several shipments of NRC equipment were already en route to Resolute. PCSP and NRC arrived at the exact dates for the NRC field program after PCSP had devised a schedule to optimize cost-sharing between all research projects and minimize the number of helicopters onsite in Resolute.

Spring 2013 program

Shortly after returning from Resolute in late May, preparations began for the 2013 field program. In hindsight, and from discussions with personnel from Discovery Mining Services, the amount of time needed to organize such a complex field program from the remote community of Sachs Harbour is expected to be comparable to organizing a remote field camp. Fully describing the year that was needed to organize the 2013 field program would consume too many pages, so the following abbreviated discussion is given to show that even trivial things can become program-threatening issues in the North.

Obtain additional funding when cost of 2013 program increases to ~$1M: The cost of the 2013 program increased immensely (from the initially estimated $500k) when it was decided that re-fuelling the aircraft on the ice would not be permitted and that it would not be possible to sling the equipment to the ice, which could be up to 150km from shore. A larger helicopter would be needed to carry the requisite amount of fuel and cargo to the ice. Personnel and equipment would need to be transported offshore with a twin engine Bell 212 helicopter, a heavy-lifting machine, rather than using two, smaller helicopters (as done by the University of Manitoba, in the spring 2012). Costs increased further when aircraft had to be chartered to transport personnel and cargo from Inuvik to Sachs Harbour, and back. Several of the boxes were too large to ship by commercial aircraft and the 10 small tanks of propane needed to be shipped on a "cargo only" aircraft. Lodging and food also increased costs considerably[9].

Contracting the helicopter, securing fuel for operations, permits needed to store fuel: By far, the most complicated aspect of organizing the field program was locating a helicopter company with sufficient experience in Arctic operations, settling upon a price, and ensuring that enough fuel was barged to Sachs Harbour (prior to the end of the shipping season) to support two-weeks of helicopter operations. Normally, this is handled by PCSP but NRC did not approach PCSP about supporting the 2013 program because their letters of support would be issued too late (Feb/March 2013) for NRC to issue the many other contracts that had to be put in place to conduct a March 2013 program from Sachs Harbour. To compound matters, NRC's 2013 field program would be split over two Government fiscal years (March to April 2013). The fiscal year split made it difficult for PCSP because (1) budgets had already been allocated for FY12/13 and (2) PCSP's budget would not be in place in time to support an NRC program from Sachs Harbour in FY13/14. The fiscal year split was necessary because the limited logistics in Sachs Harbour did not permit NRC, the University of Manitoba and York University to conduct simultaneous field programs. NRC would conduct their three-week field program from mid-March to mid-April; the University of Manitoba and York University would conduct their two-week field program from mid to late-April.

PCSP offered advice about the steps that needed to be taken to contract helicopter operations, however a considerable amount of time was spent obtaining quotations from various helicopter companies, exploring what was needed to issue such a large air charter services contract (~$500,000) through Public Works and Government Services Canada (PWGSC) through the National Master Standing Offer (NMSO) process, drafting a Statement of Work (SOW) for PWGSC, and investigating how to obtain enough fuel for helicopter operations (since none was available in Sachs Harbour – which had been nearly catastrophic for UofM's 2012 program from Sachs Harbour (K. Hochheim, personal communication)). In June 2013, discussions about barging fuel into Sachs Harbour began – discussions that continued until

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[9] The spring 2013 program was the first time that arrangements had to be made for food and lodging. Food and lodging for all past programs have been provided by PCSP (when working from Resolute) or the Coast Guard (when working from ships), for a very reasonable daily rate.

September, when it was finally determined that it would not be possible for NRC to issue a contract to barge 100 drums of fuel to Sachs Harbour in time to meet the barging company's deadline. The problem was compounded by the Terms and Conditions (of the only barging company in the Western Arctic) exposing NRC to an unreasonable amount of liability, hence being unacceptable to NRC. That meant that the 100 drums of aviation fuel would need to be flown, rather than barged into Sachs Harbour – at two to three times the cost. Various options were explored, but eventually it was realized that the 2013 field program could only occur if a third party contracted the helicopter company and provided fuel for helicopter operations. On 16 November 2012, Industry and NRC signed an agreement to cover all helicopter costs and a portion of additional program-related expenses for the 2013 program.

Contracting camp cook and groceries for three-week program involving 8 persons: A camp cook is absolutely essential when on-ice measurements require a considerable amount of heavy lifting and are conducted for 10 hours a day, at temperatures of -35°C. The work-day does not end there: all equipment has to be cleaned and data analyzed prior to conducting additional measurements the following day. Discovery Mining Services was contracted to provide groceries for the entire field party, a cook to prepare three meals each day and an assistant to help with on-ice measurements. The on-ice assistant also functioned as a secondary wildlife monitor (as discussed further below).

Transporting equipment, personnel and groceries to Sachs Harbour: Transporting equipment, personnel and groceries to Sachs Harbour required trucking the equipment from Ottawa to Inuvik. At the end of January 2013, the 4000lbs (2000kg) of NRC equipment was picked up from the NRC Ottawa laboratory and trucked to Inuvik. Once in Inuvik, the equipment was delivered to an expediting company (Aurora Expediting), where it was stored until the date of the aircraft charter to Sachs Harbour. The expediting company delivered the equipment to the Inuvik airport and loaded it onto the chartered aircraft. This may not sound complicated, but the likelihood of the aircraft being delayed due to adverse weather required the expeditor to be flexible and deliver the cargo when it was needed, rather than the date/time for which it was scheduled. It was imperative that the scientific equipment and, more importantly, the perishable groceries were delivered to the airport at the correct time, there being no warehouse to store any cargo onsite. Leaving such a large amount of equipment on the tarmac at such cold temperatures (-30°C) was not an option. Two aircraft had to be chartered (from Aklak Air) to transport equipment, personnel, baggage and groceries to Sachs Harbour. A DC-3 transported the equipment (4000lbs), furnace (1000lbs) and groceries (3000lbs), consuming the aircraft's capacity. A Twin Otter was then chartered to transport the NRC field team (five personnel) and their baggage from Inuvik to Sachs Harbour. The fact that all of the NRC equipment arrived in Sachs Harbour undamaged, at the scheduled time, testifies to the competency and care taken by all persons involved in the shipping aspect of the program (PREP Services who delivered all equipment to Inuvik and provided documentation for NRC's dangerous goods on the return trip, Aurora Expediting and Aklak Air).

Lodging and a staging area in Sachs Harbour: Jackie and Roger Kuptana of Kuptana's Lodge (where the field party stayed for the duration of the program) played a vital role in ensuring that arrangements flowed smoothly and providing information about who should be contacted when difficulties were encountered. The Kuptanas were contacted numerous times about accommodation-related logistics before arriving in Sachs Harbour on 18 March. Once in Sachs Harbour, about 10 trips were made, using two pick-up trucks, to transport groceries and baggage from the airport to Kuptana's Lodge. The scientific equipment was moved to an area of the tarmac where it would not interfere with air traffic until it could be transferred to the staging area that had been previously discussed with Parks Canada. After several, unsuccessful attempts to contact Parks Canada (Sachs Harbour and Inuvik offices), the equipment was transferred to the unlocked, unheated Parks Canada garage. The phone-call to Parks

Canada (Inuvik) made by the Sachs Harbour Hunter's and Trapper's Organization (SHHTO) the day after our arrival, resulted in our request for garage access being declined because no Park's Canada representative was in Sachs Harbour at that time. With that, the SHHTO helped us search for other staging areas, including the RCMP, Co-op, etc. In the end, the Parks Canada garage was the only suitable staging area in Sachs Harbour. The author then received a response from Parks Canada (Inuvik) granting permission to use the garage as a workspace for the duration of the program. Only then, was the equipment unpacked and work begun in earnest.

Safety: two firearms needed on ice at all times: Having two firearms on the ice is an absolute necessity, as has long been recognized by the Polar Continental Shelf Program (PCSP) in their 'Operations Manual' (https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earthsciences/files/pdf/polar/pcsp_manual_eng.pdf). The past ten years of field programs have involved hiring a person from the community to function as primary wildlife monitor and having one person from NRC function as secondary wildlife monitor. Changes brought about at NRC over the past year have resulted in NRC personnel no longer being permitted to carry firearms, due to liability issues. As such, during the 2013 program (and all future field programs), it was necessary to contract two persons to function as primary and secondary wildlife monitors since neither could be employed by the NRC. That, in turn, increases costs because it means that a larger helicopter – or an additional helicopter – be used to transport personnel and equipment offshore.

Assembling a field team for the 2013 field program: Field technicians are essential because they are responsible for operating the equipment needed to produce results. Excellent technicians are not easy to come by. It takes years to develop the skills needed to operate customized equipment efficiently, understand the nuances of penetrating thick ice, and solve the myriad problems that occur during a field program. The spring 2012 program was the last field trip in which R. Lanthier, NRC's lead technician since 2007, could participate. His place was filled by C. Fillion, who had participated in several of NRC's past field programs on multi-year ice. C. Fillion was the only person with pre-existing knowledge of NRC's equipment and the techniques needed to conduct measurements on thick, multi-year ice. Three field technicians from NRC's office in St. John's traveled to Ottawa in January to participate in a three-week familiarization session that involved preparing the equipment, training to maintain/repair it, and familiarizing themselves with how the equipment should (and should not) be used. Upon concluding the three-week familiarization session, it was decided that only K. Brett should participate in the 2013 field program[10]. Discovery Mining Services was contacted to provide an experienced person for remote Arctic operations – since PCSP has suggested that personnel from Discovery Mining Services could help with NRC's complicated and physically demanding measurements on multi-year ice. T. Retieffe, from Discovery Mining Services, signed on to the field team in February, to function as on-ice assistant/secondary wildlife monitor. The final member of the field team was Jeff Kuptana, from the community of Sachs Harbour. By early March, the SHHTO had confirmed that Jeff met the requirements of wildlife monitor, i.e. participation in a Wildlife Monitor Training Course, current firearms acquisition certificate (FAC), registered firearm, etc. By early March, the five members of the field team had finally been assembled: M. Johnston, C. Fillion, K. Brett, T. Retieffe and J. Kuptana. The other person who was essential to the field program, but did not venture onto the ice, was T. Latimer, the camp cook from Discovery Mining Services.

[10] The decision was partly a result of NRC personnel not being permitted to carry firearms.

Helicopter operations: During the field program, it became apparent that the helicopter crew did not have the knowledge and experience to safely deliver on such a complicated field program. On 31 March, the field program was officially terminated by the author, due to helicopter-related concerns about health and safety of the field team. A detailed description of the reasons leading up to the termination is given elsewhere[11]. The two primary reasons for terminating the program include (1) the Bell 212 helicopter arrived onsite on 22 March with skid gear only (no floatation), contravening what had been previously agreed to during a conference call between the helicopter company, Industry and NRC and (2) on 29 March, after spending a night on the ice, the pilots could not articulate an emergency plan should landing on thin ice be required, which was cause for serious concern, considering the distance that needed to be traveled over open water/broken ice to reach the multi-year ice offshore.

On 1 April, the University of Manitoba's subsequent decision to cancel their field program from Sachs Harbour, which was scheduled to begin on 7 April 2013. University of Manitoba planned to use the same helicopter company, and the same helicopter, to access multi-year ice from Sachs Harbour.

Safety-related follow-up from 2013 Program

After returning from the field, several seasoned colleagues, each with many years experience accessing sea ice by helicopter and fixed wing aircraft, were contacted about their past experiences. One colleague communicated a recent experience in which the Pilot in Command fully intended to land and shut down on dangerously thin ice in a refrozen wake, as opposed to more solid ice nearby – and would have done so, had the colleague not objected violently. A very experienced logistics provider in the Arctic stated that every year, the situation seems to deteriorate: too few pilots have the expertise to land safely on sea ice. A third colleague mentioned that finding experienced, skilled pilots to undertake sea ice research in the Arctic is becoming "a real problem". All of this evidence suggests that, too frequently, pilots do not have the experience, knowledge or skill needed to safely conduct field programs on sea ice.

On 23 May 2013, the author received permission from NRC to contact Transport Canada. The Transport Safety Board (TSB) was first contacted about the matter when it was realized that NRC, as a legal requirement, cannot fail to disclose information that could prevent a much more serious accident from occurring. The TSB informed NRC that the events of the 2013 field program, although serious, were outside the scope of their jurisdiction because they did not constitute an 'incident', i.e. the field party returned home safely after each trip offshore, with minimal injuries. The TSB recommended that NRC approach Transport Canada and the Helicopter Association of Canada about the matter.

It was decided to pursue the safety-related aspect of Arctic field programs by circulating a proposal to develop Standard Operating Guidelines (SOG) for helicopter-based and ship-based field programs. A draft proposal from NRC has been in circulation since October 2013, when the importance of Health and Safety matters was underscored by the tragic helicopter accident from the CCGS *Amundsen*. As of the time of writing this report, NRC continues to work towards improving the safety-related aspects of helicopter-based fieldwork through discussions with other Government Departments and Industry.

[11] Johnston, M.E. (2014) 2013 Field Program Closure Report. Technical Report OCRE-TR-2014-003 (Protected C) for National Research Council Canada. 16 January 2014. Ottawa, ON, Canada, 54 pages.

Appendix B: Sampling Methodology

Sampling Methodology

Upon arriving on a multi-year ice floe, flagged transects are constructed on both level and deformed ice, along which the snow thickness, ice thickness and ice freeboard are measured at 10m intervals. The ice thickness is measured by penetrating the full thickness of ice using either the so-called ‘drill-hole technique’ or a steam machine. The drill-hole technique requires drilling multiple lengths of 2” auger through the ice, to a depth of up to 23m (i.e. the limit of a well-trained, physically fit, two-man team unassisted by a drill frame). After penetrating the full thickness of ice, the auger flights are retrieved, disconnected one by one and counted to obtain a rough estimate of ice thickness. A more accurate thickness measurement is then performed by lowering a weighted tape into the hole until it hooks on the underside of the ice. The tape is then slowly raised to the surface until it clears the waterline (or residual drill cuttings in the hole) to estimate the ice freeboard. The steam machine can be used to penetrate to a depth of 25m but it does not measure the thickness as accurately as the drill-hole technique, since the ice thickness is estimated from the approximate length of hose. The steam machine is much less labour intensive than the drill-hole technique but it does have some disadvantages. The smaller diameter steam hole does not allow the ice freeboard to be measured, nor does steaming through the ice provide measure of the ice integrity, unlike the ‘hard’, ‘medium’ or ‘soft’ that can be felt while mechanically drilling through the ice. At very cold air (and ice) temperatures, the steam machine consumes a considerable amount of water, which means that a considerable amount of freshwater has to be transported to site – and more importantly – prevented from freezing over the course of the day.

The ice thicknesses are used to determine where larger diameter boreholes will be made for ice property measurements. Up to five boreholes are made on each floe in both level and hummocked ice. Time constraints often prevent conducting a full set of property measurements in every borehole but vertical profiles of the ice temperature, salinity and borehole strength are made in at least one borehole per floe. When ice cores are required for temperature and salinity measurements, boreholes are made with a 150mm or 178mm diameter fibreglass corer. Temperatures are measured on each one metre long core segment by inserting a calibrated temperature probe (accuracy ±0.1ºC) into small holes made in the core at depth intervals of 200mm. The few seconds that are required for the temperature probe to stabilize are spent cutting salinity specimens from the portion of the core on which temperatures have already been measured. Semi-circular discs are cut from the core at intervals of 200mm, sealed in plastic bags, and transported to base camp. The samples are allowed to reach room temperature, after which the salinity of the melt water is measured with a calibrated conductivity meter (accuracy ±0.5%). When cores from the borehole are not needed, a 150mm or 178mm diameter ice auger is used to prepare the borehole for strength tests[12]. The ice auger allows the work to proceed much faster, but at the expense of having well documented properties from each borehole. Although the temperatures from one borehole can be used to approximate temperatures in subsequent boreholes, making some adjustments for differences in ice thickness, generally, it is not possible to interpolate salinities within a borehole (or extrapolate salinities between boreholes) because each value is unique.

Strength tests are conducted at 0.30m depth intervals throughout the full thickness of ice or to the maximum depth of the borehole, when full thickness penetration has not been achieved[13]. To minimize

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[12] Strength tests were not affected by the method that was used to create the borehole (auger or corer). The important element here, is that the cutting teeth be sharp and the rpm of the auger is comparable to the relatively low rpm at which the core barrel operates.

[13] Allowing sea water to infiltrate the borehole after penetrating the full thickness of ice has not adversely affected test results, provided the tests are conducted as quickly as possible. Even when boreholes are drilled partially

damage caused by strength tests at one depth from interfering with tests at other depths, the borehole indentor apparatus is rotated 90° between each test depth and boreholes are separated by a distance of at least 5m. Typically, strength tests are conducted from the top of the ice sheet to the bottom because that increases the likelihood of retrieving the borehole apparatus if it becomes stuck in the ice, which sometimes happens. To prevent jamming down-hole, the borehole apparatus is raised to the top ice surface after every few tests so that the indentors can be extended in free space to clear away any crushed ice that has accumulated behind the indentors. Given the tight fit between the indentors and the wall of the borehole, even a 2 to 3mm thick layer of crushed debris can prevent the indentors from fully retracting. The second reason for periodically raising the borehole apparatus to the top ice surface is to ensure that a hydraulic leak has not occurred. Problems with the borehole apparatus are to be expected, particularly given the high pressures attained in multi-year ice, but most problems can be prevented by properly maintaining the borehole system and monitoring the tests closely. Even though strength tests at each depth require less than two minutes, several hours are needed to obtain the full suite of measurements for each borehole, largely because of the sheer weight of equipment needed to sample the full thickness of multi-year ice: the borehole apparatus, with its attached hydraulic hoses, saddle and stainless steel test depth rods, weighs 125kg. The coring equipment for penetrating to a depth of 12m weighs much the same.

During a strength test, an in-line calibrated pressure transducer measures the oil pressure and two, linear variable displacement transducers (LVDTs) measure the indentor displacements. Pressure and displacement data are sampled by an external data acquisition system (DAS) at a frequency of 10Hz. Output from a large-format, pressure dial gauge and the DAS are monitored closely during every test, to ensure that the test is terminated prior to attaining the maximum capacity of the electro-hydraulic pump (10,000psi) or the maximum diametrical displacement (50mm) of the borehole indentors, whichever comes first. To verify the processed digital data, notes are made about time, maximum pressure, indentor displacements and any irregularities that occur during each test.

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through the full ice thickness, it is not possible to keep seawater from infiltrating the hole before the series of strength tests are complete in each borehole, particularly in late summer.

Appendix C: Defining the Borehole Strength

Defining the Borehole Strength

The borehole indentor system is accepted as an ISO standard for obtaining *in situ* ice strength (ISO, 2010) but standard criteria have not yet been developed to answer the essential question of how the borehole strength should be defined. In this report, the pressure vs. time plots are used to classify the ice failure processes into the categories shown in Figure 40, from which the ice failure pressure or 'ice borehole strength' (σ_f_{BHS}) is determined. The reader is referred to Johnston (2014) for a more detailed description of the approach and comparison to other approaches.

It should be noted that Figure 40 presents results from the borehole tests in terms of the oil pressure rather than the ice pressure, which is the normal convention. This was done primarily to emphasize the fact that some of the tests needed to be terminated before an ice failure stress occurred, due to the 10,000psi (70MPa) operating limit of the electro-hydraulic pump and design limit of the NRC borehole system. During analysis, the conversion from oil pressure to ice pressure (or 'plate pressure' as it is sometimes called) is one of the final steps in the analysis, to be consistent with readings noted from the large format dial gauge and DAS during the actual strength test. The ice pressure for the NRC borehole apparatus is obtained by multiplying the oil pressure by the ratio of the borehole piston area to the indentor plate area (0.56), and is specific to this particular borehole indentor system.

Type 1: Premature failure

The pressure vs. time history for premature failure (Type 1) typically exhibits a saw-tooth pattern due to the repeated ice fracturing that occurs during a test (Figure 40-a). During premature failures, the ice fractures, releasing the pressure and allowing one (or both) indentors to surge forward until encountering renewed resistance. If the damage is not too severe, the cycle will repeat itself several times before the indentors reach their full stroke but sometimes the failure is so catastrophic that one, or both indentors travel to the end of their stroke with no further resistance. Such is the case when large ice fragments around the borehole sever or 'spall', as fractures propagate to the top or bottom ice surface or a cavity within the ice. For premature failures, the ice borehole strength at failure (σ_f_{BHS}) is defined by the first fracture to cause a substantial drop in pressure, since the integrity of the borehole has been compromised from that point on.

Type 2: Upper-yield

The ice exhibits upper-yield failure (Type 2) if the pressure increases to a maximum and then decreases monotonically. For upper yield failures, σ_f_{BHS} is defined by the so-called 'stress reversal point' because from that point on, further penetration produces reduced pressures (Figure 40-b). Defining the borehole strength for upper-yield failures is straightforward because the ice failure stress and the maximum ice pressure are one in the same. The sub-categories of upper-yield type failures include 'extrapolated yield', 'well-defined yield', 'pre-yield fracture' and 'post-yield fracture'. Of all the ice failure processes, extrapolated yield failures (Type 2a) present the greatest challenge for defining σ_f_{BHS} because the strength tests conclude prior to ice failure. A curve-fitting process was used to extrapolate to a stress reversal point for tests that terminated before yield. Defining σ_f_{BHS} for the three other subcategories of upper-yield failures was much more straightforward because they each showed a well-defined stress reversal point. Two of the subcategories involved relatively insignificant ice fractures occurring before, or after yield. The fractures were different than the stress-limiting fractures of premature failures (Type 1) because they produced a relatively minor decrease in pressure and were not felt during a strength test. Figure 40-b shows that σ_f_{BHS} is defined by the first yield point, even when a second yield point occurs during a strength tests; usually the first yield condition produced higher or equivalent pressures to the second yield point.

Type 3: Poorly-defined Yield

Borehole tests qualify as poorly-defined yield failures if the initial monotonic increase in pressure is followed by an incremental change (Type 3a) or a plateau (Type 3b) in pressure that continues until the end of the indentor stroke. The absence of a clear yield point makes defining σ_f_{BHS} ambiguous for these types of tests (Figure 40-c). For that reason, σ_f_{BHS} was defined by the point at which quasi-steady state is reached, i.e. the point at which continued indentor penetration meets marginal increases in ice resistance (or ice pressure). Here, quasi-steady state is defined as the rate of change in oil pressure of 200psi/s (1.37MPa/s).

Type 4: Total Yield

Strength tests classify as total yield failures when the ice offers little or no resistance to the indentors over their full stroke (Figure 40-d). The initial monotonic increase in pressure is followed by a complete loss of ice resistance often, because the presence of internal voids or its poor consolidation means that the ice lacks competency. Quite simply, the ice cannot present sustained resistance to the indentors during Type 4a failure. ‘Minimal resistance’ failure (Type 4b), the other subcategory of this class, exhibits negligible pressure throughout the test. Note the absence of a monotonic increase in pressure. Both Type 4 failures exhibit a rate of change in oil pressure that is less than 200psi/s (1.37MPa/s) throughout the full duration of the test, with few exceptions.

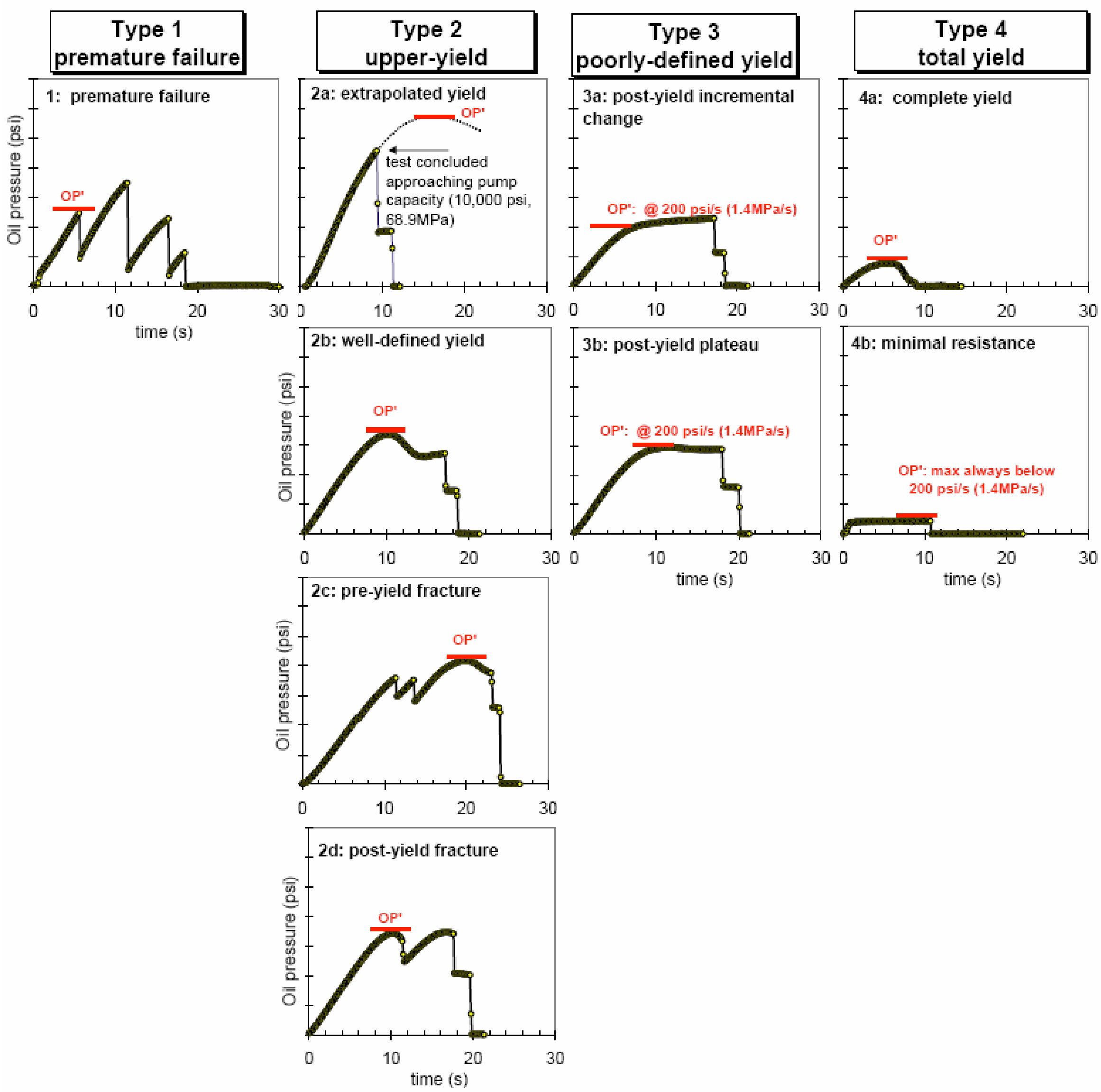

Figure 40 Failure behaviours characteristic of borehole strength tests in multi-year ice. OP′ denotes maximum oil pressure. The scale of the y-axis (oil pressure) is the same for all plots.

Appendix D: Journals for 2012 and 2013 Programs

2012 Program

3 May 2012 Thursday

Flew into Resolute at 18:30 with very good weather: clear, sunny, warm. Dinner, checked in with TM, checked that all boxes had arrived, then unpacked personal gear.

4 May 2012 Friday

Unpacked gear, ran gas engines, organized equipment by weights: what can fit into Twin (2100lbs) & what into helicopter (800lbs). Due to delays, will not get out until Tuesday. The helicopter is occupied until then. Call HTA to see whom might like to help and meet with them about the work. Suggested that I check with JA and T?; gives me the phone number of both people. JA will work with us from Tuesday until Sunday, weather permitting. Determine waypoints needed to transit to level first-year ice in Becher Bay.

5 May 2012 Saturday

Give BT and student a tour of the equipment. Get late start to Becher Bay. Use two snow machines and two komatiks to take the new borehole system, steam machine, new corer to test level first-year ice beyond the area limited by the moratorium. Takes 2 hours to travel the 16km distance. On the ice, MJ, RL and CF test the new corer first: works well and provides roughly 7" diameter cores. Salinity samples were taken from cores, then the cores were put back into the hole. Test the borehole system: works well, but there is a 2 mm offset at zero displacement in one of the displacement sensors (need to check). The 7" hole does not allow as much penetration into the ice. Test the steam machine: drill 10 holes ~10m apart. Works well. Takes about 40 to 50 seconds to drill through 1.8m thick ice. Measure the ice thickness off the hose, but it is not as accurate as obtained with weighted device in 2" drill hole. No pockets noted in the ice. Meet up with very nice Inuk couple on the way to their cabin during the return trip to Resolute. Didn't catch their names: Simon was written on his jacket; I don't recall her name. They thought we were polar bear hunters. Return to PCSP at 17:30 to see that the helicopter has arrived. Great. Then, check in with TM to hear that we are still delayed until Tuesday – the helicopter just came to change crew before heading to Devon Island, due to return on Monday evening.

6 May 2012 Sunday

Returned to Becher Bay. Had trouble getting started – didn't leave PCSP until 11:00. Snow machine #2 (Tundra) gave us problems in the morning (it wouldn't shut off when switch activated). Took about 40 minutes to arrange for a new machine. Loading drill frame took a lot of time too (strapping it down). Drill column and base was pulled by one machine on a komatik (w/ MJ and CF). Borehole system, Kovacs corer, 6.25" auger and extensions was pulled by second machine (newer type w/ RL). Arrived at site, set up borehole system, set up drill frame. First hole used drill frame/6.25" auger to make a hole for strength tests. Snow depth was 30cm. Snow was shoveled away before assembling and mounting drill frame (~45 minutes). Auger hole took ~15 minutes. This was the first time that the drill frame had been used. It functions very well. Borehole tests were completed, using drill frame to assist with moving unit to different test depths. Functioned well, but the usual problem of snow/ice accumulating behind the borehole indentors took longer to deal with using the drill frame (likely because it is new to us) than by lifting with brute force. Took a core in an (overlapping) hole next to the borehole to see whether we could see the indentation imprint left by the borehole indentor in the core itself. Saw a slight indentation at 60cm (1/8" to 1/4"). Other cores (from same hole) did not show evidence of indentation. Capturing out-of-round core with the dogs was challenging, but was do-able. Ice appeared warm and saline (30cm snow depth); not so with yesterday's core (14cm snow depth). Did not take temperature measurements or salinity measurements because the hole was filled with seawater for so long – it wouldn't have been representative. Would like to return to conduct comparison of the hole diameter on ice strength (a) 6.25" auger, (b) 7" auger, (c) corer. There doesn't appear to be considerable difference in the strength measured in the 6.25" and 7" core hole, although the amount of indenter travel (in ice) is reduced for the 7" hole. Very low visibility due to snow. Measurements were completed at 15:30 in order to return to PCSP for dinner; we had no dedicated bear monitor. Met up with dog on the way back to PCSP – it approached us while RL got his snow machine stuck trying to clear a snow bank. Needed to follow waypoints to return because of low visibility.

<u>7 May 2012, Monday</u>
Spent all day organizing and packing gear needed for tomorrow's planned helicopter/ Twin flights to multi-year ice. Idea will be to transport all of the gear by Twin Otter and 4 passengers by 206L. The Twin will deposit the equipment on the level first-year ice and the 206L will be used to ferry the equipment to the deformed multi-year ice. All equipment will be left on the multi-year ice at the end of the day. The fuel will be removed from the gas engines (generator, motorhead and gas drill). Antifreeze will be left in the steam machine, the propane (one canister will be left in the steam machine box, the other in a 45 gallon drum), the borehole jack and hydraulic pump will be left in the 45 gallon drum. The idea will be to surround the steam machine with the helix boxes and strap the bundle of boxes together with our very large ratchet straps. RL spent the day making a fixture to measure the ice thickness in the steam hole (21mm diameter), which is smaller than the hole made by the auger (2", ~50mm). We cannot connect the two steam hoes together (13m and 19m) because the coupler won't fit into the diameter of the steam hole. I check with TM in the afternoon so that I can update JA about whether we will be going tomorrow. TM has bad news: the 206L is on Devon Island and hasn't been able to do its work today because of weather. It will stay tomorrow to do the work and then hopefully leave in the evening. I asked how long the 206L would wait to accomplish the work before flying back: on which day would good weather mean that the 206L would fly back to Resolute rather than conduct the work on Devon? The <u>first</u> good weather day will be used to do the work, then return to Resolute. It could be Friday before we see the helicopter. TM offers the Twin instead – but that can't land on the deformed ice that needs to be sampled. I will wait for the combination, as planned.

<u>8 May Tuesday</u>
Walked over to see TM after breakfast, to find out about the weather on Devon Island. Skies are clear here. TM says that the weather is good there, but that the helicopter has not yet started its day yet. I ask about the work that he has to do: Martin Sharp (U. of Alberta) maintaining batteries, instruments etc. on the ice cap. I say we will sit tight today. MJ works on presentation for ISSs in the morning. At noon, TM says that the helicopter is out flying around Devon but he has no satellite communication with it. At 15:00, I walk over to give TM our game plan (Twin/helo combination, who is left where, coordinates, etc.). He says that the helicopter won't be back today. Tomorrow. So, I will take him up on his offer to use the Twin to access level ice near Floe #1 tomorrow. We will take a snow machine (Tundra, 390lbs), komatik (95lbs) and the ice thickness gear w/ the steam machine (500lbs). I call JA to let him know that we will pick him up tomorrow at 08:00. I let RL and CF know that we will not get the helicopter tomorrow: Twin Otter only and that we will snow mobile to the deformed multi-year ice. Put in a request for the komatik – PCSP frowns on this because they are so heavy and the pilots don't like to load them into the aircraft. They offer me a yellow plastic sled instead, but our experience with those is that they are like snow plows. I decline. They may have a small komatik, but it might need to be re-lashed (which RL could probably do). He arrives back with a tight komatik, but it needs a new runner and a new rope attachment. Nice and light though! RL and CF take care of it. RL makes a wedge for the scale, so that we can drive the dolly right on up without having to offload the five palettes. We weigh the loaded palettes, komatik

and Tundra. Taking the ice thickness gear tomorrow in the Twin will mean 1000lbs of gear, plus 4 people (800lbs) which comes close to the total allowable load (2100lbs).

<u>9 May Wed</u>
Weather excellent but the Twin Otter broke a ski doing another project and needs one day to be repaired. The helicopter is still on Devon, due back this evening. The helicopter arrives at base at 19:00. We make preparations to transport all gear to floe 1 tomorrow, for the first day of sampling using the Twin/helicopter option.

<u>10 May Thursday</u>
At 8:00 CF goes to pick up JA in the community. Coordinates of area of flat ice are given to the Twin Otter pilot, helicopter pilot. The helicopter pilot, Twin Otter pilot and the engineer talk about how the work will proceed. The helicopter engineer agrees to go in the Twin to help prep loads for slinging operations. Gear is loaded into Twin Otter, then Twin is fueled. We move to the helicopter for preparations. We depart at 09:00, head over land and arrive on Floe 1 at 10:00. Much of the massive floe is pretty level, then we come upon a hummocked area in the interior of the floe – many hummocks. MJ requests the pilot land in a “bowl-shaped” region between two hummocks. We call for the Twin Otter to come out. After ~1 hr, the Twin is overhead. It goes over the coordinates that I had specified (near Floe 1) and determined that the ice was too rough – certainly don’t want to break another ski! The Twin Otter heads south to where they find a very flat area of ice (off Black Point). The helicopter takes RL to meet them, so that he can prepare the loads. The gear is brought over in 3 ferry trips, then the helicopter pilot and RL fly to the cabin at Polar Bear Pass to refuel (35km west). They return to the floe at about 13:30. The afternoon is spent drilling 1 hole to measure the ice thickness on the shoulder of a hummock, digging a 4 x 4ft pit in 60cm of very hard snow, setting up the drill frame, auguring a 6.25” hole and then conducting borehole strength tests to a depth of 10.4m (the full ice thickness). We have trouble with the LVDT at a depth of 660cm; it continues to read 12mm at full retraction and 13mm at full extension. MJ decides to continue the tests, without knowing where one of the indentors is sitting in the ice (at risk overextending the borehole indenters). We continue to test until the bottom of the hole at 10.4m. Having steam to unclog the back of the indentors was absolutely essential because we were using the 6.25” hole rather than an oversized 7” hole. After the tests we take a short break and then begin preparing the gear to be left on the ice: all gas is emptied from the engines and generator, put anti-freeze in the steam machine and then surround the steam machine with other boxes. We surround the bundle of boxes with ratchet straps. We depart the floe at 18:15 and return to PCSP at about 19:00.

<u>11 May Friday</u>
Weathered because of blowing snow, high winds and low visibility. Predicted to be better tomorrow. Called JA to cancel in a.m.

<u>12 May Sat</u>
Weathered because of blowing snow, high winds and low visibility. Predicted to be better tomorrow. Called JA to postpone at 08:00; called him again to cancel at 12:00.

<u>13 May Sun</u>
Visit Nanook floe. Extract full thickness cores on ice shoulder and process. Extract partial thickness cores in nearby borehole and process for temperature.

<u>14 May Mon</u>
Weathered all day.

<u>15 May Tues</u>
Visit Nanook floe. Measure temperature and salinity in uppermost 5m of hummock crest. Conduct borehole strength tests through full thickness of ice.

<u>16 May Wed</u>
Weathered in morning. Visit Nanook floe in afternoon. Conduct thickness measurements along transect using drill-hole technique and steam hole technique. Ferry equipment to flat ice to be retrieved by Twin Otter. Field team helps load Twin Otter. Helicopter departs flat ice with all passengers.

<u>17 May Thurs</u>
Weathered. Process data.

<u>18 May Fri</u>
Pack equipment.

<u>19 May Sat</u>
Pack equipment.

<u>20 May Sunday</u>
Depart Resolute

2013 Program

16 March, Sat

Arrive at Ottawa airport at 5:30. CF showed up about 30 minutes later. KB already there when we arrived – MJ did not see, but CF met up with her later. Fly to Edmonton; arrive 10:30-ish. Taxi to hotel – MJ had no room ("did not have reservation for you") MJ called at least 4 times to confirm, most recently this morning to state check-in would be late.

17 March, Sun

Fly from Edmonton to Inuvik, arrive 13:00. Difficulty getting a taxi large enough for 3 with so much luggage. Head directly for Aurora Expediting to check gear; two trips for taxi-van. Check the number of boxes against MJ's list. All appears to be in order. Meet workers upon departure: they confirm that groceries will be delivered tomorrow in time for departure & that portable furnace would be on site also. Leave Aurora for McKenzie Hotel at 3:00 – time that Aurora closes on Sunday. CF, KB, MJ have early supper. TR not in his room at the time, he meets with them after they have eaten. TL had a very long flight, she will meet them tomorrow at breakfast. MJ sends some emails and then has an early night.

18 March, Mon

Meet TR, TL at breakfast (8:30). Remain until 12:00 (they extended check-out time for us by an hour). Meet for lunch. Take taxi to Twin Otter/DC-3 combination at 1:30. Delivered to RCMP hangar. No groceries or equipment on site yet; that will come at 2:30 or so. Team waits in airport, rather than hangar office & at 2:45 Twin Otter pilots come let us know we would depart soon (early). We head for the Twin Otter at 3:00 and depart by 3:15. DC-3 with all the gear departs behind us. Arrive in Sachs at 5:30 – trucks not on site to meet us, but we are early. MJ phones JK to let her know that we have arrived. She sends JfK for us in one truck; RK arrives in second truck. CF, MJ and TL cannot help unload the planes because they don't have safety vests (airport worker, gave us his one extra – which was given to TL). KB had reflectors on his float suit. DC-3 and Twin unloaded; planes depart. Then start moving groceries (first) and luggage to the Lodge. MJ calls BH (SHHTC) to ask about using Parks Canada garage, since MJ's contact JL is not in Sachs for her to approach. Do we need a key? Some running around to get key to Parks Building.

19 March, Tues

Morning spent finding alternatives to Parks building, which is much too nice for a work area. Check with BH, who calls RCMP. RCMP willing, but MJ finds their space too small and the other space they offered must be used to park their truck overnight. Have a storage area – but it will not work. Have the morgue – will not work (we didn't even look). Drive over to meet BH. She calls around more. Some people/company with a container, but not enough room. Different container, but no power. Picnic building on beach is available but it is too clean and difficult to access. Community centre at entrance is too clean. Co-op? They offer their container, but it would need an extension cord be strung to provide power, would be difficult to hook up furnace (inside only) and how to exit in emergency? Must be Parks Canada garage. MJ calls RF in Ottawa to see if he could call Parks but he is on a teleconference call. MJ sent message to CH (Parks, Inuvik) whom she had met during BREA trip. He was traveling but he later replied to MJ's message: proceed as you had arranged with JL. Great! Spent rest of day unpacking, hooking up furnace and arranging equipment.

20 March, Wed

First day on ice: decide to do ice thickness holes in level area just outside of Sachs. Drill 10 holes with 2" auger. Then intend to steam nearby at each 10 holes. Steam wand is frozen solid. No steam exits and no water either. Put in case to heat. No. Put in case and turn off steam machine. No. Decide to return to garage and let it thaw out. Have lunch and then return to same place to steam 10 holes. Make a comparison of thicknesses measured with ice thickness attachment for small holes (it is too soft). Measure thickness by holding hose at point where it slips through the ice (from end of wand & then from metre-markers on hose). Compare to 2" measurements but snow depth not accounted for. Move on to where JfK knows an ice ridge exists. He first stopped at a puny ridge (hardly noticeable). MJ asks "anything bigger?". JfK says takes us further on to a decent sized ridge. Lay out four flags along two transects leading up to ridge. Flag 1 on crest of ridge, followed by 2, 3, 4 leading away from crest. Flag 8 was on the shoulder of transect 2 (10m from transect 1). It was the only hole that was drilled along transect 2. Steam machine was used at Holes 4, 3, 2. Then machine ran out of water and we did not have the wrench to remove the end cap, so couldn't add more water. Auger was used to finish holes 8 and 1. Ridge was soft while drilling, but not many voids noted. Steam hose doesn't have the same sensitivity when looking for cavities, since it often hangs up and then drops through the ice. Is this hard ice vs. soft ice? Not sure.

<u>21 March, Thurs</u>

In the morning, we test both BHSs in the garage to make sure that they are working fine and to familiarize team with system. All o.k. In the afternoon, conduct tests on level ice in Sachs Harbour with BHS1 and BHS2. Strengths measured with BHS2 (15m hoses) are comparable to measured with BHS1 (6m hoses). Return to garage, open gear, start furnace and leave for lodge. Team returns after supper to clean and organize equipment.

<u>22 March, Fri</u>

In the morning, we travel to ridge that was sampled previously (for thickness). The idea is to introduce KB and TL to coring because there was a very close call in the level first-year ice yesterday (where the barrel was too far into the hole and almost became stuck/frozen: "over coring'). Three holes were cored leading up to ridge and the fourth hole was augured. Very different techniques for both. The hole that was augured was thicker than the core barrel and 4 extension rods that we had taken, but it gave an introduction to coring thick ice. Coring complete by lunch time. Return to lodge, clean up and prepare weights for following day (ice thickness only) to match the previously agreed "1500lbs for 150km". Helicopter arrives about 4:00.

<u>23 March Sat</u>

Take helicopter and 1500lbs (including 5 passengers) to two ice floes. Trouble with gas powered drill – it will not start. CF and JfK work on it for about 40 minutes and MJ suggests moving on to the steam machine. Use the steam machine to measure thickness at 10 holes. Ice thickness less than ideal, so we pack gear and move on to Floe 2. On Floe 2, ten holes made on a linear transect and then 7 more holes were made along the peaks (mostly) of hummock that stretched across the floe. Thickest was 9.5m on hummock. Leave outhouse tent on floe because the beacons from Environment Canada have not yet arrived, nor have the replacement beacons ordered by Industry (from Canatec).

<u>24 March, Sun</u>

Depart in the morning for coordinates of two new floes. Weather is cloudy and as we fly it looks like weather is moving in. Light gets flat, so seeing the floe topography becomes difficult. Helicopter maintains too high an altitude (500m) to see floes properly. MJ requests to go lower, needs to be closer to the ice. The floes at the lat/longs specified are not of interest; surprisingly the "tent floe" from yesterday crosses our path, which is slightly different than yesterday's flight path. The ice has shifted, which explains why the floes at the lat/longs are not the same as in the satellite imagery. Finding floes in this manner is exceptionally difficult since we only have a very limited amount of fuel on board & it does not permit looking around for very long. Working with the 1500lbs, 150km limit is difficult. We are pared down about as far as we can go, without decreasing the number of people in the team. New approach talked about: once the beacons arrive, MJ and one other person will take beacons and small amount of auger (7 flights) to scope out floes of interest. Beacons will be placed on each floe – probably four beacons will be used (2 CALIBS, 2 Canatec). Beacons due to arrive on Monday's flight (16:00 arrival). Until then, we will have to wait or again seek ice by the old method (days old satellite images).

<u>25 March, Mon</u>

Weather day. Weather poor in morning but clears in afternoon. Poor weather coming in, which causes problems for flying even though skies are clear in Sachs Harbour. Go to Co-op to purchase gas for Kuptana's truck which is down to ¼ tank. While at Co-op, stop in to see BH. She goes over JfK's invoice (work hours) with me to make sure that all is correct. Call KM to discuss program: problems with weight/range, seeing out windows in helicopter due to frost, targeting drifting floes with old satellite imagery and no beacons, poor weather, inexperienced pilots on ice, flying too high, etc. The plan is to have two people (MJ, CF) go out to scout and deploy beacons at first opportunity, Then we will return to the floes to sample for thickness and possibly ice strength. Aklak flight arrives at 3:45 and CF and MJ go to airport to see that the Environment Canada beacons (x6) and Canatec beacons (x2) have not arrived. Disappointed because the field program depends upon using beacons. Call KM to say "no beacons". Call ST at Canatec and ask to check on them. ST reports back that Aklak bumped the beacons and the next flight to Sachs is Thursday. Call CG to report no EC beacons arrived yet. Call Canadian North (no record of EC beacons, "probably in Rankin Inlet waiting for plane to Sachs"). MJ needs to come up with new plan.

<u>26 Mar, Tues</u>

Weathered. Pilots go to airport several times during day to get a better perspective (higher up) of the weather but there is still very poor visibility and high winds. Track down beacons (Canatec and EC) but neither shipment made it on yesterday's or today's flight. MJ decides to ask KB if he would consider returning home on Thursday's flight. She explains that CF stays because he is most experienced. TL stays because he is the secondary wildlife monitor. JfK has to come each day because he is the primary wildlife person. MJ will send a message to RP, KB's supervisor. KB says he will look into it.

<u>27 Mar, Wed.</u>

Weather was decent for flying in morning. Aircraft crew was driven to airport at 9:00, then KB returned to pick up CF, TR and MJ and take us to the garage to get pack our few pieces of equipment. The idea was for MJ and CF to go, with minimal equipment, so that the helicopter could travel as far as possible – and spend the time scouting out ice floes. We arrived at the airport with the gear and PIC said that I could bring one more person. Had I known that to begin with, we could have planned differently. I told TR that he was now needed on the flight, so TR had to beat it back to the Lodge to get his cold weather gear, sat phone, firearm etc. Had we known, JfK could have come instead, but I had already called him to tell him there was only room for two people (MJ and CF). While we wait for TL to return, the crew has problems fuelling the helicopter. They had trouble with the fuel pump – it would not pump. Spent probably one hour trying to fix it, until finally it worked. MJ took the opportunity to call KD at Aklak about getting the Canatec and EC beacons on the next scheduled flight to Sachs. KD said that he would look into charters, because the scheduled flight was full. MJ, CF and TR departed in the helicopter but as soon as we reached the open water lead, the pilots couldn't see the other side, decided to head further north to see if they could cross, couldn't, then turned around and headed back to Sachs. MJ suggested they try to pass off Cape Kellett because the Radarsat image indicated that the lead was much narrower there.

The PIC said the cloud looked were even worse off Cape Kellett. Returned to Sachs to reassess. About two hours after arriving at the Lodge, the weather became worse. MJ phoned AC in Ottawa to see if she could get HRPT images geo-referenced to display in the helicopter and superimpose the flight path. AC confirmed that they were gif files and that they were not geo-referenced. She then called TW at CIS to find out (1) could she get geo-referenced HRPT images and (2) how often Radarsat images were being acquired. TW said that she could work on geo-referencing the NOAA images (cloud-free) and put them as the CIS website. She also stated that CIS was only ordering Radarsat images on Sat/Sun because they were not supporting shipping at this time of year. She would request additional images be acquired next week and the following weeks (for KH from UofM). She sends a message to MJ stating that CIS would be ordering the images for us and that we would have three scenes next week. MJ recommends proceeding with ordering the 29 March Rsat image for Box #1 – which covered the largest area. MJ receives a message from TC (Aurora Expediting), KD (Aklak) and MF (Kavik Axys) that the beacons would either go on the Joint Secretariat chartered flight tomorrow (arriving at 12:30) or on the scheduled flight (arriving at 5:00). It was likely that the beacons (dangerous goods) would not arrive on the scheduled flight. KM calls at 1:45 to say that MDA says the 29 March image is no longer available. An image on 31 March is available, but MJ says that CIS should be ordering that themselves. Receive beautiful geo-referenced MODIS image from DH, Canatec. Provides a different, and complimentary perspective, than Radarsat. PIC says, if we fly, we would have to leave by no later than 18:00hrs. Weather doesn't cooperate. No flight.

<u>28 Mar, Thurs</u>

MJ downloads MODIS imagery from DH at 06:30. Checks for updates on MrSids: none. Receives email from TW that CIS cannot order the Rsat images for next week because they are not for CIS operations. Requests NRC contact MDA directly. MJ sends message to AB to see if she can respond; cc' KM. TR leaves for airport at 06:30 to check weather atop hill. PIC prefers to wait: no decisions until later. MJ gives load/range curve to First Officer to discuss with PIC. PIC explains how simplistic the load/range curve is – does not take into account winds, direction, dog-legs due to weather & ice etc. MJ needs to determine whether to send KB home: how much weight for how many km? Conclude that we can assume full fuel (2600lbs) for 200km which allows us to carry 1200lbs (passengers & gear). MJ says "o.k. then KB goes home". PIC also stated that it takes a lot of fuel to start the engine: MJ will "deploy" beacons by exiting the helicopter while it is running, then helicopter will move on to the next floe. We can also retrieve beacons while helicopter is running, to avoid start ups. MJ phones JfK to say that we are on standby (09:00). AB, Ottawa, phones to say that she will contact KM about contact at MDA, will talk to TW about what CIS had planned for ordering imagery next week, then will contact MDA about ordering the images. Pilots go for airport 09:25.

Team in helicopter at 10:15 ready for take off. The idea is to fly a line as direct as possible to the tent floe, locate it as a waypoint, deploy beacon, then move on to the largest floes (Sachs 10, Sachs 11) furthest a field. Pass over tent floe and attempt to land on larger, rougher adjacent floe for sampling. Pilots couldn't land because of snow cover. Fly to another site, then return to Tent floe. They tried to land again as CF prepared to toss the beacon out the door, as discussed. CF tossed the beacon, but then we ended up landing in that very spot. We drilled 10 holes, the ice was very uniform. Did we land where I had intended? There was no way of telling because I couldn't see out the fogged up windows. Perhaps we were in a melt pond? CF and JfK walked over to the hummocked area that we had sampled the other day to deploy the beacon. They deployed Klaus #1 beacon (rather than Klaus #2 which was dropped) on the tent floe and then walked back. We then took off for another floe – flying north to re-deploy Klaus #2 beacon. We flew for about 14km and then located a small floe with a hummock on it. Helicopter landed on the wrong area of ice, MJ mentioned that "this is not the correct floe", pointed to the feature that needed to be accessed, then they started up to reach the correct floe: "over the ridge, towards the smooth bump" were the directions given. We landed and then drilled one hole on the flat part of the ice (4m) then onto the hummock to drill a second hole (8m). Klaus #2 beacon was deployed in the level part of the floe. At our limit for flying time, we had to turn back to Sachs. We hadn't reached Sachs 10 (Sachs 11 was out of the question), although we did get to within ~10km of the floe's estimated position, but had to return back because of fuel considerations.

Once in Sachs, the helicopter was refueled. The EC and Canatec beacons had arrived. TR went to retrieve the beacons from where he had taken them to the Lodge. I made a call to AC to check to see if Klaus #1 and #2 beacons were working. They were. TR returned with the beacons and we sorted through them on the back of the truck. I selected the two Canatec beacons (Can #1, #2) and two CALIB beacons from EC and removed the magnetic strip from all. Four beacons were loaded into the helicopter, refueling complete and we headed back offshore. This time we headed directly for Sachs 10 and, once over it, I was amazed because there was nothing distinctive about the floe we passed over – was it the correct one? We decided to turn around and visit some prospective floes that had been seen on the way out. Here, the First Officer, on the opposite side of the helicopter, did a great job suggesting floes to sample. He now understands what we need. Can#2 beacon was deployed on Sachs 16 – a pretty flat looking floe. Can#1 was deployed on Sachs 17 a very hummocked floe with linear pattern of hummocking. The floe is reminiscent of some of the floes that we saw in Norwegian Bay and Nares Strait in past years. The Canatec beacons were deployed while the aircraft was still running (shut down consumed fuel). First Officer and MJ got out, walked over and wedged the yellow pelican case into the snow, snapped a picture or two, then returned to the helicopter. That complete, we headed for Sachs Harbour (18:16 hrs). As we neared Banks Island, MJ's GPS/computer combination closed down because her battery power expired: no computer, no GPS. Helicopter encounters weather while trying to find a way to pass over the lead, needs to spend a considerable amount of time doing so - all the while flying over thin, broken first year ice and open water. It was a very dynamic area. Finally, we are able to pass across the lead into the rubbled landfast ice. At 19:17 the helicopter banks hard to the left and right looking for a place to land. The PIC wonders about landing in the rubbled ice - questions whether it is thick enough – MJ says that it is, and asks JfK if he agrees. JfK agrees. The PIC attempts to land but cannot, replying that helicopter would need to head back offshore. MJ states that we should not go back offshore, that we should land here because the ice is landfast and thick. The PIC sees a flat spot and tries another landing. The First Officer watches the tail rotor as the helicopter lands.

Shut down, secure the helicopter and call the Lodge for weather reports. At 21:00, when the weather has not lifted, we settle in for the night. Their small generator is used to keep the engine warm and the wind cover is put on. Calls are made (outside for reception). MJ remains in the helicopter to retain warmth, unsure of who was called or what was said. Settle down for spending the night on the ice. JfK and the First Officer appear to sleep most of the night. CF looks cold and tries to warm his feet. The First Officer wakes up at about 02:30 or so, saying that it has gotten much colder. MJ checks her watch regularly as the night passes.

<u>29 Mar, Fri</u>

At 06:30 the light is coming up and the pilots make ready to fly. The weather has cleared and we are able to fly home. TR is at the airport to pick us up. We arrive at the lodge, eat breakfast and head for bed. MJ wakes up at noon and makes some calls, send emails, etc. She discusses yesterday's events with the PIC.

30 Mar, Sat
Day passes. Poor weather but the whole program has stopped until this can be settled. Pop-outs were supposed to be on the machine at the start. She goes to the airport with KB to check on whether he will be able to make the charter flight, home or not. Offsite, discussions are underway.

31 Mar, Sun
Send message that MJ is not comfortable continuing with present crew. Formally terminates program.

1 Apr, Mon
UofM cancels their program. Pilots depart Sachs Harbour with helicopter.

2 Apr, Tues
Emails and discussions. Analyze data.

3 Apr, Wed
Emails and discussions. Analyze data.

4 Apr, Thurs
Field team packs equipment

5 Apr, Fri
Field team packs equipment

6 Apr, Sat
Field team packs equipment.

7 Apr, Sun
Field team departs Sachs on chartered DC-3.

END OF REPORT