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Properties of Decaying First Year Sea Ice: Two Seasons of Field Measurements

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ABSTRACT

This paper reports on two seasons of field measurements conducted on landfast, first year sea ice in the Canadian Arctic. Field measurements began in mid-May, when the ice was still cold and continued, on a regular basis, until June and July. During the field programs the snow and ice thickness were monitored, as were the ice temperature, salinity and strength of the ice. The *in situ* ice borehole strength was measured in more than 100 borehole jack tests each season. Measured borehole strength was compared to the calculated flexural strength of the ice. During the period that the strengths overlapped, there was good agreement between trends in the measured ice borehole strength and the calculated flexural strength.

Introduction

Considerable effort has been devoted to measuring the properties and strength of cold, winter sea ice (Sinha, 1986; Sinha, 1990; Spencer et al., 2001). Typically, ice strength measurements have been conducted before mid-May. That is because in spring, warm air temperatures become problematic for ice sampling. Once the ice warms, logistics and ice sampling become more difficult and ice properties change immediately after a core has been removed from the ice sheet.

The absence of data on the properties of warming first year sea ice led to the development of a field program during which the properties and *in situ* strength of the ice would be measured throughout the winter-spring transition period and into early summer. Two seasons of strength and property measurements have been conducted on landfast, first year sea ice in McDougall Sound (75°14.4'N, 97°09.3'W), Canadian Arctic. This paper provides a summary of the data acquired during the field programs.

Description of 2000 and 2001 Field Programs

The first field season extended from 21 May to 19 July 2000 and the second season was from 14 May to 28 June 2001. There was considerable overlap in measurements between the two seasons. Measured properties included the snow and ice thickness, air and ice temperature, ice salinity and the *in situ* ice borehole strength. Property measurements were obtained at individual ice stations, distributed over a 900 m² area of ice. The ice site was visited several times each week and a new ice station within that area was selected (about 5 m from the previous test station). During each site visit, a fibreglass corer was used to make three 0.15 m diameter boreholes in the ice, as shown in Figure 1. Individual holes were made about 1.5 to 2.0 m apart to minimize any influence from nearby test holes. After cores were extracted from each hole, the ice thickness, freeboard and snow depth were measured. The core from the first hole was used to profile the ice temperature, the second core was used for ice salinity measurements and the third core was used (early in the season) for ice density measurements. The reader is referred to Johnston et al. (2000) for a more thorough description of the field program.

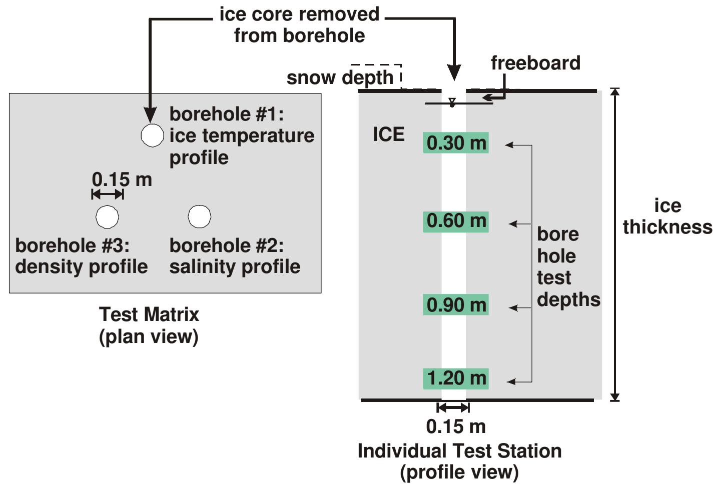


Figure 1 Borehole test matrix and ice stations

A borehole jack assembly was used to measure the *in situ* confined compressive strength of the ice (borehole strength) in each of the three holes. The borehole jack consists of a high-strength, stainless steel, hydraulic cylinder with a laterally acting piston and two indentor plates, curved to match the wall of the borehole. Once activated, the piston inside the body of the jack applies hydraulic pressure to the front and back indentor plates. The oil pressure and displacement of the indentor plate were recorded by an external digital data acquisition system, which subsequently was used to determine the ice pressure during indentation.

Borehole jack tests for each of the three holes were conducted at depth intervals of 0.30 m (Figure 1). Typically, four borehole jack tests were performed at each hole before the bottom of the ice was reached. During the tests, the main indentor plate was extended continuously until the limit of the stroke ram was reached (50 mm total diametrical displacement) or concern was expressed about overloading the jack. At that point, the indentor plate was retracted fully, the jack was rotated 90° and lowered to the next test depth.

Ice Properties and *In situ* Strength Measurements

The following sections focus upon the air and ice temperatures, salinity profiles and ice borehole strengths measured during the two field seasons. The discussion is based upon the average ice properties measured (in two to four boreholes) at each ice station, at a given depth. The time scale used in the different plots corresponds to the Julian Day (JD) for the year 2001. To obtain the JD in year 2000, a leap year, subtract one beginning at JD60.

<u>Air Temperature</u>

Figure 2 shows the mean air temperatures at Resolute for years 2000 and 2001 (data courtesy of Atmospheric Environment Service). The Resolute weather station is about 60 km southeast of the ice sample site in McDougall Sound. The 2000 field season extended from 21 May to 19 July (JD142 to JD201). The 2001 field season started about one week earlier, on 14 May (JD134) and terminated about one month earlier than the 2000 season. The mean daily air temperatures for the two years were very similar. At the beginning of the two programs the mean daily air temperature was below –10°C. After 13 June (JD164), air temperatures remained above freezing and continued to increase steadily throughout the remainder of the programs.

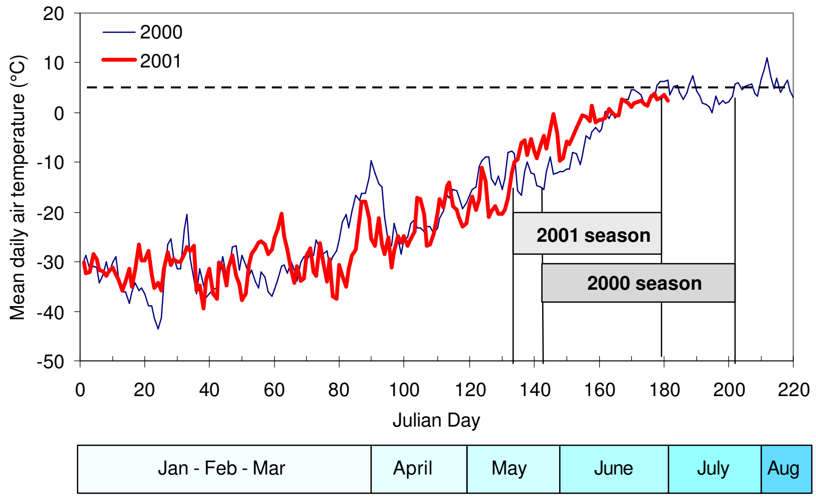


Figure 2 Mean daily air temperatures at Resolute for years 2000 and 2001

Ice Temperature

Temperature profiles were obtained from one of the extracted ice cores. Every attempt was made to measure the ice core temperatures immediately after core extraction; however warm ambient air temperatures did affect the measurements. For this reason, it was preferable to use the *in situ* ice temperatures measured by a string of thermistors installed at a nearby meteorological station (about 2 km west of the ice measurement stations). The *in situ* ice temperatures were available only for the 2001 decay season (courtesy of University of Manitoba). The thermistor string was installed on 7 May (JD127) and re-covered with the removed, but relatively undisturbed, snow. An analog temperature signal was logged continuously at 15-minute intervals until 3 July (JD184).

Figure 3 shows a contour plot of the *in situ* ice temperatures as a function of ice depth and Julian Day, in the early morning (0600 hours). When the program began there was a temperature gradient in the ice from about –10°C at the ice surface to –3.5°C at a depth of 1.0 m (the last measurement on the thermistor string). As the season progressed the temperature of the ice at all depths steadily increased. After about 9 June (JD160) more than half of the full thickness of ice was isothermal at –3°C. By 20 June (JD170) the entire ice thickness was isothermal at –2°C during the stable morning hours. By the end of the program, 3 July (JD184), the temperature gradient had been inverted; ice in the surface layers was warmer than the bottom ice. The positive ice surface temperatures (shown in black), most likely resulted from ice melt exposing the top of the thermistor string.

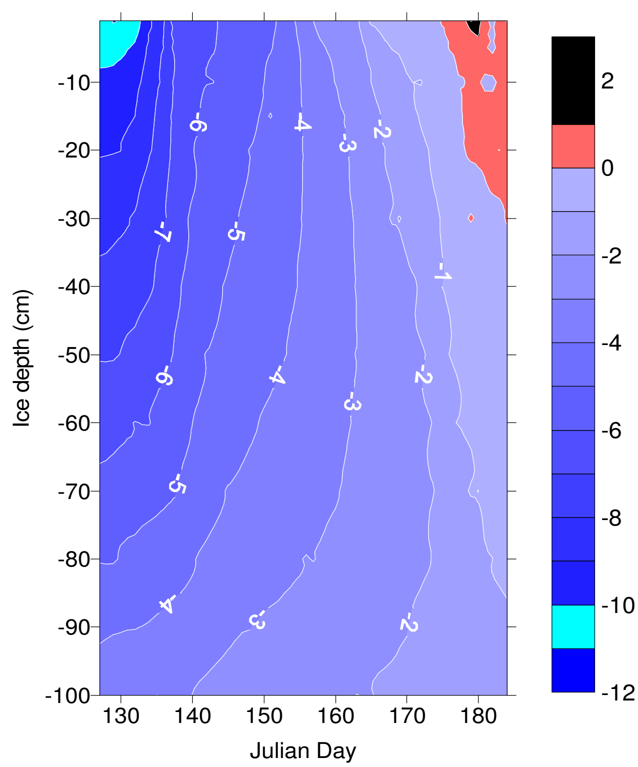


Figure 3 *In situ* ice temperatures (06:00 hours during 2001 season)

Snow and Ice Thickness

Figure 4 shows snow depth (h_s) and ice thickness (h_i) in relation to air and ice surface temperatures. Temperature measurements in the figure were based upon the 2001 season. There was great similarity between snow and ice thickness measurements for the two seasons. That is to be expected, since air temperatures for the two years were quite similar (Figure 2). During the first month, snow depth ranged from 0.14 to 0.39 m. After about 13 June (JD164) sustained warm air temperatures caused the snow to melt rapidly. Comparison of snow measurements on JD164 and JD172 showed that, within one week, tens of centimeters of snow had reduced to only 40 mm. By JD179 the mean daily Resolute air temperature and the temperatures measured by the upper portion of the thermistor string were nearly equal (2.0°C and 2.9°C respectively). The similarity indicated that the snow cover and ice around the top of the thermistor string had melted and exposed the string to the air.

During both measurement seasons, the ice thickness ranged from 1.30 to 1.55 m until mid-June, when the ice thickness began to decrease. The onset of ice ablation in mid-June coincided with the point at which the snow cover had melted completely, the ice surface had been exposed and the ice cover was characterized by a –1.8°C isotherm (Figure 3). Whereas ice thickness measurements in the year 2001 terminated before significant ice ablation occurred, measurements in 2000 season continued well into the advanced stage of ice decay. Those measurements showed that the ice ablated from an average thickness of 1.51 m to 0.83 m in about four weeks. The 2001 field measurements, which terminated after about one week of ablation, showed that the ice thickness decreased from about 1.44 m to 1.20 m. The ice thickness decreased at a relatively constant rate of 22 mm/day during the four weeks of ablation in year 2000 (Johnston et al., 2000) whereas the ablation rate in year 2001 was slightly higher, 34 mm/day.

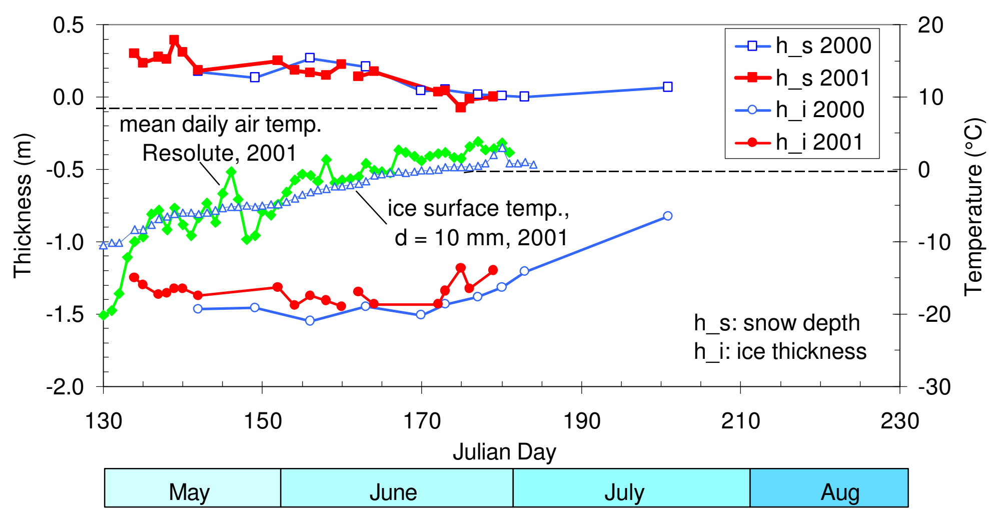


Figure 4 Snow and ice thickness for 2000 and 2001 seasons

Ice Salinity

Figure 5 presents representative salinity profiles for five sampling dates during the 2000 and 2001 field programs (expressed as JD-year). Measurements show that, from the beginning of the field studies in mid-May until mid-June, the salinity of the bulk layer of ice remained relatively constant at about 5‰. After mid-June the surface salinity decreased from about 5 to 0‰. The salinity of the bottom ice also changed in late June; in year 2000 the salinity of the bottom layer decreased from 4 to 2‰ whereas the bottom layer of ice had completely desalinated by late June 2001. The change in salinity that occurred in late June (in both years) coincided with the onset of ice ablation (see ice thickness in Figure 4). By the end of June the ice was nearly devoid of salt. On 19 July (JD201) the ice had a salinity of less than 0.5‰ throughout its full thickness of 0.83 m. The low ice salinity measured late in the season indicated that the brine channels had become well established. The interconnected nature of the channels would have facilitated brine drainage and produced a measured ice salinity that was, most likely, significantly lower than the *in situ* ice salinity.

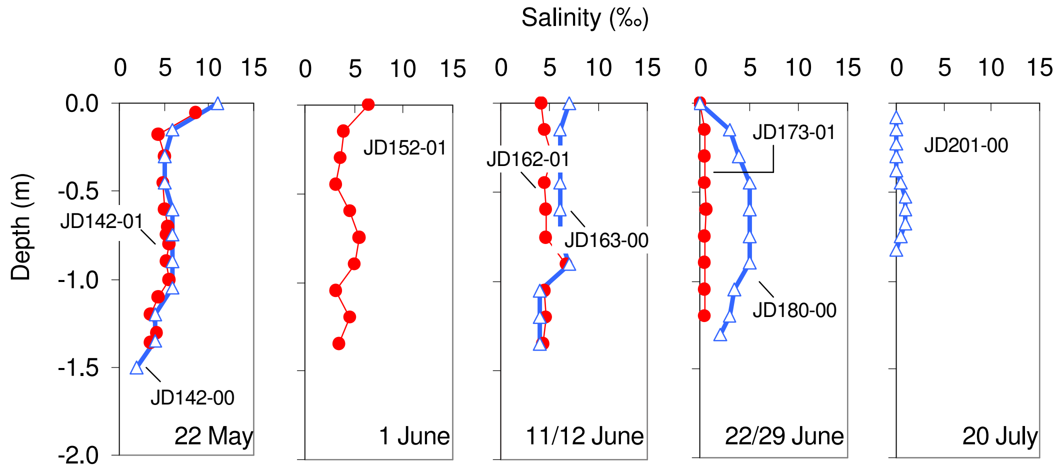


Figure 5 Ice salinity profiles during 2000 and 2001 seasons

<u>Ice Borehole Strength</u>

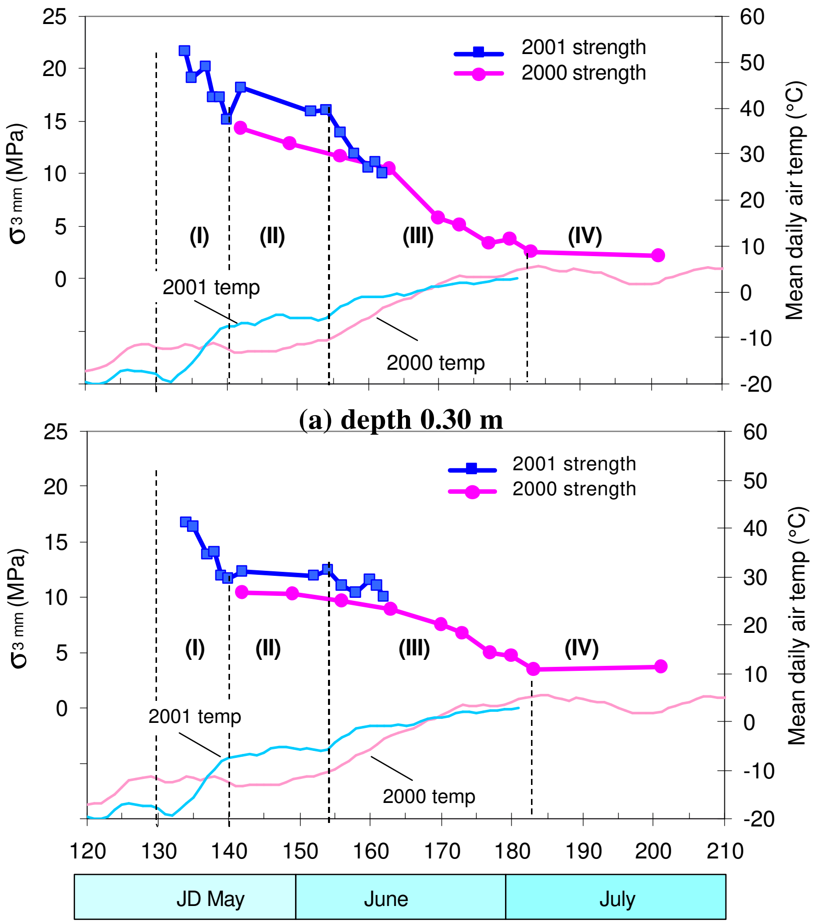
A significant component of the field programs conducted in years 2000 and 2001 was measuring the *in situ*, confined compressive strength of the ice (borehole strength) with a borehole jack. Strength measurements were obtained at least twice per week in the early season and more frequently as the season progressed. Results from the different borehole jack tests were compared using the ice pressure at an indentor displacement of 3 mm (σ_{3mm}). The reader is referred to Johnston et al. (2000) for a more complete description of the analysis procedure.

Figure 6 shows the average, ice borehole strength (of three or four holes) at ice depths 0.30 and 0.90 m for the two measurement seasons. Since air temperatures and ice thickness for the two seasons were comparable, there is good agreement between the sets of borehole jack tests. Although only the strengths for two ice depths are shown in Figure 6, ice strength at depths 0.60 and 1.20 m behaved similarly (Johnston et al., 2000; Johnston and Frederking, 2001).

Despite a certain amount of deviation, ice strengths from both seasons showed four different stages that were marked by varying rates of decreasing strength. Figure 6 shows a direct correlation between trends in the ice strength and the mean daily air temperature (shown as a 7 point moving average). The correlation illustrates that the stages (and their duration) are highly dependent upon air temperatures and initial ice thickness. Consequently, the four stages discussed below are valid only for the 2000 and 2001 measurement seasons, which were very similar. The decrease in ice strength in other years may not be characterized by these trends.

Only the 2001 season provided information about the first stage, which occurred from JD134 to JD140. The first borehole measurements showed an ice strength of 21.7 MPa in the surface layer of ice (depth 0.30 m, see Figure 6). The literature was consulted to compare the strength in early May to the mid-winter ice strength. Blanchet et al. (1997) reported strengths of 24 to 27 MPa for cold, mid-winter first year sea ice. Based upon those measurements, the ice strength measured during Stage I was lower than the mid-winter ice strength. The considerable snow depth (0.27 m) and subzero ice temperatures (–10 to –6°C) did not preclude a 5 to 7 MPa decrease in the ice borehole strength during Stage I. During Stage I the ice lost 25 to 30% of its initial, mid-May strength.

From JD140 to JD154 there was only a 1 to 2 MPa decrease in ice strength (less than 5% decrease in two weeks). That period of stable ice strength was classified as Stage II. In general, the mean daily air temperatures gradually increased during Stage II, but remained below zero. Temperatures within the surface layer of ice increased to within several degrees below zero (–5 to -4°C).



(a) depth 0.30 m

(b) depth 0.90 m

Figure 6 Changes in ice borehole strength at two depths

Stage III was defined by a notable decrease in ice strength that started on JD154 and continued until about JD183. By the end of Stage III, the ice strength had only 65 to 80% of the strength that it had initially, in mid-May. Mean daily air temperatures were consistently above zero, which caused the snow cover to melt rapidly and the *in situ* ice temperatures to increase above –3°C.

After JD183, there was another plateau in ice strength; ice at all depths maintained a strength of 2 to 3 MPa (Johnston and Frederking, 2001). Measurements showed that the ice strength remained stable for about three weeks (JD183 to JD201). By the end of Stage IV, the surface layer of ice had decreased by 85% of the initial, mid-May ice strength whereas strengths at the other depths remained the same in Stage IV as during Stage III.

Discussion

The preceding section showed the feasibility of using the borehole jack assembly to measure the borehole strength (*in situ*, confined compressive strength) of decaying first year sea ice. Nevertheless, the flexural strength of the ice is more relevant in some ice applications. How then, does the *in situ* confined compressive strength relate to the flexural strength of the ice?

The flexural strength of sea ice has been measured in more than 1000 tests. Timco and O'Brien (1994) compiled the results from those tests. The authors showed that the data could be described by an inverse relation between the brine volume and flexural strength of the ice, as shown in Equation 1.

$$\sigma_f = 1.76 \exp(-5.88 * \sqrt{\upsilon_b}) \qquad (1)$$

where σ_f is the flexural strength of the ice and the brine volume (ν_b, expressed as a brine volume fraction) is determined using Equation 2, after Cox and Weeks (1982)

$$\upsilon_b = \rho_i \, S_i \, / \, F_1(T) \qquad (2)$$

where ρ_i is the bulk ice density, S_i is the bulk ice salinity and $F_1(T_i)$ is based upon the two ranges of ice temperatures (T_i) shown below

$$F_1(T_i) = -4.732 - 22.45\,T_i - 0.6397\,T_i^2 - 0.01074\,T_i^3 \qquad \text{for } -2 \geq T_i \geq -22.9$$
$$F_1(T_i) = 9899 + 1309\,T_i + 55.27\,T_i^2 + 0.716\,T_i^3 \qquad \text{for } -22.9 \geq T_i \geq -30$$

Figure 7 shows a comparison between the calculated flexural strength of the ice and the measured ice borehole strength throughout the full thickness of ice (average ice strength at depths 0.30, 0.60, 0.90 and 1.20 m). The figure also shows the average, full thickness ice temperature and the brine volume, both of which were used to calculate the flexural strength of the ice.

Both the ice borehole strength and the calculated flexural strength decrease throughout the season. Results show that the full thickness ice borehole strength decreased from 18 MPa in mid-May to about 3 MPa in early July. In comparison, the calculated flexural strength of the ice was 0.53 MPa in mid-May and decreased to 0.25 MPa by 9 June (JD160). After early June, the flexural strength of the ice was not calculated because the ice temperature and brine volume had increased to the point where Equation 1 was no longer appropriate. This is because the equation for flexural strength relies upon calculations of the brine volume (equations which are not valid at near melting ice temperatures). Over the range for which the strengths were comparable, the ratio of ice borehole strength to flexural strength varied from 21 to 48.

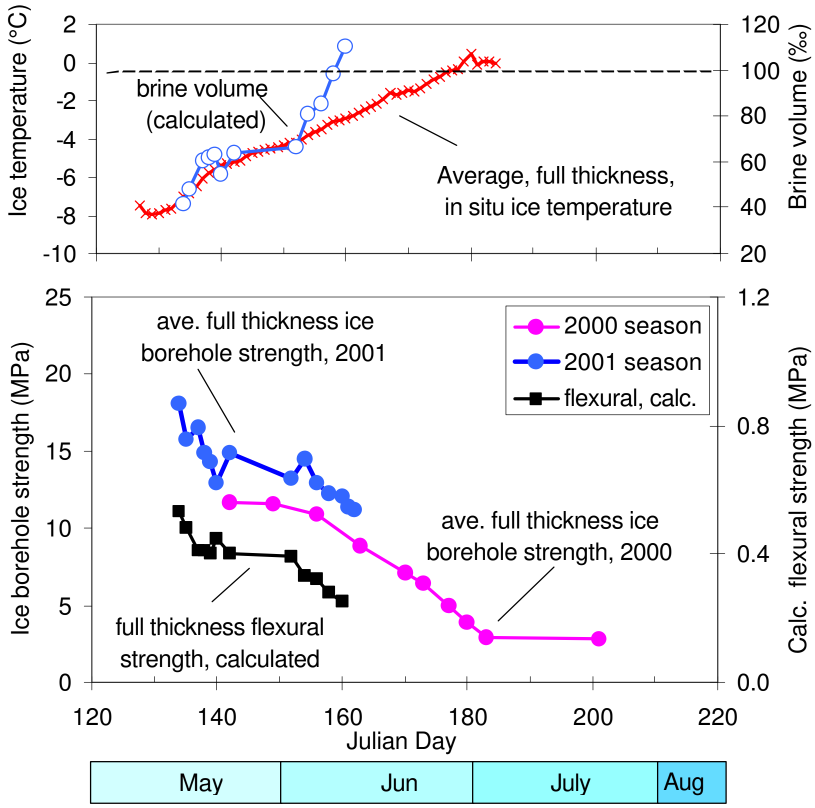


Figure 7 Comparison of *in situ* ice borehole strength and calculated flexural strength

The borehole jack is very beneficial for providing information about the ice strength in the region where the flexural strength equation is no longer valid. Essentially, the borehole jack is the only convenient means of measuring the strength of deteriorating sea ice. The time-series trace of the ice borehole strength shows that there is a trend of decreasing strength until early July when the ice strength reached a plateau of 2 to 3 MPa.

Conclusions

Two seasons of strength measurements were conducted on landfast first year sea ice in McDougall Sound during the decay season. Comparison of mean daily air temperatures recorded at Resolute for years 2000 and 2001 revealed similar temperatures. There was considerable overlap between borehole jack tests conducted during the first and second measurement seasons. Measurements showed that similar trends occurred at various ice depths during the two years.

Examination of ice borehole strength data from two field seasons revealed that, in general, there were four stages, each marked by varying rates of decreasing ice strength. Stage I occurred from mid-May to late-May. During Stage I the snow was up to 0.27 m thick and temperatures in the ice surface layers ranged from –10 to –6°C. The ice strength had already begun to decrease in mid-May, despite the presence of a 0.27 m thick snow cover and subzero ice temperatures. Stage II extended for two weeks, from late May to early June. Due to stability in the mean daily air temperatures, the ice borehole strength changed by 1 to 2 MPa during Stage II. Stage III occurred from early June to early July and was the period during which most of the decay in strength occurred. During Stage III mean daily air temperatures that were above zero caused the 0.27 m snow cover to melt rapidly, thereby exposing the ice surface. By the end of Stage III the ice was isothermal and the ice strength was 2 to 3 MPa. By the time that the ice reached Stage IV its strength was only 15 to 20% of the mid-May ice strength. Ice strength at all depths remained stable at 2 to 3 MPa during Stage IV. Results showed that once air temperatures remained above zero for an extended period, the ice strength decreased dramatically.

Acknowledgements

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References

Blanchet, D. Abdelnour, R. and G. Comfort (1997) “Mechanical Properties of First Year Sea Ice at Tarsiut Island”, Journal of Cold Regions Engineering, March 1997, Vol. 1, No. 1, pp. 59 – 83

Cox, G. and Weeks, W. (1988) Profile Properties of Undeformed First-year Sea Ice. CRREL Report 88-13, Hanover, N.H., USA.

Johnston, M., Frederking, R. and G Timco (2000) Seasonal Decay of First Year Sea Ice, Technical Report by Canadian Hydraulics Centre HYD-TR-058, April 2000, 24 pp.

Johnston, M. and R. Frederking (2001) Decay Induced Changes in the Physical and Mechanical Properties of First year Sea Ice, Port and Ocean Engineering under Artic Conditions (POAC’01), Ottawa, Canada, 12 – 17 August 2001, Vol. 3, pp. 1395 - 1404.

Sinha, N.K. (1986) “The Borehole Jack, Is It a Useful Arctic Tool?”, Proc. Fifth Int. Offshore Mech. and Arctic Eng. Sym. (OMAE’86), Tokyo, Japan, 13 – 17 April, 1986, Vol. IV, pp. 328 - 335.

Sinha, N.K. (1990) “Ice Cover Strength Decay using Borehole Indentor”, Proc. Tenth Int. Sym. on Ice (IAHR), Espoo, Finland, Vol. 2, pp. 735 – 744.

Spencer, P., Masterson, D. and K. Yockey (2001) Floating Sea Ice Road Strength from Borehole Jack Data: Northstar 2000, Port and Ocean Engineering under Artic Conditions (POAC’01), Ottawa, Canada, 12 – 17 August 2001, Vol. 1, pp. 183 – 192.

Timco, G.W. and S. O’Brien (1994) “Flexural Strength Equation for Sea Ice”. Cold Regions Science and Technology, Vol., 22, pp. 285 – 298.