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Property Changes of First-year Ice and Old Ice during Summer Melt

M. Johnston, R. Frederking and G. Timco

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Final Report

M. Johnston, R. Frederking and G. Timco
Canadian Hydraulics Centre
National Research Council of Canada
Montreal Road
Ottawa, Ontario K1A 0R6

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Abstract

Seasonal measurements from three field seasons on first-year ice are summarized. Results showed that the properties of first-year ice change dramatically during summer melt. The ice had reached an isothermal state by mid-June and, by mid-July, the ice was nearly devoid of salt throughout its full thickness. First-year ice had 12% of its mid-winter strength by mid-July. Strength remained at that level until measurements were concluded three weeks later. Measurements on old ice were conducted in June and August. Second year ice behaves much like first-year ice during the decay season, in that it had only 19% of its mid-winter strength in August. Two multi-year floes were sampled in June (each about 5 m thick) and another floe in August (over 6 m thick). In June, ice salinity was less than 2‰ to a depth of 1.4 m. The strength of the multi-year ice was 56% and 47% of its maximum mid-winter strength (30 MPa) in June and August, respectively. The floeberg ice was so-called because it was about 30 m thick, was extremely level and the extracted 1.2 m core had no measurable salinity. In June, the temperature profile of the floeberg ice showed that ice above a depth of 1.6 m was warmer than –2°C, whereas below that depth the ice was –6.8°C. Comparison of the strength profile of the floeberg ice and multi-year ice showed that ice strengths were comparable at a depth of 0.30 m however, as ice depth increased, there was greater difference between ice strengths in each borehole. In June, the uppermost metre of floeberg ice had a borehole strength of about 19 MPa, compared to 16 - 17 MPa in the multi-year ice.

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Property Changes of First-year Ice and Old Ice during Summer Melt

1. Introduction

This report describes results from the field program that was conducted from May to August 2002. The 2002 field season focused upon obtaining property measurements on first-year ice and multi-year ice in the central Canadian Arctic. The information acquired on first-year ice would be used by Canadian Ice Service (CIS) to validate their prototype Ice Strength Charts. As such, CIS participated in and financed field work on first-year ice. The multi-year ice component of the field work was funded by Transport Canada. Multi-year ice results in most of the damage events that involve ships in Arctic ice-covered waters (Kubat and Timco, 2003). Since very little is known about the decay of multi-year ice, one of the objectives of the 2002 field program was to provide information about the effect of summer melt on the strength of multi-year ice. Measurements from both programs were consolidated into a single report because first-year ice and multi-year ice are of interest to both Transport Canada and Canadian Ice Service.

2. Previous Two Seasons of Decayed Ice Measurements

Typically, measurements on first-year ice are conducted in mid-winter or early spring when the ice is still cold, measurements are straightforward and ice access is not a problem. In 2000, the Canadian Hydraulics Centre initiated a field program to gather information about ice decay by monitoring landfast first-year ice during summer melt. Those measurements have been conducted for the past three seasons now. The first two measurement seasons examined landfast first-year sea ice near Truro Island (75°13.9’N, 97°09.3’W) in the central Canadian Arctic. Measurements from the past two seasons were used to develop a prototype Ice Strength Chart for landfast first-year ice on the approach to Resolute (Gauthier et al., 2002).

Field measurements were used to document the snow and ice thickness, ice temperature, ice salinity and the *in situ*, confined compressive strength of the ice. Details of the measurement techniques are provided in Appendix A. Measurements were made about twice per week, from May until July. The program was terminated after the first week of July, when an open water gap developed between the coastline and the relatively intact ice sheet. The open water gap makes it difficult (if not impossible) to access the ice by snowmobile. If alternate means of ice access are available, the measurement program can continue until well into July, since the ice still has sufficient bearing capacity. Such was the case in July 2000, when the Canadian Coast Guard LOUIS S. ST-LAURENT was used to access the ice near Truro Island. Alternate means were not available in year 2001, the second season. As a result, that measurement program ended much earlier.

2.1 Information Gathered during Previous Seasons of Field Measurements

The mean-daily air temperatures at Resolute, the nearest weather station, were comparable in years 2000 and 2001. As a result, the ice consolidated under similar conditions during the two years as shown by the good agreement between the ice thickness and properties during the first two measurement seasons (Johnston et al., 2001). In both years, the ice thickness was about 1.4 to 1.5 m in May and decreased to 1.2 m in late June. Similarly, the ice ablation rate was 22 mm/day and 34 mm/day, for years 2000 and 2001 respectively (Johnston et al., 2001).

The 2000 and 2001 seasons provided two continuous records of the decrease in strength that occurs in landfast first-year ice around Truro Island. Much of the decrease in strength occurred in June, once the mean daily temperatures remained above freezing for about one week and the snow cover had melted (Timco and Johnston, 2002). By early July, the average (full thickness) ice strength was only 15% of the typical, mid-winter strength of first-year ice. The ice strength remained at the 15% level until the last measurements were conducted, three weeks later.

3. Objectives of the Third Year of Measurements

One of the objectives of the third measurement season, in year 2002, was to confirm the late-season strength measurements obtained in year 2000. In addition, the measurement area was expanded from the first-year ice around Truro Island to various areas in Parry Channel. Doing so would provide information about ice decay in a larger context. Multi-year ice was also included in the field program, in efforts to further the understanding of the decay process of different ice types.

The planned field studies required sampling ice types in McDougall Sound, Parry Channel and Wellington Channel from May until August 2002. The best approach for achieving the outlined project objectives was to conduct two separate field programs and operate them simultaneously. The first program focused upon decaying first-year ice in McDouall Sound and Parry Channel, while the second program examined multi-year ice near Little Cornwallis Island and Wellington Channel.

4. Time-Frame for 2002 Measurement Programs

Measurements during the 2002 season began in May, when air temperatures were well below freezing and the ice was snow covered. Figure 1 shows the mean daily air temperatures for Resolute (the nearest climate station) from January to September 2002. The Resolute mean daily air temperatures in 2002 were about 5 to 10°C warmer than the 30-year normal during some periods in January and early February. Much of February, April, July and August was characterized by colder than normal temperatures. In fact, temperatures in July and August were about 5°C colder than normal. The cold summer affected the ice decay process, something that will become apparent in later discussions.

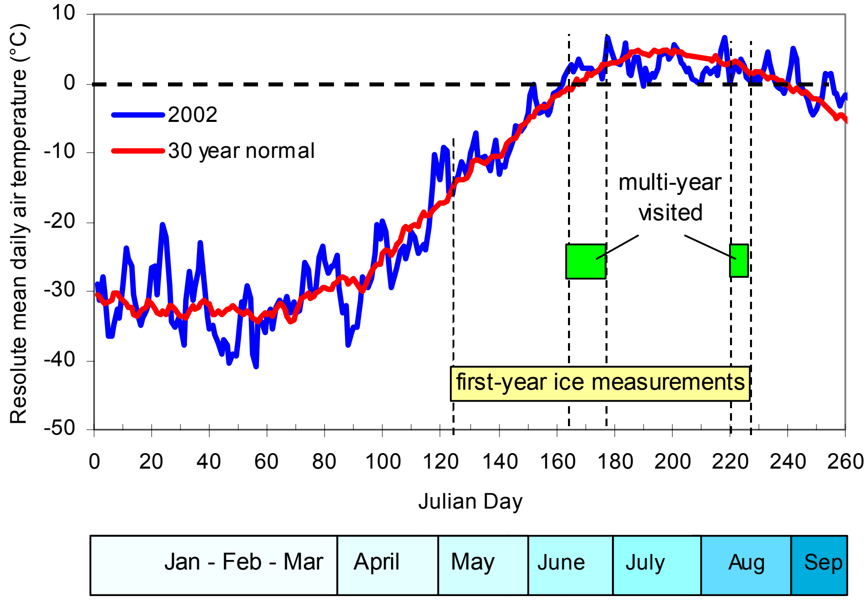


Figure 1 Mean daily air temperatures for Resolute during 2002 field season

The time frames during which the first-year ice and multi-year ice programs were conducted are superimposed on the air temperature data in Figure 1. First-year measurements began on 2 May (JD122) and continued until mid-August 2002. Measurements on multi-year ice were conducted in June and again in August. The first phase of the multi-year program was made in June because previous measurements showed that strength of first-year ice deteriorates rapidly in June (Johnston et al., 2001). Since June was an active period for first-year ice, it was thought that significant changes might also occur in multi-year ice at that time. The second phase of the multi-year ice program was planned for mid-August, after two months of warm air temperatures, yet before temperatures began to decrease (Figure 1).

5. Sampled Areas of First-year Ice

Five first-year ice sites around Cornwallis Island were sampled during the 2002 season (Figure 2). The sites included landfast first-year ice at Truro, Barrow, Griffith and Leopold and Allen Bay. Property measurements were made, intermittently, at those first-year ice sites from May to August 2002 using the methodology outlined in Appendix A. A general description of the ice conditions at each of those sites is given below. In future discussions, the reported snow and ice thickness represent the average of the boreholes sampled at each site.

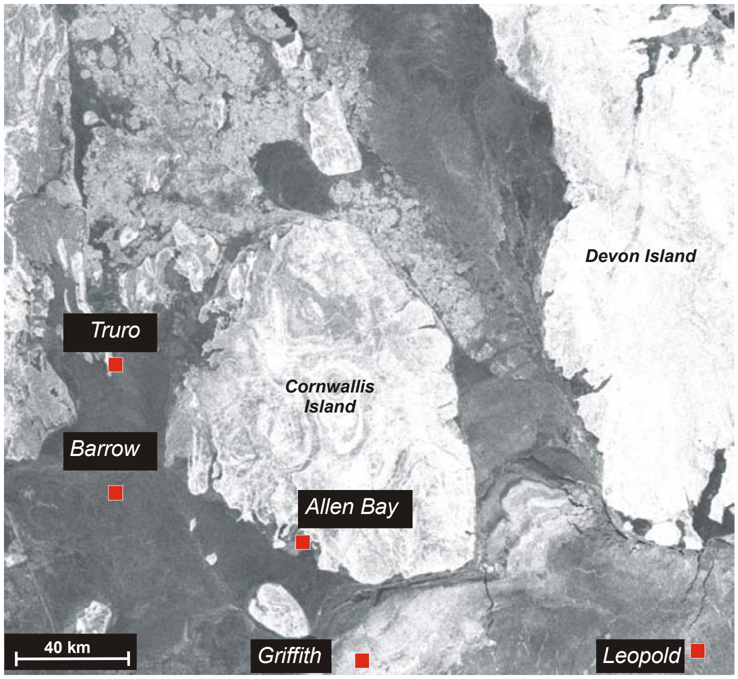


Figure 2 First-year ice sites sampled during 2002 season
(January 2002 RADARSAT image courtesy of CIS)

5.1 Truro Island (74°14′N, 97°13′W)

Unlike previous years at the Truro site (74°14′N, 97°13′W), regular bi-weekly strength measurements could not be made during the 2002 field season. Reliable strength data for the Truro site are only available for 29 May (Julian Day, JD 143) and 2 June (JD186). Despite the absence of a continuous record of strength data, ice properties such as the thickness, temperature and salinity continued into early July.

The ice thickness at Truro site began to decrease in mid-June; on 24 June (JD 175) the ice was 1.43 m thick and had decreased to 1.18 m by 5 July (JD186, Figure 3). There was good agreement between the decrease in ice thickness at the Truro site for the three measurement seasons. Typically, the ice began to ablate in late June and continued to decrease in thickness until July, when the last measurements had been made. The ice thickness decreased at a rate of 22 mm/day, 32 mm/day and 30 mm/day respectively in years 2002, 2000 and 2001.

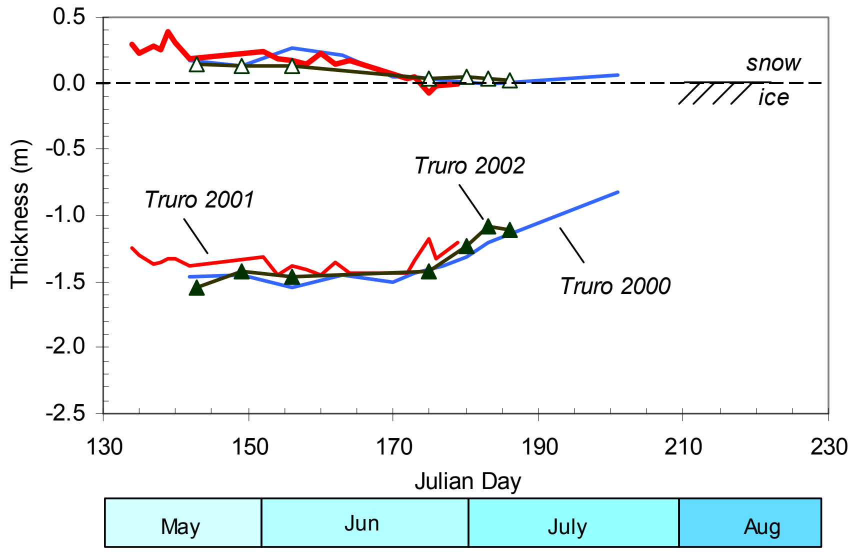


Figure 3 Three years of snow and ice thickness measurements at Truro Island

5.2 Allen Bay (74°44'N, 95°15'W)

Allen Bay is close to Resolute and is easily accessed by snowmobile from the base at Polar Continental Shelf Project (PCSP). The mouth of the Bay is about 12 km wide and enters into Parry Channel. Various ice sites in the Bay were sampled for two-weeks in June, once in late July and once in mid-August, as discussed below.

June: Level ice in southern Allen Bay (74°43.97′ N, 95°15.00′ W) was sampled intermittently from 14 to 25 June (JD165 to JD176). On 21 June, the ice in Allen Bay was typical of the ponding stage of decaying first-year sea ice: the ice surface was covered by melt ponds interspersed by raised areas of white ice (Figure 4).

During the two-week sampling period, ice thickness at the site in southern Allen Bay decreased to 1.85 m from 2.07 m (Figure 5). The average ablation rate was 20 mm/day for southern Allen Bay, in mid-June.

Figure 4 Ice near May Island, eastern Allen Bay on 21 June (JD172)

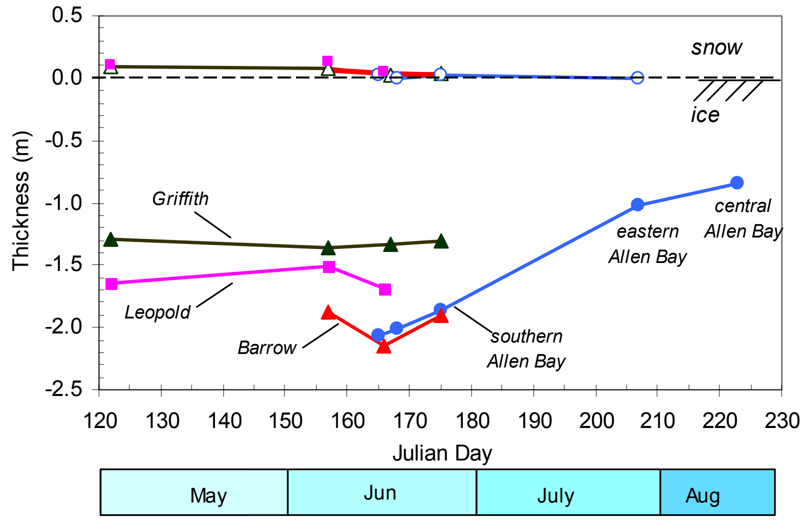


Figure 5 Profile of snow/ice thickness for Allen Bay and Parry Channel sites (three-hole average)

In addition to the site in southern Allen Bay, two sites in eastern Allen Bay (near May Island) were also sampled on 17 June. One of those sites was on level first-year ice and the other was on deformed first-year ice. Ice at the level site was 2.24 m thick on 17 June (JD168) whereas the nearby, deformed ice was 1.90 m thick. The deformed ice was thinner than the level ice because it was grounded on a shoal near May Island. The June measurements at those two sites were not shown in Figure 5.

July: By July 26 (JD207), it was no longer possible to access the ice by snowmobile. The only available means to access the ice was by foot. Since all of the ice sites visited the previous month were too far to travel by foot, two level ice sites were selected in eastern Allen Bay, as close to the coast as possible. The ice thickness was 0.85 m at the first site (74°43.23′ N, 95°04.46′ W) and 1.18 m at the second site (74°43.19′ N, 95°04.19′ W). The average ice thickness of the two sites (1.02 m) was used for the JD207 data point in Figure 5, the data point called eastern Allen Bay.

August: The ice in Allen Bay was again visited on 11 August (JD224), for the last time. By that time, the site in southern Allen Bay that had been visited in June had completely broken-up. The previously sampled level ice in eastern Allen Bay (near May Island) could not be accessed either, since it had rotted to the extent that it was pocked with melt holes and would not support the weight of the helicopter. The only acceptable ice for sampling was a solid sheet of considerably thicker ice in central Allen Bay (west of May Island). Normally, the ice sheet in Allen Bay melts entirely, however the cold summer temperatures enabled the ice to persist throughout the summer. Figure 6 shows the dry area of white, hummocked ice (and its surrounding melt ponds) that was selected for measurements (74°46.15′ N, 95°17.29′ W). The ice was 1.27 m thick in the white area and 0.90 m thick at the edge of the melt pond.

Figure 6 First-year ice in central Allen Bay, 11 August (JD224)

5.3 Barrow

Figure 5 shows that on 2 May (JD122) first-year ice at the Barrow site (74°51.1′N, 97°07.4′W) was over 1.5 m thick and had a 70 mm snow cover. The exact ice thickness at Barrow was not reported on JD122, due to time constraints (R. DeAbreu, personal communication). The site was visited again on 6 June (JD156) and 15 June (JD166), when the ice thickness was respectively 1.87 m and 2.15 m. Measurements imply that the ice thickness increased between the two visits however that was not the case. The increase in thickness was not due to ice growth, but because different locations were sampled each visit (due to landing limitations of the fixed wing aircraft). The variable ice thickness at the different locations indicated that ice near the Barrow site was non-uniform.

By 24 June (JD175), the absence of snow precluded landing the fixed wing aircraft (with skis). A helicopter was used to visit the Barrow site instead. Unlike the fixed wing aircraft, the helicopter allowed landing on ice at the exact coordinates sampled the previous visit. Figure 5 shows that, between 15 and 24 June (JD166 and 175), ice thickness at Barrow decreased from 2.15 to 1.90 m. That difference in thickness was due to ice ablation, not because different areas of ice were sampled.

5.4 Griffith

Ice at the Griffith site (74°21.1′N, 94°51.3′W) was sampled four times during the 2002 season. Measurements showed that ice at Griffith was the thinnest of the sampled sites in Parry Channel. In addition, ice at Griffith had more uniform thickness than sites sampled elsewhere in Parry Channel. Recall that using a fixed-wing aircraft to visit Barrow site had resulted in very different ice thickness measurements. In the case of Griffith, ice thickness in the different areas of ice was in the narrow range of 1.29 to 1.37 m (Figure 5). Ice ablation at the Griffith site began in mid-June. From 16 June (JD167) and 24 June (JD175) the ice thickness decreased to 1.30 m from 1.34 m.

When cores of ice near Griffith Island were extracted on 16 June (JD167), a large amount of brown algae was attached to the core bottom. The bottom 0.30 m of ice had extensive brine drainage channels, in which colonies of algae had become established. In comparison, algae were not seen on ice cores from thicker ice (i.e. at Barrow) at any time during the field program. The large amount of biological activity near Griffith Island is the primary reason that the Arctic Research Division of the Fisheries and Oceans Canada established their 2002 seasonal camp near Griffith (C. Michel, personal communication).

Figure 7 First-year ice at the Barrow Site, June 24 (JD175)

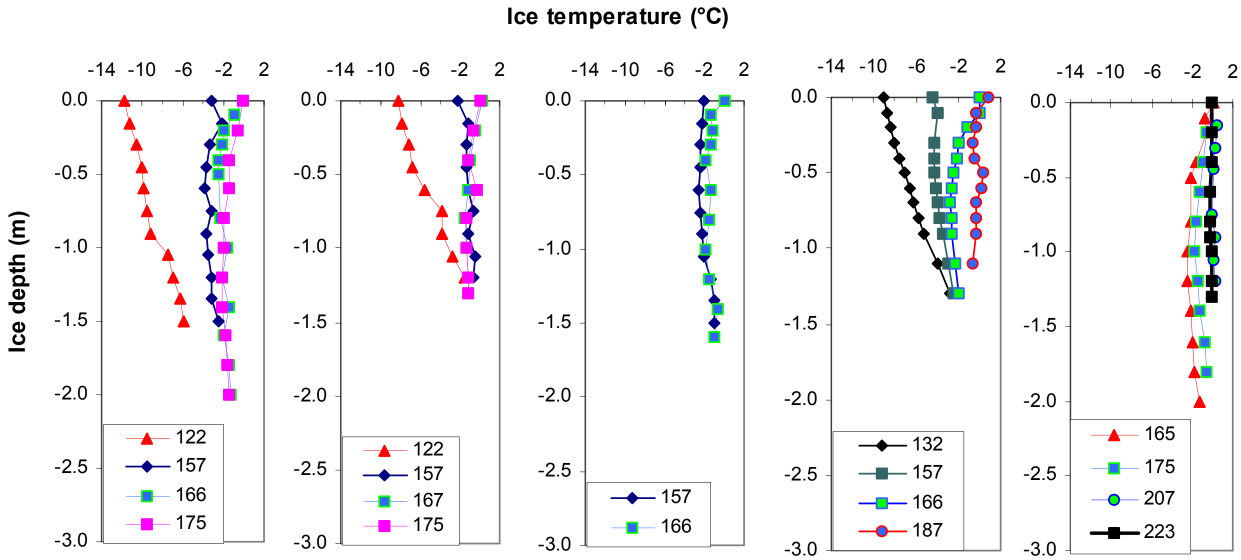
Figure 8 Drainage channel, algae in bottom core at Griffith site, 16 June (JD167)

5.5 Leopold

Figure 2 shows that the Prince Leopold site (74°19.5′N, 91°08.6′W) was the furthest east of the sites sampled in Parry Channel. The first-year ice at the Leopold site was sampled three times during the field program: 2 May, 6 June and 15 June (JD122, JD156 and JD166). Figure 5 shows that the ice thickness during the three visits was 1.65, 1.51 and 1.69 m. No trend in ice thickness can be established since two of the three sites were at different coordinates (fixed-wing aircraft was used).

6. Temperature Profiles of Sampled First-year Ice

Ice temperature measurements give rise to physical changes in the ice. Realizing that ice temperature is key to describing the ice behavior, a considerable amount of time was devoted to making and installing an *in situ* temperature chain to continually record temperatures at the Truro Island site (Johnston et al., 2002). Once installed, the chain recorded the *in situ* temperatures of first-year ice at the Truro Site from 12 May (JD132) until 6 July (JD187). The temperature profile of ice at sites other than Truro was measured from one of the extracted ice cores (see discussion in Appendix A). Figure 9 shows the temperature profiles of ice at each of the first-year ice sites during the sampling period.



(a) Barrow **(b) Griffith** **(c) Leopold** **(d) Truro** **(e) Allen Bay**

Figure 9 Ice temperature profile according to site and Julian Day, 2 May (JD122) to 11 August (JD223)

The earliest temperature measurements of the 2002 season were made on 2 May (JD122) at the Barrow and Griffith Sites (Figure 9 **(a) Barrow** **(b) Griffith** **(c) Leopold** **(d) Truro** **(e) Allen Bay**
Figure 9-a/b). In early May, the ice at all sites was close to its winter state, as shown by the linear temperature gradient that extended from colder top ice to warmer ice at the bottom. The cold-winter temperature profile can be used to determine the ice thickness for the Barrow site on 2 May (JD122)[1]. Early measurements of ice thickness at Barrow are of interest because measurements showed that in June the ice was still 2.15 m thick (Figure 5).

The temperature gradient was extrapolated to the depth at which the ice temperature is -1.8°C (the freezing point of sea water). The extrapolation showed that ice at the Barrow site was about 2.4 m thick in on 2 May (JD122). Although there are no other measurements for comparison in the Barrow area, the 2.07 m thick ice in southern Allen Bay was also unusually thick for first-year ice in mid-June.

Figure 9 shows the gradual transition that occurred as the winter temperature profile of the ice changed to an isothermal temperature profile, characteristic of decayed ice. Gradually, the top ice warmed yet the ice interior remained cold. As the upper surface warmed, the winter temperature profile (linear) transformed to a parabolic one (see for example Figure 9-d, JD166). First-year ice at all the sites in and around Barrow had a full-thickness temperature of –1.8°C by

[1] Ice thickness was not measured due to time constraints.

mid-June (JD175), which indicated that the ice was in a decayed state. After the ice reached its melting point, it could warm no further. Absorbed energy was directed towards melting the ice (rather than heating it), as the Allen Bay profiles clearly show (Figure 9-e).

Comparing the temperature profiles from the first-year ice sites would indicate how the decay process proceeds in different areas of Parry Channel. Figure 10 shows a comparison of the temperature profiles in mid-June (arbitrarily selected as JD165/166/167). The profiles for each site show slight differences in temperature, however in all cases the interior of the ice was colder than its top and bottom surfaces. The coldest ice (interior) was measured at Truro and the warmest ice was observed at the eastern sites (Griffith and Leopold).

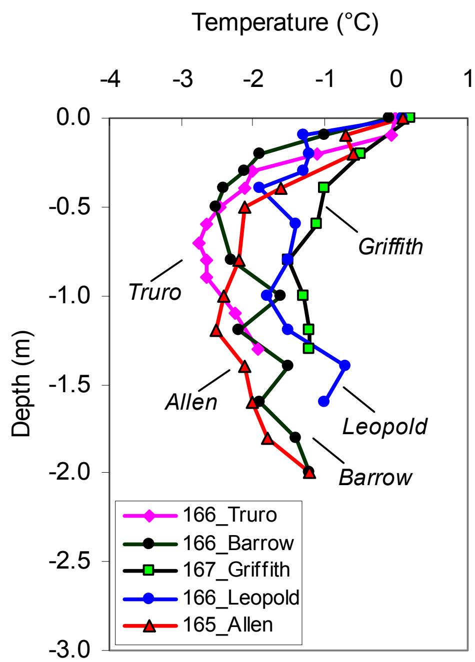


Figure 10 Comparison of ice temperature profiles for all Sites in mid-June

The difference in temperature profiles at the sites was not a result of the snow thickness. All sites were covered by 100 to 500 m thick layer of snow in May; the snow thickness decreased to 20 to 50 mm in mid-June. Air temperatures at the different sites may have played a role. Figure 11 shows a comparison of the mean daily air temperatures at Truro Island and Resolute, which were separated by a distance of about 120 km[2]. Initially, air temperatures in Resolute were colder than at Truro (from JD133 to 162). However, that trend reversed in mid-June, when temperatures at Truro were colder than Resolute (JD162 to 186). Air temperatures might explain why the ice in Allen Bay was thicker than Truro (2.07 m compared to 1.3 m at Truro) and why the ice at Truro was colder than Allen Bay on 15 June (JD166).

[2] Mean daily air temperatures at Resolute were obtained from Canadian Ice Service while the mean daily temperatures for Truro were obtained from the above-ice sensor in the *in situ*, temperature string.

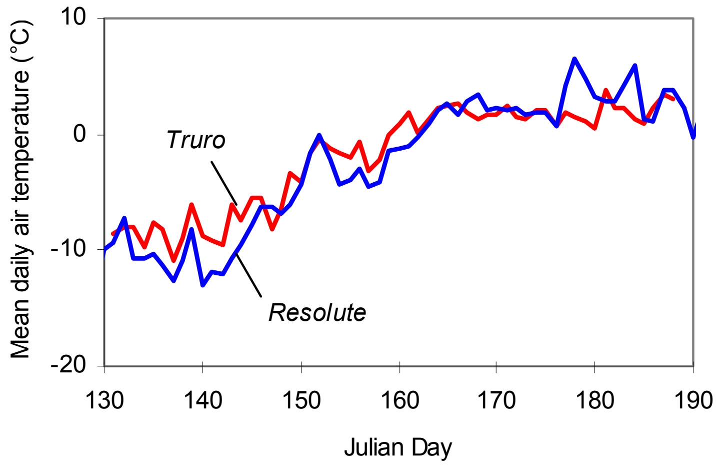
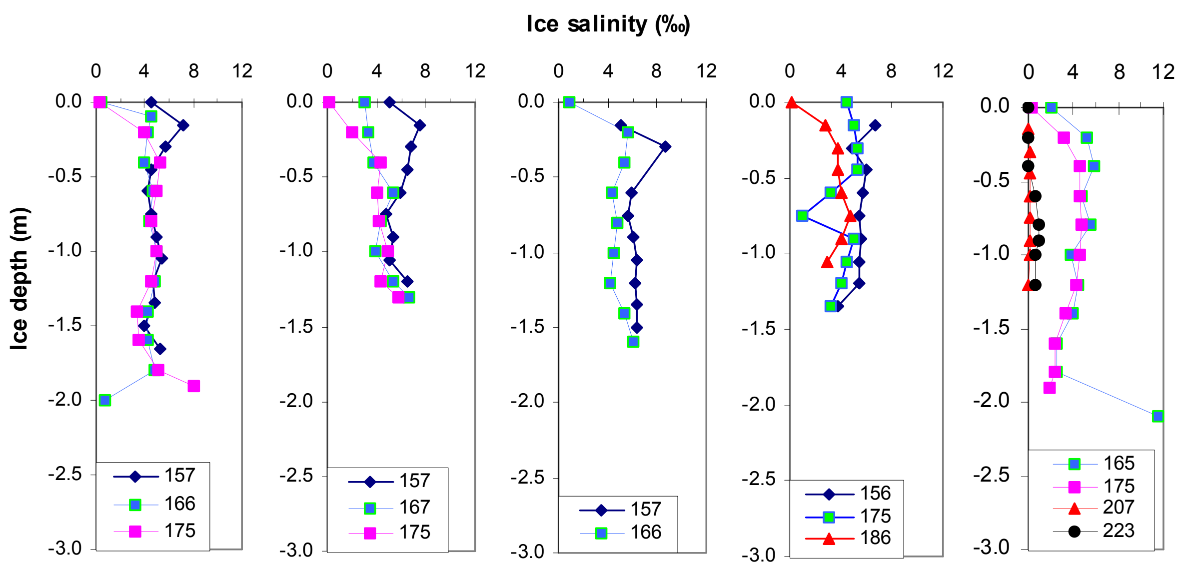


Figure 11 Comparison of air temperatures for Resolute and Truro Island

7. Salinity Profiles at First-year Ice Sites

Previous years' measurements have shown that although ice salinity has a high degree of spatial variability seasonal trends can be established. For instance, Figure 12 shows a clear trend of desalination during the summer. The first-year ice began to desalinate in its upper and lower surfaces. Initially, salinity in the ice interior remained essentially unchanged however as the season progressed, the ice interior began to desalinate. By late-July the ice sheet was devoid of salt. Evidence of a completely desalinated ice sheet was provided by the Allen Bay profiles on 26 July (JD207) and 11 August (JD223), as shown in Figure 12-d.



(a) Barrow **(b) Griffith** **(c) Leopold** **(d) Truro** **(e) Allen Bay**

Figure 12 Changes in ice salinity at each site

CHC

NRC·CNRC

8. Borehole Strength of First-year Ice

The ice borehole strength was measured at specific depths, in typically three boreholes at each site (Appendix A). The earliest borehole strength measurements were at the Barrow, Griffith and Leopold sites on 2 May (JD122). One would expect the ice strength in early May to have been greater than subsequent strength measurements, since the ice was still quite cold and had not yet decreased in thickness. However, the strengths measured in early May did not differ appreciably from later measurements. In fact, the reported strengths for Barrow in May were actually lower than subsequent measurements.

The unusually low strengths were also associated with long test durations (noted at the time by R. DeAbreu, personal communication). The early May tests took about two to three minutes when, normally, individual borehole tests took less than one minute. Since the tests took two to three times longer than normal, the stress rate associated with those tests was also lower. The lower stress rate affected the ice strength, underscoring the importance of accounting for stress rate when comparing ice strengths.

8.1.1 Rate Effect and its Influence on Ice Strength: Predetermined Curves

Figure 13 shows that the same ice has greater strength at higher stress rates. Three cases are shown: cold, first-year ice, temperate first-year ice and warm freshwater ice. The rate equations for those ice types were determined by Sinha, who conducted borehole jack tests at controlled stress rates in different types of ice. The cold, columnar grained first-year sea ice in Mould Bay was tested in April, when the ice was 1.9 m thick and had a temperature of –10°C at a test depth of 0.85 m (Sinha, 1986). The rate effect in the Mould Bay ice was governed by an exponent of 0.32 (Figure 13). In March, tests were conducted in low salinity (less than 1.0‰) first-year ice in Botwood Bay, Newfoundland (Sinha, 1997). The ice was 0.63 m thick, the test depth was 0.35 m and the ice temperature at that depth was –3.5°C. The rate effect in the Botwood Bay temperate ice had an exponent of 0.15. The third case shown in Figure 13 is for decaying freshwater ice (Sinha, 1990) and was conducted in late March, when the ice surface temperature was 0°C and the ice was 0.45 m thick (the ice cover had already ablated 0.17 m). The stress rate exponent was 0.11 for decaying freshwater ice.

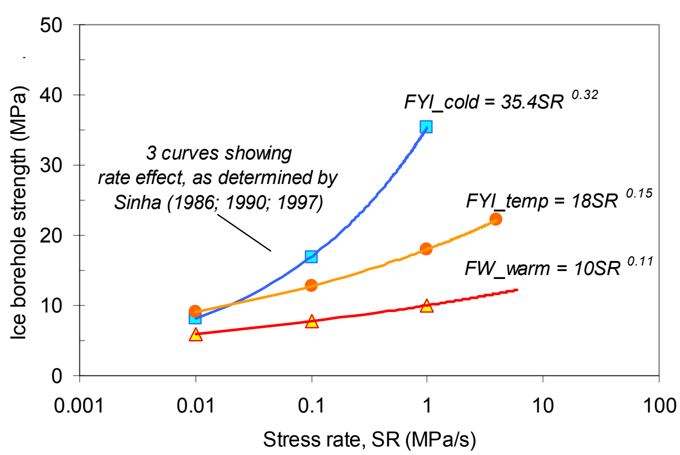


Figure 13 Stress rate effect for first-year sea ice (FYI) and freshwater ice (FW)

8.1.2 Rate Effect, as Applied to Three Seasons of Decay Measurements

Unlike the system used by Sinha (1986, 1990, 1997), the borehole jack systems used for the past three seasons of decay work did not allow the loading rate to be controlled. The borehole jack was activated by an electric pump whose flow rate depended upon the ice resistance. The resulting non-uniform flow rate produced a wide range of stress rates for tests conducted during three seasons of decay seasons (Figure 14)[3]. Tests were run until the pressure leveled-off or a penetration of 3 mm was attained. The pump took longer to reach the specified platen indentation of 3 mm (Johnston et al., 2001) in early May because the ice was still cold. As the ice warmed, the 3 mm penetration was attained more quickly.

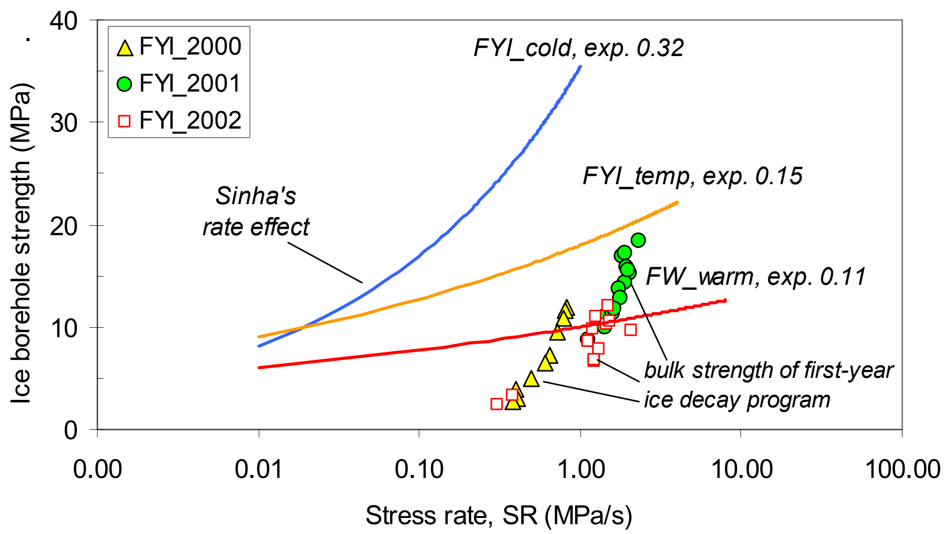


Figure 14 Rate effect, as applied to first-year ice decay measurements

The ice borehole strength for decaying sea ice is shown in Figure 14, in terms of the bulk ice strength[4]. The first-year ice decay measurements in Figure 14 were determined using a platen penetration of 3 mm (Johnston et al., 2001). In contrast, Sinha's measurements did not rely upon a specified penetration but rather used the peak failure stress recorded during each borehole jack test. Another difference was that Sinha used measurements from one test depth only instead of a depth-averaged ice strength. Despite those differences, there is good agreement between the seasonal decay measurements in cold, first-year ice (from May 2002) and Sinha's equation for temperate first-year ice (exponent 0.15). The two different techniques did not result in significant differences in the reported strengths.

[3] Because the ice strengths (and stress rates) for Barrow, Griffith and Leopold sites on 2 May 2002 (JD122) were lower than expected for cold, first-year ice, those measurements were not included in Figure 14.

[4] Depth-averages of the strengths in each borehole and the mean of that averaged strength were determined for the number of boreholes tested at the designated time/site.

Figure 14 shows that the rate effect of strength measurements of decaying first-year ice cannot be represented by a single equation. Each of the rate equations determined by Sinha resulted from a series of borehole jack tests that were conducted, *on the same day*, at a certain depth in uniform ice. In comparison, the first two seasons of decay measurements (2000/01) were conducted at the same site, over a three-month period. The third measurement season (2002) tested ice in different regions at different times. The fact that measurements made during the three decay seasons do not lie neatly along one of Sinha's curves shows that the decrease in ice strength was not dominated by a stress-rate effect. The reduction in strength resulted from, predominantly, property changes in the ice as it decayed.

Certainly, the measured ice borehole strength was influenced by the range of stress rates (0.1 to 2.4 MPa/s) that occurred during the three decay seasons. Accounting for the stress rate effect required two steps: first, that an appropriate exponent be selected for representing the rate effect and second, that the ice strengths be compared for a common stress rate. The exponent for the stress rate effect was determined as 0.25, since that is between cold first-year ice (0.32) and temperate first-year ice (0.15). Analysis showed that most data were not very sensitive to the exponent that was selected for standardization (within the range of exponents 0.15 to 0.30). Conversely, the exponent did affect early season (JD120) strength measurements, in that the exponent was directly proportional to the strength of cold ice.

When the loading rate cannot be controlled, a common stress rate needs to be selected by which to standardize the strength measurements. Figure 14 shows that the stress rate that occurred most frequently during the first-year ice decay measurements was about 1.0 MPa/s. By standardizing the ice strength to a common rate, the measured ice borehole strength would either increase (if the stress rate was less than 1.0 MPa/s) or decrease (if the stress rate was greater than 1.0 MPa/s). In that sense, the ice strength follows a sliding scale that is based upon one of the curves in Figure 14.

The rate effect compensation was achieved by entering the exponent of 0.25 and the common stress rate of 1.0 MPa/s into Equation (1).

$$\sigma_c = \sigma_m \left(\frac{SR_c}{SR_m} \right)^{0.25} \tag{1}$$

where

σ_c = compensated ice strength

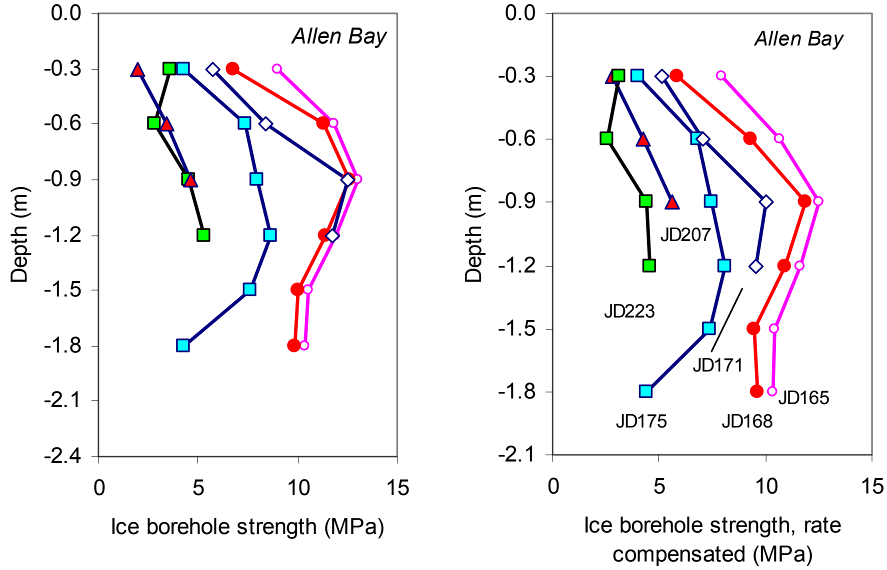
σ_m = measured ice strength (*in situ* ice borehole strength)

SR_c = stress rate used for standardization (1.0 MPa/s)

SR_m = measured stress rate

8.1.3 Rate-Compensated Strength Profiles

Equation (1) was used to compensate the strengths measured during three decay seasons for rate effect. Figure 15 shows an example of the uncompensated and compensated strength profiles of the first-year ice in Allen Bay. Because the ice in Allen Bay was already quite warm by June (about –2°C), compensating the measured strengths for rate effect resulted in small, but noticeable differences. Both the uncompensated and compensated profiles showed a decrease in strength with time, however the compensated data show a more systematic trend.



(a) uncompensated profiles **(b) compensated profiles**

Figure 15 Ice borehole strengths for two sites, compensated for rate effect (note that ice depths below 1.20 m were not tested on JD171)

Figure 15-b shows that, as expected, ice strength in the surface layer was greater than at the bottom surface. The ice strength began to decrease first in the surface layer, then in the bottom ice and finally in the ice interior. Similar trends were seen in profiles of compensated strengths for first-year ice at Barrow, Griffith and Leopold (not shown).

8.1.4 Rate-Compensated Data: Seasonal Changes in Ice Strength

Figure 16 shows three seasons of rate-compensated strength data for decaying first-year ice[5]. Early season measurements in cold, first-year ice showed the greatest rate-related changes in strength. The rate-compensated strength for the Barrow ice (on JD120) was 19.8 MPa, as opposed to the measured, uncompensated strength of 12.5 MPa. Other data showed less significant changes, since they involved warmer sea ice with actual stress rates that were closer to the standardized rate of 1.0 MPa/s.

[5] The strength data are a depth-averaged, mean of the number of tested boreholes (up to three). The average ice strength was used to represent each site on a particular day.

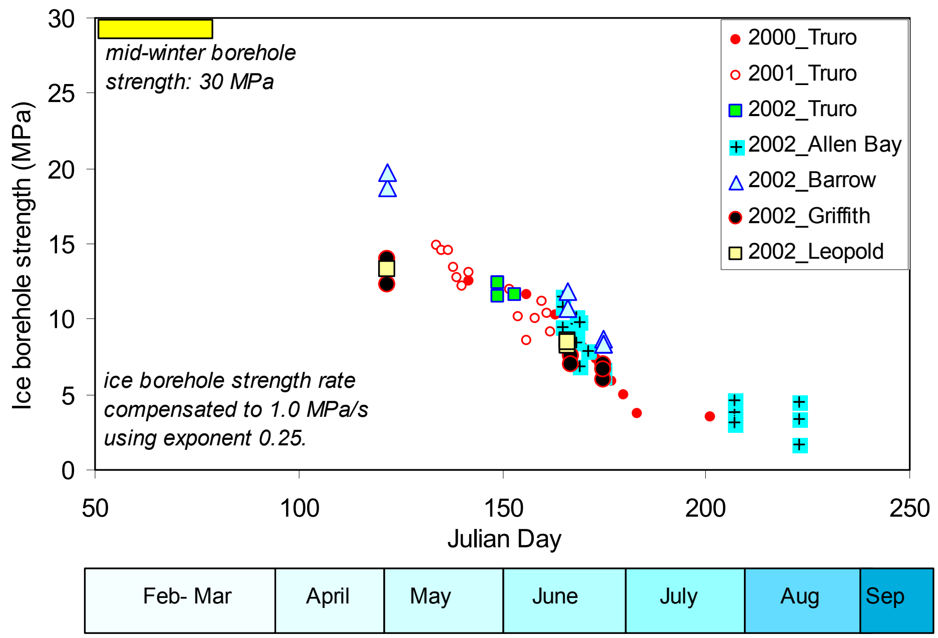


Figure 16 Ice borehole strength measurements, three seasons

There was excellent agreement between the strength of first-year ice measured at the same location in three separate years, as well as between the five sites in Parry Channel. The agreement is remarkable, considering the different ice thickness and the 120 km distance between the sites. Scatter in the borehole strength measurements was less than 4 MPa, with the exception of the 7 MPa variability in measurements on JD122. Much of the scatter on JD122 was likely due to the uncertainty in those measurements. When the overall trend of decreasing strength is compared to the early-season strengths at Barrow, agreement is quite favorable.

Compared to the mid-winter, maximum strength of first-year sea ice[6], the ice strength in early May had decreased considerably (Figure 16). Apparently, the ice strength begins to decrease well before the above freezing, mean daily air temperatures (in June, Figure 1). To determine when the ice strength first began to decrease, the general decay trend was hindcast to the maximum, mid-winter strength (assuming that the decay process has the same slope everywhere on the curve). Extrapolating the strength curve suggests that the strength of first-year ice begins to decrease around Spring Equinox (20 March, JD79), when the sun shines for half the day (at latitude 75°N). Figure 1 showed that, typically, in late-March air temperatures begin to increase, yet remain well below freezing.

[6] The mid-winter strength was based upon borehole jack tests in cold, Arctic, first-year sea ice (Sinha, 1986 and Blanchet et al., 1997). For the purposes of this report, those strengths were rate-compensated to 1.0 MPa/s, using Equation (1).

The average, bulk ice strength continued to decrease steadily until the beginning of July, when the ice strength at Truro was 3.8 MPa (2 July, JD183). The ice remained at the 3 to 4 MPa level until mid-August (JD223), when the program was terminated. Evidently, the ice strength decreases to about 3 MPa and remains there for six weeks or longer, depending upon when the ice breaks up or survives to become second year ice.

8.1.5 Seasonal Changes in Ice Strength, expressed as a Percentage

Figure 16 showed that the sampled first-year ice underwent a gradual, uniform decrease in strength during the decay process. It was suggested that the decrease in strength began in late March and extended until early July, at which point the ice strength stabilized at a small fraction of its mid-winter strength. Figure 17 shows the fractional strength of the ice, or percent strength remaining, in terms of the mid-winter ice strength[7]. Measurements from the 2000 and 2001 seasons are shown as the depth-averaged, mean strength for each sampling day. More detailed measurements are given for the 2002 data, which are shown as the depth-averaged strength of *each hole* tested at the different sites.

Figure 17 shows that when the first strength measurements were made in early May, the ice had about 40 to 70% of its mid-winter strength. The ice strength had decreased to about 30% of its mid-winter strength by the middle of June (JD165) and by the beginning of July the ice had only 15% of its mid-winter strength. The ice strength stabilized at the 15% level throughout July and into the middle of August. That ice strength in July and August is particularly important because most commercial shipping occurs in late summer, after first-year ice had reached an advanced state of decay.

The preceding sections focused upon the property measurements of landfast first-year sea ice. Figure 17 showed the importance of the decay process in terms of the reduction in ice strength. The excellent agreement between ice strength at the five different sites suggested that first-year ice in Parry Channel decayed quite uniformly in both space and time. Having characterized the decay of level, landfast first-year ice, the decay process of old ice will be next examined.

[7] The mid-winter strength used in this report was based upon the mid-winter maximum strength reported by Sinha (1986) and Blanchet et al (1997).

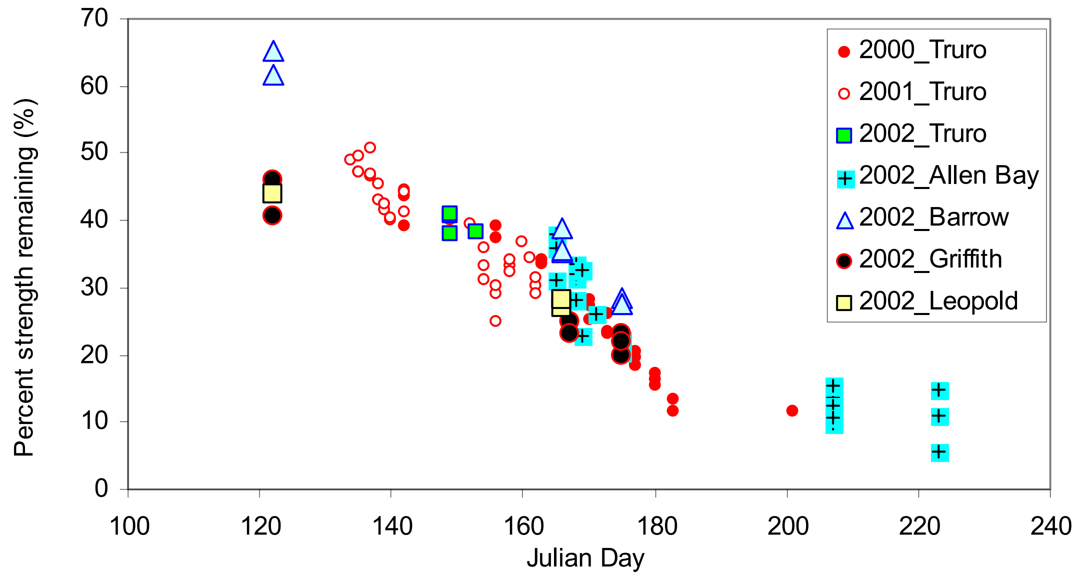


Figure 17 Percent strength remaining in terms of the maximum, mid-winter strength from 10 April (JD100) to 28 August (JD240)

9. Areas of Old Ice Sampled during the 2002 Season

Measurements on old ice were made in mid-June and mid-August. Two weeks prior to the June field trip, the Canadian Ice Service (CIS) provided assistance in locating old ice floes of interest. Hard copies of Radarsat images of the fast ice around Cornwallis Island were printed and the GPS coordinates of certain, targeted old ice floes were noted. Figure 18 shows the location of the targeted old ice sites, relative to the previously discussed first-year ice (FYI) sites, and the months in which the old ice sites were visited.

Satellite images were used to select two, isolated, multi-year floes in Wellington Channel (MYI) and a third floe west of Little Cornwallis Island. Landfast ice in Templeton Bay, Little Cornwallis Island was also identified as a potential sampling area. Imagery from the previous year showed that the ice in Templeton Bay had survived the summer of 2001 and become second year ice (SYI) in the fall of 2001.

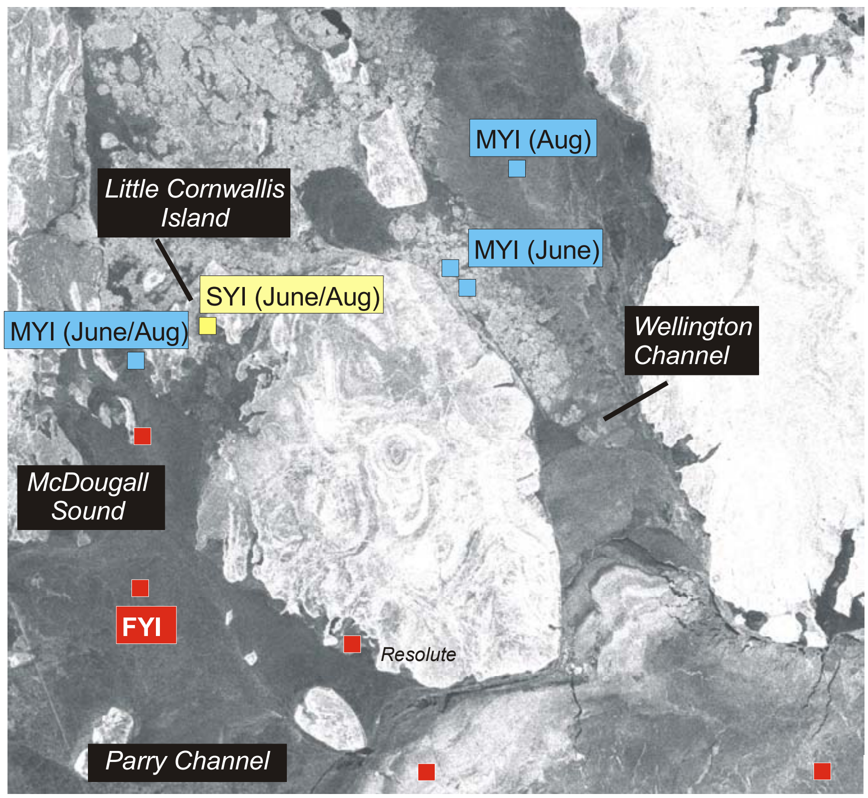


Figure 18 First-year (FYI), second year (SYI) and multi-year (MYI) sites sampled in 2002 (Images shown from Radarsat June 2002, courtesy of CIS)

In June, the weather in Resolute was cooperative and work at the old ice sites was completed in a timely manner. As a result, there was time to make a series of measurements at the first-year ice sites. During the second field visit in August, things did not go as smoothly. Persistent fog plagued the central Arctic, making flying impossible. The one and only time that the weather in Wellington Channel cleared enough to allow a site visit was the late afternoon of 14 August (JD226). The sites near Little Cornwallis Island were visited on two days in August (11/12 August, JD223/224), because weather in that area was much better than in Wellington Channel.

9.1 Second year Ice in Templeton Bay (75°29.15'N, 96°23.50'W)

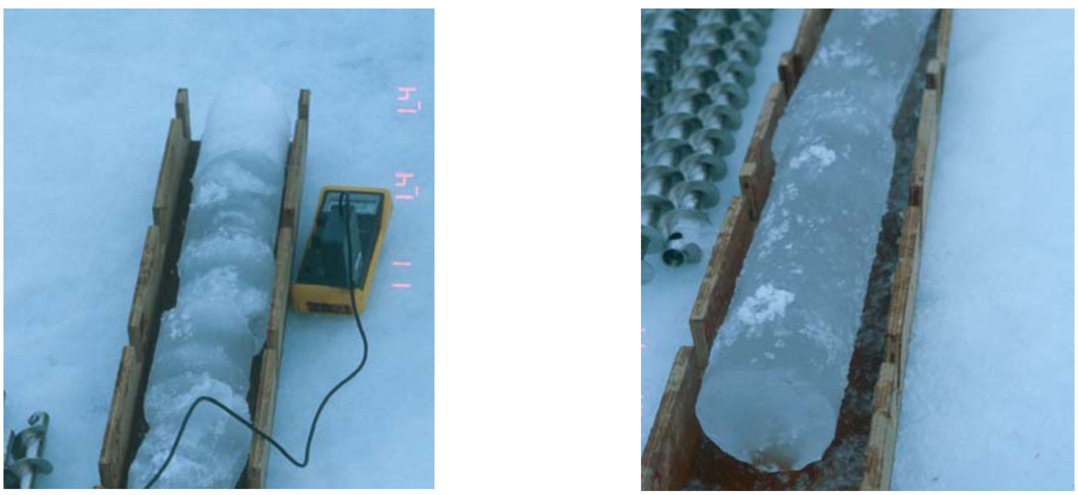
Initially, the second year ice in Templeton Bay was sampled on 19 June (JD170). In mid-June, the air temperature was +2°C, the average ice thickness was 2.45 m and melt ponds were just beginning to form (Figure 19-a). The ice surface was a contrast of white, snow-covered regions and dark, depressed areas of pooled water. The entire ice cover was water logged, which made it impossible to find a dry place to conduct measurements. It was decided to perform the measurements on a white, raised area of ice that was covered by 150 mm of wet snow.

The second visit to Templeton Bay was made two months later on 11 August (JD223). Air temperatures were around +2°C as in June, however there was heightened contrast between the white, raised areas of ice and ponded areas. The areal extent of the melt ponds had not changed much since June, yet the melt ponds had become much deeper (Figure 19-a/b). As a result, the ice was beginning to develop well-defined hummocks, as typical of second year ice. The ice thickness was measured (in three places) on a white, raised area of ice. The average ice thickness was 1.63 m in August, compared to 2.45 m in June. Measurements showed that in the raised areas, the ice had ablated about 0.82 m. Ice beneath the melt ponds would have ablated significantly more than that.

(a) 19 June, JD170 **(b) 11 August, JD223**

Figure 19 Second year ice in Templeton Bay

Figure 19-a shows that part of the ice surface was white in June. Areas were white because they were slightly elevated and covered by snow. In August, the raised areas of ice were devoid of snow yet they were white (Figure 19-b). The retrieved cores showed that, in August, the uppermost 0.20 m of ice appeared white because it consisted of porous, bubbly ice (Figure 20-a). Bubbly ice in the surface layer of second year ice has also been observed by Bjerkelund et al. (1985). Portions of the cores also showed evidence of extensive ice decay, such as the large hole that occurred at a depth of 0.20 m in one of the cores (not evident in Figure 20-a). The hole was 60 mm wide by 10 mm high and extended into the core. The surface of the cores showed visible signs of decay, yet bottom ice in two of the three retrieved cores was quite solid (Figure 20-b).



(a) core from 0 to 0.60 m depth **(b) core from 1.10 to 1.65 m depth**

Figure 20 Cores of second year ice in August

9.2 Multi-year Floes in Wellington Channel

During the 2002 season, three multi-year ice floes in Wellington Channel were sampled. The floes were designated as WC1, WC2 or WC3. Figure 21 shows the Radarsat image of fast ice of Wellington Channel used to identify floes WC1 and WC2. The multi-year floe that was sampled in August (floe WC3) was not in the satellite image shown in Figure 21.

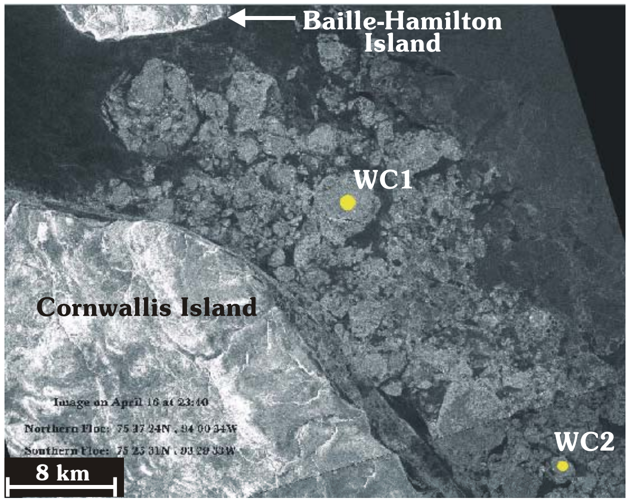


Figure 21 Satellite image of multi-year floes sampled on 22 June
(subsection of 16 April Radarsat image, courtesy of CIS)

9.2.1 <u>WC1 (75°37.24′N, 94°00.34′W)</u>

Floes WC1 and WC2 were both sampled on 22 June (JD173). Floe WC1, the larger of the two floes, was about 5 km in diameter and had a relatively level surface. Portions of the ice surface were covered by a 20 mm crust of dry snow, while other areas of ice were slightly depressed and had a 0.30 m thick layer of wet snow. Melt ponds had not yet started to develop on floe WC1 in June. The thickness of the multi-year ice floes was measured using (up to) six sections of one metre, stainless steel auger flighting (2” diameter). The thickness of floe WC1 was measured in four places (each about 3 m apart, making a quadrant). The ice thickness in three holes was 5 m and thickness in the fourth hole, drilled atop a hummock, was over 6 m thick.

One of the primary objectives of this program was to examine melt-induced changes in multi-year ice. That meant, ideally, the same floe should be visited in early and late summer. Visiting the same floe after the ice had become mobile in August required tracking its position. Floe tracking was done by deploying a beacon (courtesy of CIS) on one of the floes. The beacon continuously transmitted a signal that was recorded (several times each day) by CIS. The beacon was deployed on the larger of the two floes sampled in June (floe WC1), where it was placed on a hummock, in a 0.30 m deep hole.

Floe WC1 was tracked from the time that the beacon was installed on 22 June until 1 September 2002, when the beacon batteries expired. In Figure 22, the track of floe WC1 was superimposed on a satellite image corresponding to the initial floe location. Several (arbitrary) dates were given to illustrate the mobility of the floe. Initially, floe WC1 moved 80 km south along the coast of Cornwallis Island, crossed Wellington Channel and then turned north along the coast of Devon Island. When the second visit to Wellington Channel was made on 11 August, floe WC1 had circulated nearly the full length of the Channel. In fact, the last signal from the beacon indicated that floe WC1 was further north than when it was sampled in June!

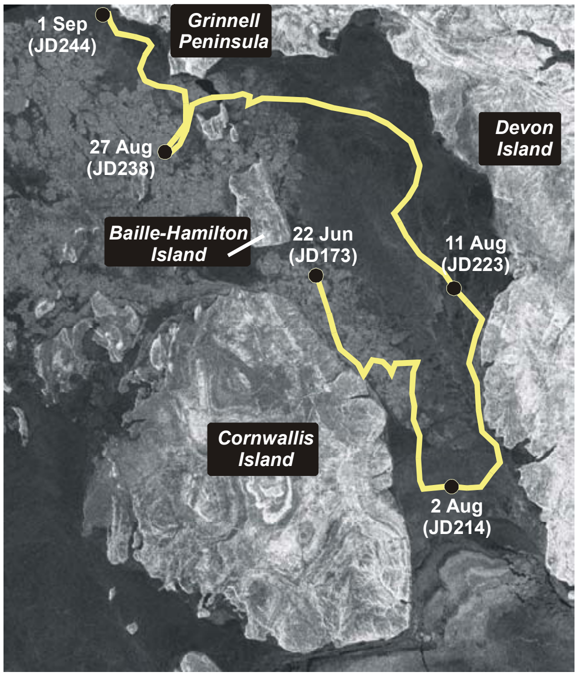


Figure 22 Track of floe WC1 on which beacon was deployed
(subsection of 16 April Radarsat, image courtesy of CIS)

9.2.2 WC2 (72°25.31′N, 93°29.33′W)

The other multi-year floe that was sampled in Wellington Channel in June was about 24 km south of Floe WC1. The second floe was about 2 km in diameter and was mostly flat, except for a 2.5 m high hummock. Some areas of floe WC2 were covered by 80 mm of snow, while other regions were bare or were beginning to develop melt ponds (Figure 23).

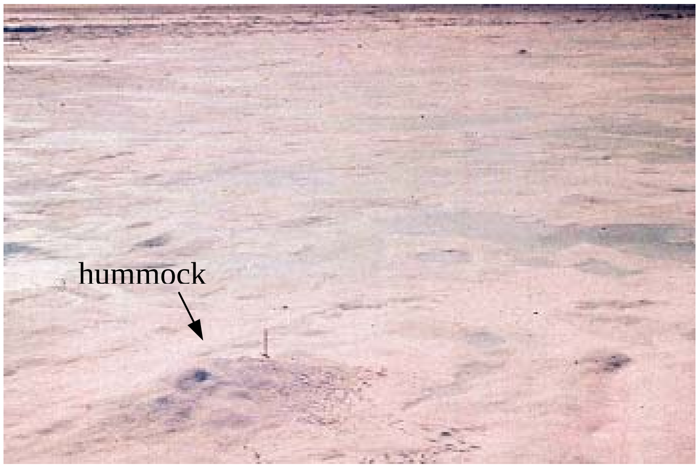


Figure 23 Surface topography of WC2 on 22 June

Measurements showed that the level ice of floe WC2 was 5.5 m thick whereas on a hummock the ice was more than 6 m thick. A site marker was placed on top of the hummock in hopes of locating the floe during the second part of the field program (vertical marker shown in Figure 23).

9.2.3 WC3 (75°46.22′N, 93°07.71′W)

As previously mentioned, the intent was to revisit floe WC1 when Wellington Channel was revisited in August. In that case, up-to-date coordinates of the floe position were essential because the ice was extremely dynamic. As it happened, the floe coordinates could not be obtained on the only day that a site visit was possible (14 August). As a result, attempts to locate floe WC1 (and its marker) were based upon coordinates from the previous day. After several circular tracks were flown over the loosely consolidated pack ice, it was necessary to abandon the search (due to the limited fuel supply) and settle upon a different multi-year floe. Floe WC3 was selected for sampling on 14 August (JD226). As measurements were being conducted on floe WC3, the GPS readout showed that the floe was moving westward rapidly.

Floe WC3 had numerous large, well-established melt ponds yet it did not have any hummocked areas of ice. Due to time constraints, the ice thickness was measured in two holes only, each about 10 m apart. The first hole was made in level, dry ice where the ice was more than 6 m thick and the second hole was drilled at the edge of the melt pond, where the ice was only 4 m thick. The melt pond in which the second hole was drilled is shown at the far right of Figure 24. The walls of the melt ponds sloped down rather steeply which showed that the ponds were very deep. For example, the water was 0.16 m deep at the edge of the melt pond shown in Figure 24 (about 10 m across). The pond would have been considerably deeper at the centre of the pond.

Figure 24 Surface topography of floe WC3, visited on 11August (JD223)

9.3 Floeberg along Little Cornwallis Island (75°26.64'N, 97°00.07'W)

Figure 21 showed that satellite imagery is a powerful tool for identifying floes of interest before arriving in the field. On occasion, the ice floes identified in the satellite image are not as promising as hoped. Such was the case when the targeted floe near Little Cornwallis Island was visited (Figure 18). The floe looked promising in the satellite image, but when it was seen from the helicopter the floe was similar to the surrounding level first-year ice (except that the identified floe had a slightly rougher surface). The targeted site was abandoned and a much more interesting group of floes along the coast of Little Cornwallis Island was visited (Figure 25-a). The three floes, the so-called floebergs, rose about 3 m above the surrounding first-year ice and had a very level surface. Each of the floes was about 100 m in diameter, which explains why they were not readily detectable in the satellite imagery[8].

The first visit to the floebergs was made on 19 June (JD170), after the ice in Templeton Bay had been sampled. Arbitrarily, the southwest floeberg was selected for sampling in June. Large chasms separated the three floes, which had embedded veins of sediment and were not snow covered. The ice was over 6 m thick (the maximum thickness capable of being measured). Property measurements of the floe were aborted on 19 June when both the data acquisition system and the temperature sensor malfunctioned. They malfunctioned because they had gotten wet several hours earlier in Templeton Bay. With little else to do, it was decided to leave a site marker and return to Resolute to dry out the equipment. The second visit to the floeberg was made on June 21 (JD172) and the full suite of property measurements was conducted.

(a) 21 June, JD172 **(b) 11 August, JD223**

Figure 25 Floeberg west of Little Cornwallis Island

[8] RADARSAT ScanSAR imagery has a pixel spacing of at least 100 m, depending upon the mode used.

Ice west of Little Cornwallis Island had broken-up and moved on several weeks prior to the August field trip. The odds were against finding the floebergs at their previous site, since they probably had been pushed south during breakup. On 11 August, after sampling ice in Allen Bay and Templeton Bay, it was decided to continue across Little Cornwallis Island in hopes of finding the floebergs. Two floebergs had moved south during the season but, quite remarkably, one of the floebergs was left (Figure 25-b). The remaining floe was the one that had been furthest inshore in June; its presence in August indicated that it must have been grounded on the seabed. The freeboard of 3 m indicated that the ice was about 30 m thick, which was in good agreement with the 30 m water depth in that area that was obtained from bathymetric charts.

It was a relief to find the floeberg in August, after thinking that surely it had moved south during break-up. That gratitude was soon tempered because the corer became stuck after retrieving only the upper two metres of ice! Having visited two sites already, the day was getting late. It was decided to return to Resolute and return to the site with a chainsaw the next day. Two attempts had been made obtain property measurements on the floeberg in June and it looked like two days would also be required in August.

Fortunately, the weather cooperated and the site was visited the next day, on 12 August (JD224). All efforts focused on recovering the corer because it was an expensive piece of equipment and it had been borrowed from a colleague. The only possible way to free the corer was to saw a pit along the length of the corer. It took an entire day to make the pit. At the end of the day, just when the top of the top of the corer was visible, the pit began filling with water. That was galling, because the top of the corer was within reach, yet the water prevented further use of the chainsaw. The situation was made worse by the fact that no data had been acquired on the properties of the floeberg in late-season! In hindsight, the backup corer (used at floe WC3) should have been used to make strength measurements on the floeberg *before* attempting to recover the embedded corer. Especially since the corer was not recovered anyway!

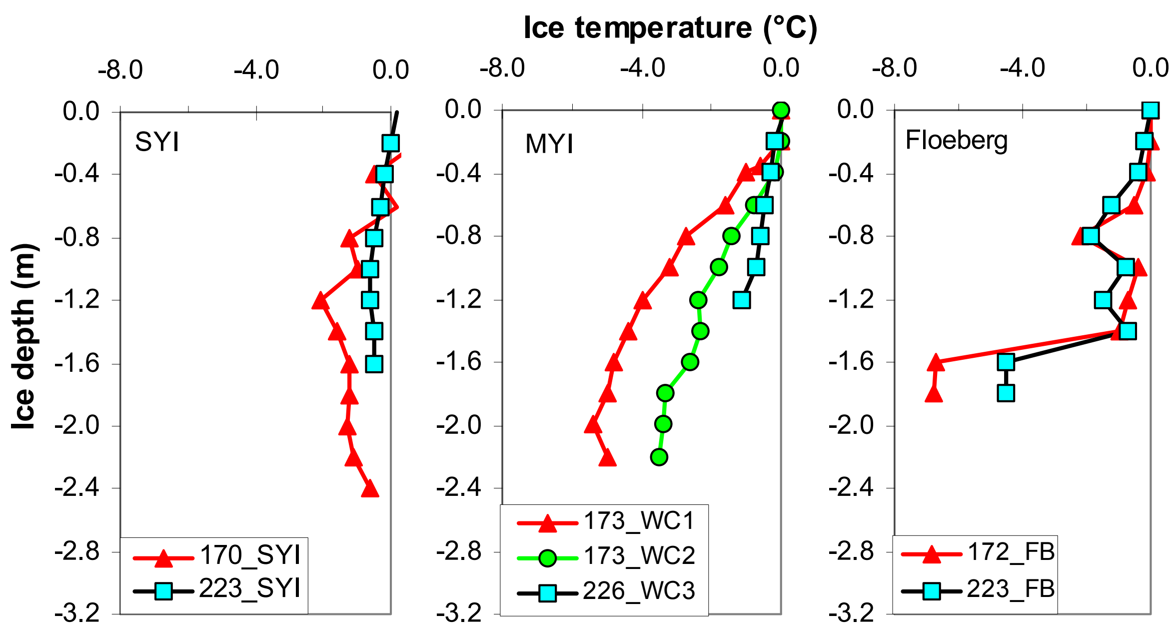
Figure 26 Pit dug attempting to retrieve corer

10. Temperature Profiles at Old Ice Sites

The following discussion gives a brief description of the temperature profiles of the old ice sites visited during the 2002 field season. Figure 27 compares the profiles of second-year, multi-year and floeberg ice in June and August (where data are available). The temperature profiles were obtained using a calibrated, digital thermistor at 0.20 m intervals throughout the length of retrieved cores (similar to the methodology discussed in Appendix A).

10.1 Second year Ice in Templeton Bay

In June, the temperature profile of second year ice resembled that of first-year ice in that it was above –2°C throughout its entire 2.45 m depth (Figure 27-a, JD170). The variation in temperature with depth indicated that the second year ice had not yet reached an isothermal state. When the second year ice was visited again in August (JD223), the ice was indeed isothermal and its thickness had decreased by 0.82 m.



(a) second year ice **(b) multi-year ice** **(c) floeberg**

Figure 27 Temperature profiles of old ice in June and August

10.2 Multi-year Ice in Wellington Channel

Figure 27-b shows temperature profiles of the two multi-year floes sampled in June (floes WC1 and WC2, JD173). The profiles show that the temperature of floe WC1 was colder than floe WC2 by as much as 2°C (at a common depth). The only multi-year floe that was sampled in August was floe WC3. Comparison of the temperature profiles shown in Figure 27-b shows that the uppermost 0.60 m of ice in each of the three floes had a temperature near -0.3°C yet temperatures began to diverge with increasing depth. In August, the interior of the multi-year ice (floe WC3) was as much as 3°C warmer than multi-year ice in June (for the same depth). No comparison can be made below a depth of 1.2 m, since the cores were not retrieved (the backup corer did not retrieve cores as effectively as the primary corer, embedded in the floeberg).

10.3 Floeberg along Little Cornwallis Island

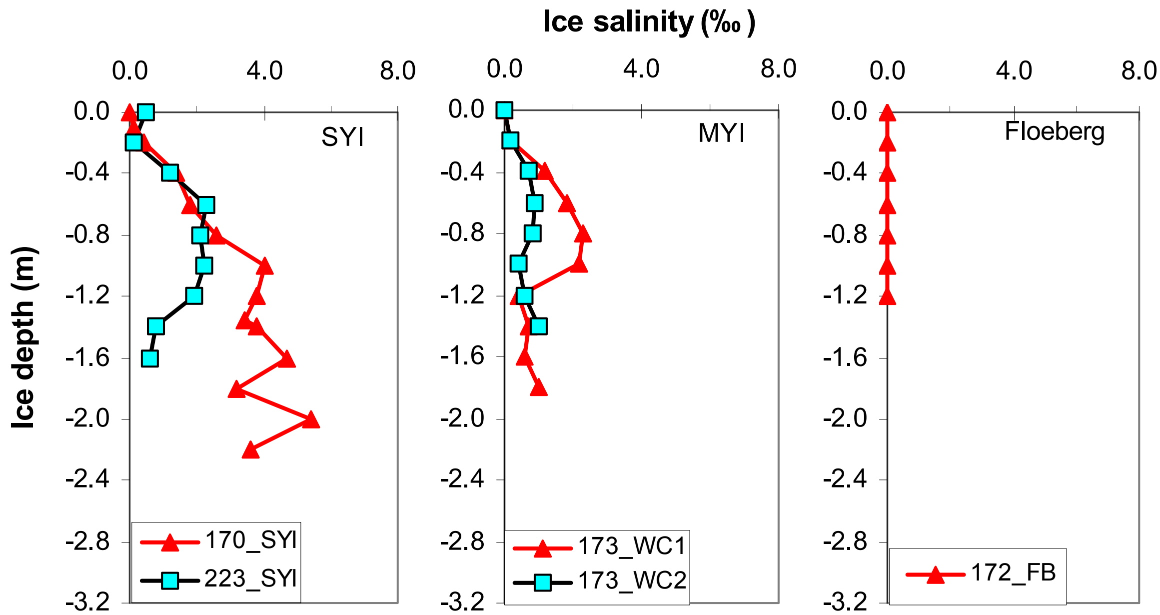
The temperature profile of the floeberg ice indicated a sharp transition at a depth of 1.6 m (Figure 27-c). Ice above that depth had temperatures warmer than –2°C, whereas below that depth the ice was considerably colder. Note that the temperature of ice above the transition zone did not increase considerably from June to August, yet below the transition zone ice temperatures warmed by about 2°C. The coldest temperature recorded in the floeberg was –6.8°C in June and –4.5°C in August. The temperature profiles provide insight as to why the corer became stuck at a depth of about 2 m in August; temperatures at that depth were at least 4°C colder than water infiltrating the hole during coring. Since the floe did not have any standing water on its surface, the water infiltrating the hole must have been seawater penetrating through the porous ice.

11. Salinity Profiles at Old Ice Sites

Salinity profiles of the old ice sites in June and August are shown in Figure 28. Ice salinity was measured by sectioning the ice into 2 cm thick discs at depth intervals of 0.20 m. The samples were transported to base camp, where they were brought to room temperature and the salinity of the melt water was measured with a calibrated, digital salinometer (Appendix A).

11.1 Second year Ice in Templeton Bay

Full thickness cores were removed from the second year ice in Templeton Bay in June (JD170) and August (JD223). Figure 28-a shows that, in June, the uppermost metre of ice was characterized by low salinity ice that gradually increased to 4‰ (the salinity for typical first-year ice) at a depth of one metre. The ice salinity remained relatively constant at 4‰ from depths 1.0 to 1.4 m. Ice salinity from depths 1.6 to 2.2 m showed greater variability (3.2 to 5.4 ‰).



(a) second year ice **(b) multi-year ice** **(c) floeberg**

Figure 28 Salinity profiles of old ice in June and August

In August, the uppermost 0.60 m of second year ice in Templeton Bay was characterized by low salinity layer (less than about 2‰). Below that depth, the ice salinity remained relatively constant at about 2‰, until a depth of 1.40 m. Measurements showed that the salinity of the bulk layer of ice decreased from about 4‰ in June to 2‰ in August. In August, the salinity profile of the second year ice was similar to that of first-year ice, as shown by the negligible salinity of the upper and lower ice surfaces.

Comparing salinities for a particular depth using superimposed salinity profiles from June and August can be misleading. Strictly speaking, the salinity profile of the ice in August should be shifted down along the depth axis to account for ice ablation at the upper ice surface. The August salinity profile was not offset to account for the effect of ablation because measurements had not been conducted to determine the amount of ablation occurring at the upper (and lower) ice surfaces.

11.2 Multi-year Ice in Wellington Channel

Salinity profiles for the multi-year ice floes are available only for the two floes sampled in June (JD173). Recall that both multi-year floes consisted of level ice about 5 m thick, yet floe WC1 was about 2°C colder than floe WC2. Figure 28-b shows that the salinity of the larger, colder floe was less than 1‰, except where it increased to about 2‰ from depths 0.60 to 1.0 m. The salinity profile of floe WC2 was less than 1‰ throughout the 1.4 m core.

11.3 Floeberg along Little Cornwallis Island

The salinity profile of the floeberg ice in June showed no measurable traces of salt throughout the length of 1.2 m core taken. Salinity measurements of the floeberg ice were not available for August, however the ice would have shown no evidence of entrained salt at that time either.

12. Borehole Strength of Old Ice

The borehole strength of the ice was measured at the second year, multi-year and floeberg ice in June and August (in most cases). Depth profiles of the ice borehole strength were conducted at intervals of 0.30 m in three holes (see Appendix A). The following sections discuss test results from each old ice site. As with the first-year ice data, strength data for the old ice sites were rate-compensated using Equation (1) to account for the different rate effects that characterized each test. To be consistent with the first-year ice sites, a standardized stress rate of 1.0 MPa/s was used in Equation (1) along with an exponent of 0.25.

12.1 Second year Ice in Templeton Bay

Figure 29-a shows the strength profiles[9] of second year ice in Templeton Bay for June (JD170) and August (JD223). In June, the ice borehole strength of second year ice ranged from 12.1 to 8.9 MPa, depending upon the particular depth. Ice strength at a depth of 0.30 m was greatest and the strength decreased with increasing depth. Between depths 0.60 and 1.50 m, the borehole strengths were tightly clustered around 10 MPa. The strength decreased to 9 MPa from depths 1.80 to 2.10 m.

The August borehole jack tests showed the pronounced effect that summer melt had upon the strength of second year ice. The borehole strength of second year ice at depth 0.30 m decreased to 5.7 MPa in August, compared to 12.1 MPa in June. Below a depth of 0.60 m, the ice strength steadily increased with increasing depth. In August, the strength ranged from 3.5 MPa (at 0.60 m depth) to 9.4 MPa (1.5 m depth). In comparison, the strength of the bottom ice had not changed appreciably since June. Had it not been for the resistance encountered when coring through the bottom layer of ice in two of the three boreholes, the high-strength bottom ice would have been thought erroneous. The resistance in coring the ice showed that the rate-compensated strengths of 11.1 and 11.6 MPa were indeed real[10]. The reason for the surprisingly high strength of the ice bottom needs to be explored further.

[9] The profiles were obtained by averaging the borehole strength in the three holes at each particular depth.

[10] Bottom ice in the third hole had a borehole strength of 5.7 MPa, which is why the average of the three holes was reported as 9.4 MPa in Figure 29-a.

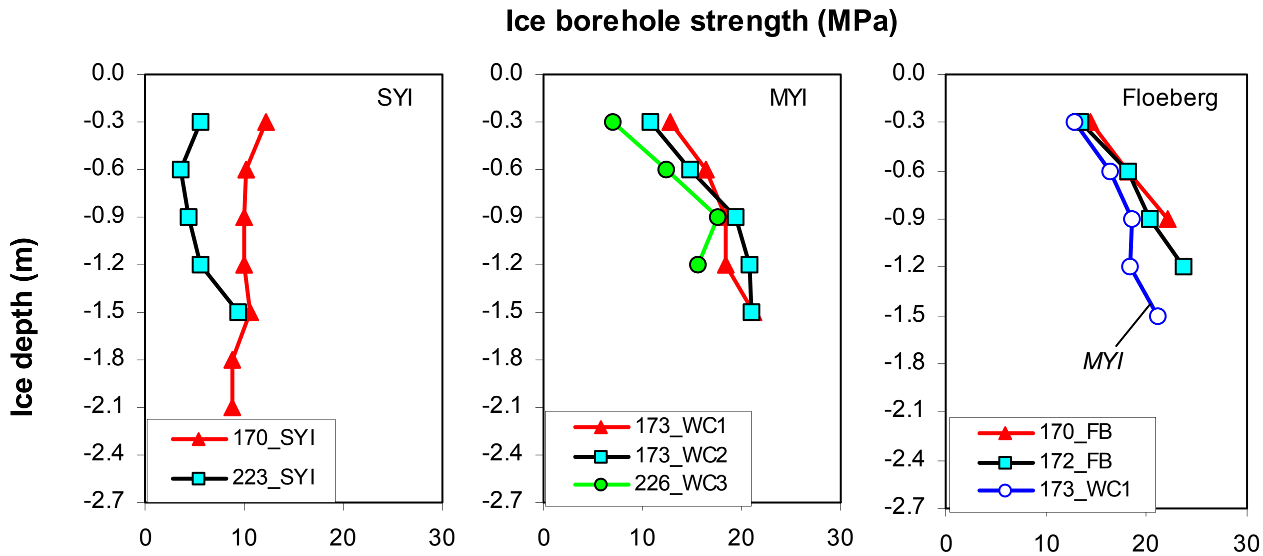


Figure 29 Rate compensated borehole strength of old ice in June and August

12.2 Multi-year Ice in Wellington Channel

Figure 29-b shows the average strength profiles of multi-year floes WC1, WC2 and WC3. Strength measurements made in June on floes WC1 and WC2 showed that the borehole strength ranged from 10.5 to 21.1 MPa. The ice strength increased with increasing depth, as one might expect based upon the temperature profile (Figure 27-b). The uppermost 0.60 m of ice in floe WC1 was 2.0 MPa stronger than in floe WC2, even though both the floes were about 5 m thick. That trend changed however, at depths 0.90 and 1.20 m, where the strength of floe WC2 exceeded the strength of floe WC1 by about 1.0 MPa.

When the second trip to Wellington Channel was made in August, property measurements were made on floe WC3, a large level floe over 6 m thick. August measurements showed that the ice strength did not change much over the summer, relative to the two floes sampled in June. The average strength profiles for multi-year ice show a difference of about 2 MPa for each location in June and August (Figure 29-b). Strength profiles for individual holes differed by about 6 MPa, at most (individual holes not shown).

In August, the attachment mechanism for the borehole jack was damaged on floe WC3 after testing at depth 1.2 m in the first hole. Without the attachment to position the jack in the borehole, it was necessary to use the hydraulic hoses. Because of the tight fit, the hoses could only be used to position the jack at a depth of 0.30 m. Since measurements were limited to the ice surface strength, it was decided get salvageable data from ice beneath the melt pond. Measurements showed that the strength of the ice at the edge of the pond was 8.2 MPa (depth 0.30 m, beneath 0.16 m of water). In comparison, the borehole strength of dry ice was 12.8 MPa at a depth of 0.30 m (Figure 29-b, the strength of the melt pond was not shown).

12.3 Floeberg along Little Cornwallis Island

Figure 29-c shows two strength profiles for the floeberg ice, both profiles were obtained in June. One of the profiles shown in Figure 29-c is for 19 June (JD170) and the other profile represents the return visit on 21 June (JD172). The June measurements showed that the floeberg had a strength of 14.5 MPa at a depth of 0.30 m. The strength increased to a maximum of 24.5 MPa at a depth of 1.2 m. The previously discussed complications precluded strength measurements from being conducted in August.

For comparison purposes, the strength profile of floe WC1 (multi-year ice) was superimposed on the June profiles of the floeberg ice in Figure 29-c. The strengths of the multi-year ice and floeberg ice were about the same at a depth of 0.30 m, however the floeberg ice was about 2 MPa stronger than the multi-year ice at depths 0.60 and 0.90 m. The was even greater difference in strength at a depth of 1.20 m; the floeberg ice was about 5 MPa stronger than the multi-year ice.

13. Strength Comparison: First-year Ice versus Old Ice

Three years of seasonal measurements on first-year ice produced a substantial amount of reproducible data. Those data were used as a basis for forecasting the deterioration in strength of first-year ice, which is reflected in the Ice Strength Charts (Gauthier et al., 2002). Measurements showed that first-year ice lost up to 85% of its strength by the end of summer. Obviously, the decay process caused a significant reduction in strength in first-year ice. Did the same sort of reduction in strength occur in second year and multi-year ice?

Strength data collected on the various ice types were complied in Figure 30. The ice types included first-year ice, second year ice, multi-year ice and the floeberg ice. The first thing to note from the figure is that the mid-winter strength of first-year ice far exceeds strengths measured in the various ice types from May to August. That is to be expected, since measurements by Sinha (1986) showed that the strength of first-year ice was comparable to multi-year ice strength in mid-winter. The mid-winter strengths are comparable because, although the brine pockets in first-year ice outnumber those in multi-year ice, the pockets are small and consist mostly of solid salts. In spring, the first-year ice begins to warm causing the brine pockets to enlarge and the salts enter solution. This process is accompanied by a reduction in ice strength. The primary difference between first-year ice and multi-year ice is that the latter has fewer brine pockets. That difference is one of the reasons why increased temperatures in multi-year ice cause less pronounced changes in ice strength (compared to first-year ice).

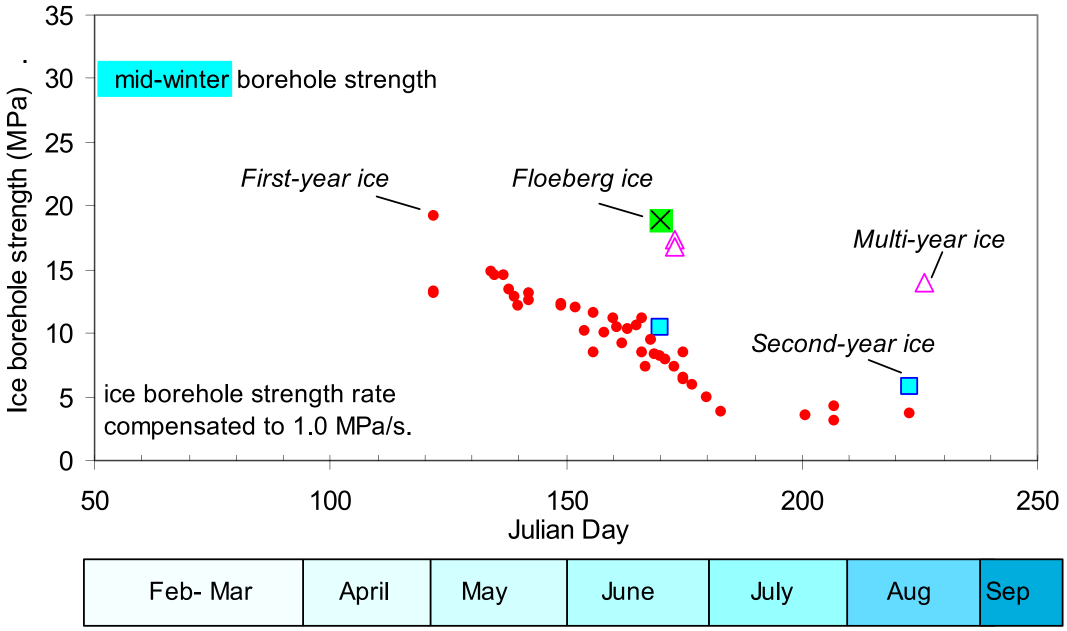


Figure 30 Comparison of strength for different ice types

Based upon Sinha (1986), the maximum mid-winter strength of first-year ice is also, most likely, representative of the second year and multi-year ice. In that case, the reduction in strength that occurs in all ice types during summer can be referenced to a maximum mid-winter strength of 30 MPa. Figure 30 shows that, by mid-June (JD170) the full thickness strength in first-year ice was about 26% of its mid-winter strength. In comparison, the full thickness strength of second year ice was 35% of its mid-winter strength. The uppermost metre of multi-year and floeberg ice had roughly 56% and 63% of their mid-winter strength.

Figure 30 shows that the strength of first-year ice began to deteriorate very rapidly after mid-June, once above-freezing air temperatures were sustained. By mid-August, the strength of first-year ice was about 12% of its mid-winter maximum. The sampled second year ice also showed a substantial reduction in strength by mid-August. The second year ice had only 19% of its mid-winter strength. In comparison, the top metre of multi-year ice was still quite strong, since it retained 47% of its mid-winter strength. In fact, the two months of above freezing air temperatures between June and August had caused the strength of multi-year ice to decrease by only 9% (to 47% from 56%). Strength measurements were not available for the floeberg ice in August.

14. Conclusions

Seasonal measurements from three field seasons on first-year ice were summarized. Property measurements from the three field seasons were good agreement. Measurements from four different sites in Parry Channel showed that first-year ice in the Strait decays in a similar fashion. Results showed that the properties of first-year ice change dramatically during summer melt. The linear temperature gradient that characterizes winter first-year ice gradually transforms into a parabolic profile in which ice at the upper and lower surfaces are warmer than the ice interior. By the mid-June, the ice is in an isothermal state, in which the full thickness of ice is at (or near) its melting point. Desalination of the ice began at the upper and lower ice surfaces. The expulsion of salt from the top surface affected salinity measurements at lower depths. By the end of July, the ice was nearly devoid of salt throughout its full thickness. Borehole jack tests of decaying first-year ice at the different sites in Parry Channel from May to August showed that first-year ice steadily loses its strength during the summer. By mid-June, the first-year ice has 26% of its mid-winter strength and by mid-July the ice strength was 12% of its mid-winter maximum. The ice strength remained at between 10 – 15% level during from mid-July to mid-August. At that point, the ice broke up or survived to become second year ice.

Measurements on several types of old ice were also reported, including second-year ice, multi-year ice and floeberg ice. Where possible, measurements were conducted at the same location in June and August. Based upon profiles of the ice temperature, ice salinity and borehole strength it was concluded that second year ice behaves much like first-year ice during the decay season. One of the differences between first-year and second year ice was the presence of a low-salinity layer of ice that was about one metre thick in June. The surface layer in the second year ice was about 30% stronger than first-year ice, for the same depth and sampling date. In August, the low salinity surface layer was about 0.50 m thick (as opposed to about one metre in June). The strength of the ice had decreased from about 10 MPa (in June) to about 6 MPa in August. In terms of its mid-winter strength, the second year ice had 35% and 19% of its mid-winter strength in June and August, respectively.

Three multi-year ice floes were sampled. Two floes were sampled in June (each about 5 m thick) and the third floe (over 6 m thick) was sampled in August. Measurements showed that the uppermost 0.60 m of multi-year ice was near -0.3°C. Temperatures began to diverge with increasing depth. In August, ice at a depth of 1.2 m was about 3°C warmer than multi-year ice in June (for the same depth). In June, ice salinity was less than 2‰ to a depth of 1.4 m. Borehole jack tests in the uppermost 1.5 m of ice showed an increase in strength with increasing depth. A maximum ice borehole strength of 20 MPa was measured at depth 1.5 m. The strength of the multi-year ice was 56% and 47% of its maximum mid-winter strength (30 MPa) in June and August, respectively. As a result, two months of above freezing temperatures caused the ice strength to decrease by an additional 9%.

The floeberg ice, so-called because it was about 30 m thick, was extremely level and the extracted 1.2 m core had no measurable salinity. In June, the temperature profile of the floeberg ice showed that ice above a depth of 1.6 m was warmer than –2°C, whereas below that depth the ice was –6.8°C. Temperature of the ice above the transition zone did not change between June and August, yet ice below a depth of 1.6 m warmed to –4.5°C by August. Comparison of the strength profile of the floeberg ice and multi-year ice showed that ice strengths were comparable at a depth of 0.30 m, however the strengths deviated with increasing depth. In June, there was a 5 MPa difference in strength between the two ice types at a depth of 1.2 m. The uppermost metre of ice in the floeberg had a strength of about 19 MPa, compared to 16 - 17 MPa in the multi-year ice. Measurements in August were not available for the floeberg ice.

Three years of measurements on first-year ice showed good repeatability in the ice strength. The reported strengths on old ice should be qualified however, since they are a product of one field season only. Observations on second year ice seem reasonable in light of the fact that second year ice that has grown in a sheltered bay may be, in fact, mostly first-year ice. Depending upon environmental conditions during summer and the rate of ice ablation, only the upper surface of ice may be low-salinity second year ice. In that respect, the decay process (and reduction in strength) of second year ice would be comparable to first-year ice. Measurements during the 2002 field season provide evidence of that.

Measurements made on multi-year ice showed that, at the end of the summer season, the ice retained 47% of its mid-winter strength. It should be noted that, in both June and August, measurements were conducted on a sizable multi-year floes. Each of the three floes had substantial freeboard. It is probable that multi-year ice with appreciable freeboard has not decayed significantly. On the other hand, multi-year ice with very little (or no) freeboard has been observed (R. Gorman, personal communication). Multi-year with little freeboard may not have much strength however there have been no measurements to support such a conjecture.

15. Acknowledgments

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Appendix A

Methodology for Property Measurements on Decayed Ice

During the 2002 field program, measurements at Truro Island were performed in a 900 m^2 area of level, landfast first-year ice. The first-year ice sites in Parry Channel were part of a distributed sampling program, in which the same area of ice was visited up to three times from May to July 2002. Measurements at the old ice sites were conducted as follows: two visits were made to the second year ice in Templeton Bay, two visits to the floeberg ice off Little Cornwallis Island and one visit each to the multi-year floes in Wellington Channel.

Introduction

Measurements conducted at each of the sites included freeboard (where applicable), snow thickness, ice surface temperature, ice thickness, ice salinity and the ice temperature. A motor driven, fibre-glass corer was used to make three boreholes in the ice (0.15 m diameter), each about 1.5 to 2.0 m apart (see Figure A-1). The ice thickness, freeboard and snow depths were measured at each borehole. A full thickness core was retrieved from the first-year and second year ice sites. At the multi-year ice sites, a core up to 2.20 m long was removed from each of the three holes.

Core 1

The first ice core was used to obtain a profile of ice temperature. The contents of the core barrel were emptied into a wooden holder. A thermal probe was inserted into small holes made in the core at depth intervals of 0.15 to 0.20 m. Since the length of the core barrel was only 0.90 m long, ice that was thicker than that was retrieved by taking multiple cores. Temperatures of the individual core pieces were measured as soon as they had been removed from the core barrel in attempts to minimize the influence of warm air temperatures and solar radiation.

Core 2

The full thickness core from the second borehole was used to profile the ice salinity. Discs about 20 mm thick were cut from the core at intervals of 0.15 to 0.20 m. The sections were cut as quickly as possible to minimize brine drainage. Samples were promptly bagged, transported to base camp and left to melt at room temperature. The salt content of the meltwater was later measured with a calibrated, digital salinometer.

Core 3

Usually, the core from the third borehole was not used for measurements. However, when possible, the third core was placed in a cooler and transported to cold storage facilities at Polar Continental Shelf Project in Resolute. At the end of the field program, core fragments were shipped to the laboratory at the Canadian Hydraulics Centre of the National Research Council in Ottawa, Ontario. Upon arriving in Ottawa, the cores were checked, put in cold storage. Core fragments remain in cold storage for future microstructural studies, time permitting.

Borehole Jack Tests

Each time a core was removed from the ice, the hole that it left was used to measure an *in situ* ice strength profile. The *in situ* confined compressive strength of the ice was measured using a borehole jack system, as described in Masterson (1996). Two types of borehole jack systems were used during the 2002 field season. The first type of borehole jack had simpler mechanics, in that it had one mobile platen and an opposing fixed face (curved to fit flush to the curvature of the borehole). The jack had a potentiometer to measure the displacement of the indenter platen. The second borehole jack system that was used had two opposing, mobile platens. Two linear variable displacement transducers (LVDT) were used to measure the displacement of those platens. In both cases, oil pressure to displace the patens into the ice is measured with a pressure transducer.

Borehole jack tests were conducted at depth intervals of 0.30 m until the bottom of the ice was reached or until the uppermost two metres of ice had been profiled (Figure A-1). The depth to which tests were conducted depended upon the amount of time required to retrieve the borehole jack from each test depth. No significant problems were encountered retrieving the jack in first-year and second year ice however, when the ice was cold and strong, it became exceedingly difficult to retrieve the jack from test depths (below 0.30 m depth). Since the jack was retrieved by manpower alone, tests were not conducted below a depth of 1.50 m at the multi-year ice and floeberg sites in June.

When positioned at the specified test depth, the borehole jack indenter plates were extended and the platen displacement and oil pressure were output to a Campbell Scientific data logger. The test continued at a specified depth until the pressure gauge showed that the external oil pressure had stabilized or decreased. The plates were then fully retracted, the jack was rotated 90° and lowered to the next test depth. The jack was rotated 90° between tests to avoid the region of ice that was damaged during the previous test. Measurements from the different borehole jack tests were compared using the ice pressure at an indenter penetration of 3 mm. The measured borehole strengths were rate compensated to 1.0 MPa/s to account for the rate effects that characterized the ice during testing.

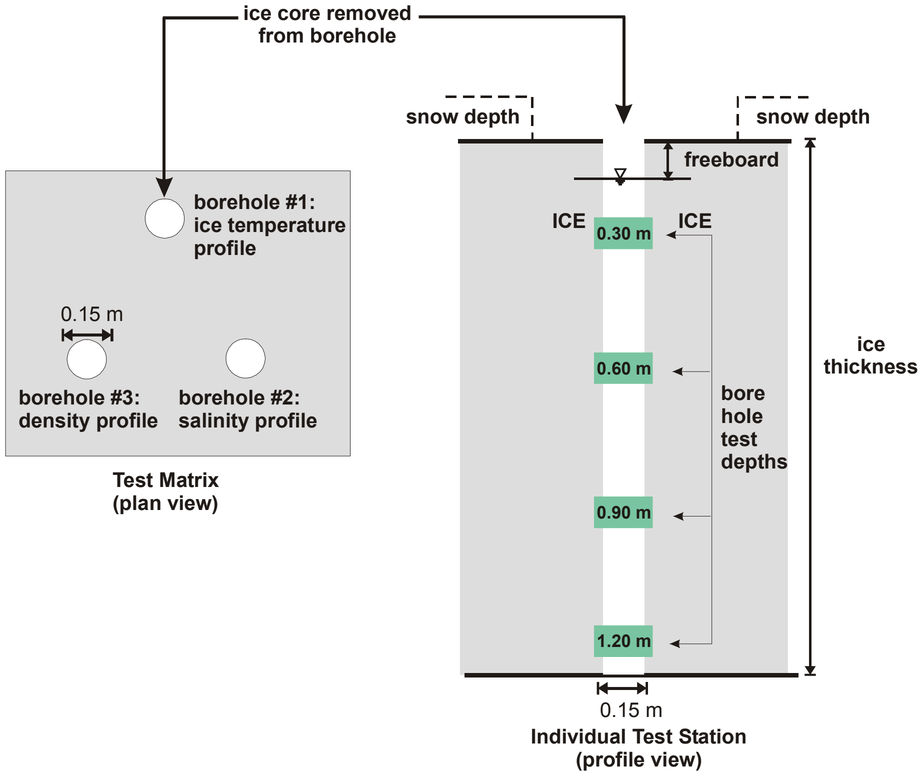

Figure A-1. Test matrix for ice borehole strength measurements