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ONE SEASON OF A 1ST YEAR SEA ICE RIDGE INVESTIGATION - WINTER 2009

Lucie Strub-Klein[1,2], Knut V. Høyland [2,1]

[1]The University Centre on Svalbard, UNIS, Longyearbyen, NORWAY

[2]The Norwegian University of Technology, NTNU, Trondheim, NORWAY

ABSTRACT

A small first-year ridge was investigated in the Van Mijen fjord, Svalbard, from 14 February to 14 May 2009. It was visited 6 times and the thickness of consolidated layer (h_c) was measured by drilling along two lines across the ridge. The average h_c grew from 1.17 to 1.54m in line 1 and from 1.04 to 1.37m in line 2 whereas the surrounding level ice grew from 1.0 to 1.25m. The block thicknesses in the sail were fairly constant and of 0.2m until May when they decreased due to solar radiation. TDS profiles were done 5 times and the average salinity of the consolidated layer was more or less constant. The micro-porosity increased during the season, mostly because of increasing temperatures. Uniaxial horizontal compressive strength was tested in field during 2 visits and the results fit reasonably well with the empirical formulas of Timco and Frederking (1990) and Moslet (2007). Two lines of four thermistor strings were installed and recorded temperatures from 4 March to 14 May. The rubble consistency was very soft and eroded, even more than in previous ridge studies in the Van Mijen fjord. We suggest that this is because the ridge was small and therefore the oceanic fluxes became more important.

INTRODUCTION

A sea ice ridge is formed when the ice is broken by the wind or the currents and piles up. It consists of water, ice blocks, consolidated ice, slush and air. The part above the waterline is defined as the sail and the part below the waterline is defined as the keel. The keel itself is divided into a consolidated layer and a lower unconsolidated part, the rubble. Ridges can be categorized by first-year and old ice features.

Sea ice ridges appear in most of cold offshore regions and are a major problem for winter navigation. From an engineering point of view, they can generate high loads against offshore structures (Blanchet, 1998) and in the absence of icebergs they often give the design ice action. However, models and codes describing the load they exert are still incomplete partly because of the lack of knowledge about temporal and spatial variability of both geometrical and mechanical properties of ice ridges. The consolidation of first-year ice ridges have been studied by e.g. Leppäranta et al. (1995) and Høyland (2002), and the spatial variation in both geometry and small-scale uniaxial compressive strength was studied by Shafrova and Høyland (2008), but little has been done on the combined spatial and temporal development and (to our knowledge) nobody has studied the temporal development of mechanical properties.

LOCATION AND EXPERIMENTAL SET-UP

The ridge was located on Van Mijenfjorden, Svalbard, 2km away from Kapp Amsterdam and 10km from the mining town Svea. It was situated 150m from the shore, slightly protected from the main currents coming from the outer basin. It was orientated almost along the main stream and seems to follow its change of direction (see Figure 1 for location and orientation). Water depth was measured at low tide to be 4.20m and the ridge was not grounded. The ridge was 4m wide and 7m long.

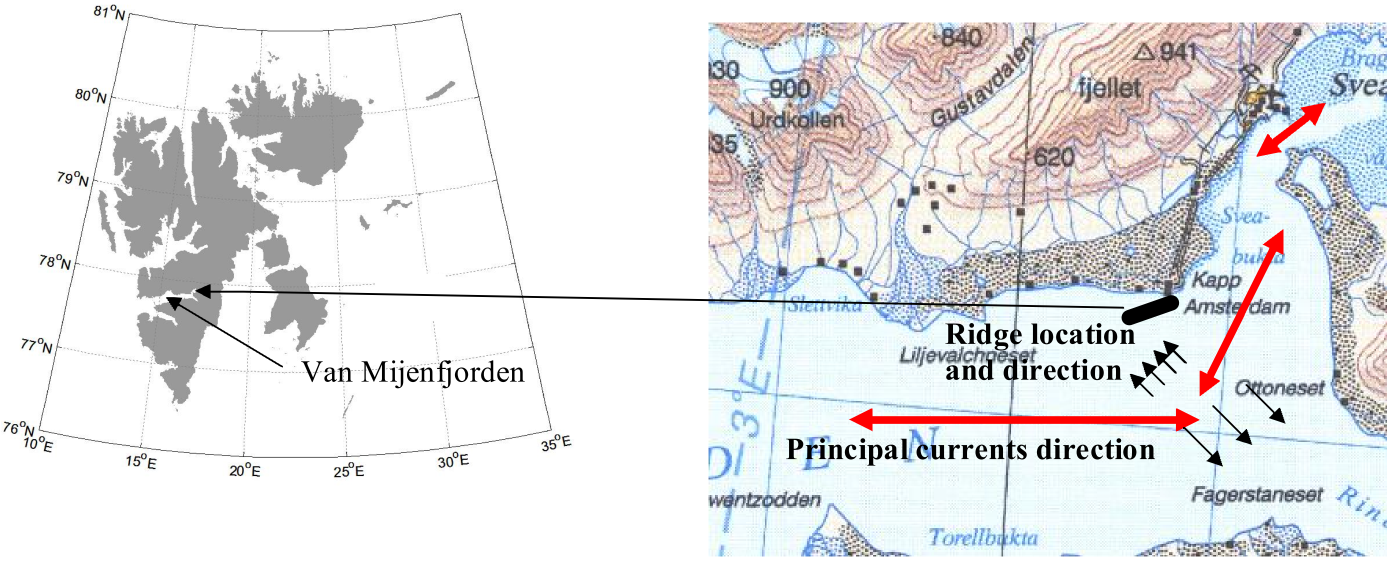

Figure 1: Location of the ridge on Svalbard

Different properties were investigated on site. First, two cross sections were drilled using 2'' augers at each visit along the thermistor strings line to determine the thickness of the ridge and some potential gaps. Any sudden drop of the drill was monitored. The consolidated layer was delimited by the transition from ice to slush or by any gap felt under the water line by drilling and can be related to the temperature measurements, as described by Høyland (2005). More details on the methodology used to study ice ridges are given in Strub-Klein et al (2010).
In most visits cores were taken and temperature, density and salinity (TDS) profiles established. The temperatures were measured every 5cm and density and salinity every 8cm. The relative air and brine volumes were calculated from the equations of Cox and Weeks (1983) for T<-2°C and Leppäranta and Manninen (1988) for T>-2°C. During two visits some cores were taken and uniaxial compression tests performed in field with the compression rig KOMPIS (see Moslet, 2007 for a description of the rig). The nominal strain-rate was 10^{-3} s^{-1}.
Table 1 gives an overview of the activities performed during fieldwork. Drillings and measurements of block thicknesses in the sail were done at every visit while the dates when TDS, uniaxial strength and level ice characterization were done are given in the table. Eight EBA thermistor strings were placed every meter in two lines crossing the ridge (Figure 2). Line 1 was the westernmost line whereas line 2 was the easternmost line. These two lines were standing two meters apart from each other and recorded temperatures from 4 March to 14 May.

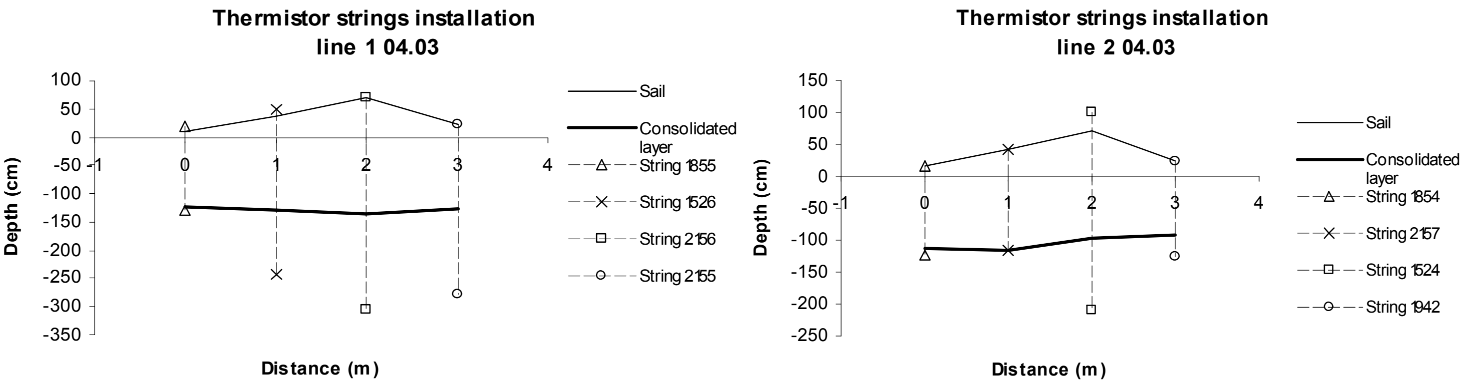

Figure 2. Ridge profiles and positions of the thermistor strings in both lines on 4 March.

Table 1. Field activities

	Morphological profile	TDS profile	Uniaxial tests	Level ice investigations	Thermistor strings
14.02.2009	x			x	
04.03.2009	x	x			installed
19.03.2009	x	x			
01.04.2009	x	x	9 samples	x	
16.04.2009	x	x[a]	12 samples		
14.05.2009	x	x			removed

[a]: no temperature measurements – no micorporosity calculations possible
T: Temperature, D: Density, S: Salinity

ICE GROWTH- STEFAN'S LAW

Stefan's law offers a simple way of estimating level ice thickness and growth. It assumes no snow, no oceanic flux, no solar radiation, a linear vertical temperature profile through the ice cover and (when using *FDD's*) that the ice surface temperature ($T_{i,surface}$) equals that of the air (T_a). The two assumptions about no snow and that $T_{i,surface} = T_a$ are often oversimplifications. An empirical coefficient ω can be introduced to account for this and Stefan's law then can be expressed (Leppäranta, 1993):

$$h_i^2 = h_{i,0}^2 + \omega \frac{2k_i}{\rho_i l_i} FDD \tag{1}$$

where h_i and $h_{i,0}$ are the current and initial level ice thicknesses, ω the correction factor to account for the assumptions given above, l_i is the latent heat of ice, ρ_i is the density of ice, k_i is the thermal conductivity of ice and *FDD* are the freezing degree days. The thermal conductivity of sea ice is different from that of freshwater ice and varies with the state of the ice (mostly the size and shape of the brine channels/pockets). Schwerdtfeger (1963) derived an expression for sea ice where no brine movement is assumed so that the thermal conductivity of sea ice becomes less than that of freshwater ice. The question of brine movement with the sea ice matrix is not a trivial question. McGuiness et al. (1998) did field measurements and suggest that the conductivity increases with increasing brine volume. This means that there are two unknown parameters in Eq.(1): ω and k, but they can be treated as one ($\omega \cdot k$). Høyland (2009) discusses level ice growth in the Van Mjien fjord. For a better comparison with his study, we will further use $k = 2.1$W/°Cm and find the factor ω that makes the model fit the measurements.

Finally the Stefan's law can also be used to predict the growth of the consolidated layer in first-year ice ridges (Leppäranta et al., 1995 and Høyland, 2002) by expressing the latent of the unconsolidated layer:

$$l_{ridge} = l_i \cdot \eta \quad (2)$$

where η is the macro-porosity of the ridge.

RESULTS

Met-Ocean data

Air temperature, air pressure, wind speed and direction are recorded every third hour by the airport of Svea, and figure 3 shows the air temperature (T_a) record of the 3 months period during which the ridge was surveyed. T_a fluctuated a lot and sometimes rapidly. It clearly increased at the end of April. The minimum temperature recorded was -33.1°C on 2 April.

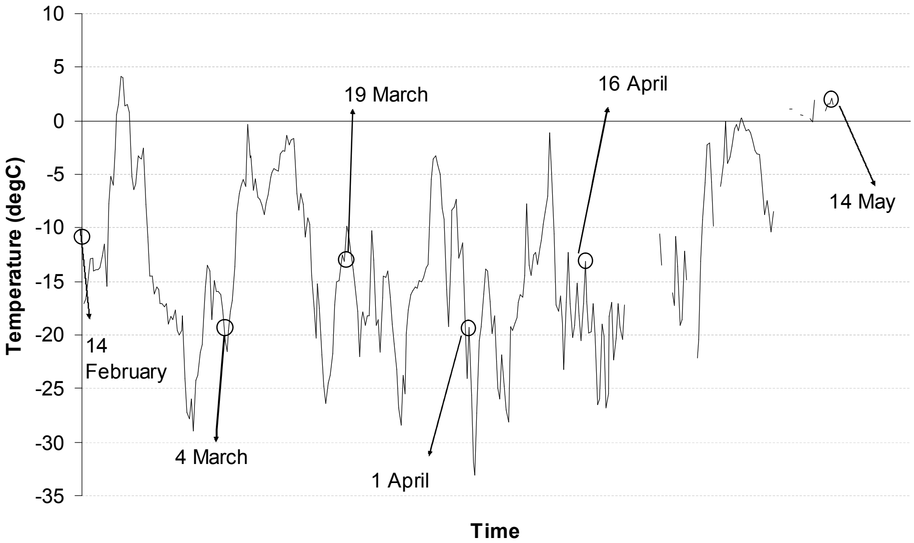

Figure 3. Air temperature evolution in Svea airport, Winter 2009.

The wind always follows a natural corridor formed by the fjord and the valley situated in the continuation of the fjord. It mostly came from the East, but the highest velocity was 16.8 m/s and came from the west.
Snow thickness has been measured close to each thermistor string, the loggers and the battery and at the eastern and western parts of the ridge. It was packed on the sides due to strong wind actions but soft close to the loggers and the battery. It varied between 0 and 35cm.
Water salinity in Van Mijenfjorden was measured inside Svea Bay early March 2009 by UNIS students and showed a variation between 30 and 35 ppt. We will assume a water salinity of 34 ppt which gives a freezing point of the ice at T_f= -1.86°C according to the UNESCO formula given in Lepparänta and Manninen (1988).

Level ice thickness, ridge geometry and block thicknesses

The surrounding level ice grew from 1.0 to 1.25m between 14 February and 14 May. In the Svea Bay, about 5 km further in the Van Mijen fjord, the level ice grew from 0.75 to 0.98m.

When drilling through the ridge it was difficult or impossible to estimate the keel depth. The rubble was so eroded and soft that there was no clear evidence whether it existed at all. Figures 2, 4 and 5 give the sail and consolidated layer thicknesses (h_s and h_c) on 3 occasions. The profiles show that the lines were too short to include the full width of the consolidated layer / ridge. In this way the average h_c may have been somewhat underestimated. At the first visit a few small gaps were felt when drilling. However, on all later visits no voids could be detected anymore. Figure 9 presents the measured h_c, and between 19 March and 1 April little or no ice growth was measured in both lines. This corresponds to an increasing snow accumulation, which changed from 4.5 to 13.5cm (in average) between these dates.

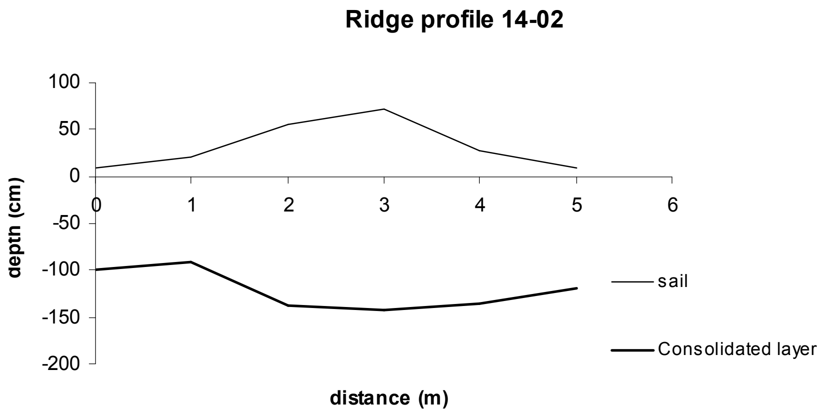

Figure 4. First cross-section on the ridge - 14 February

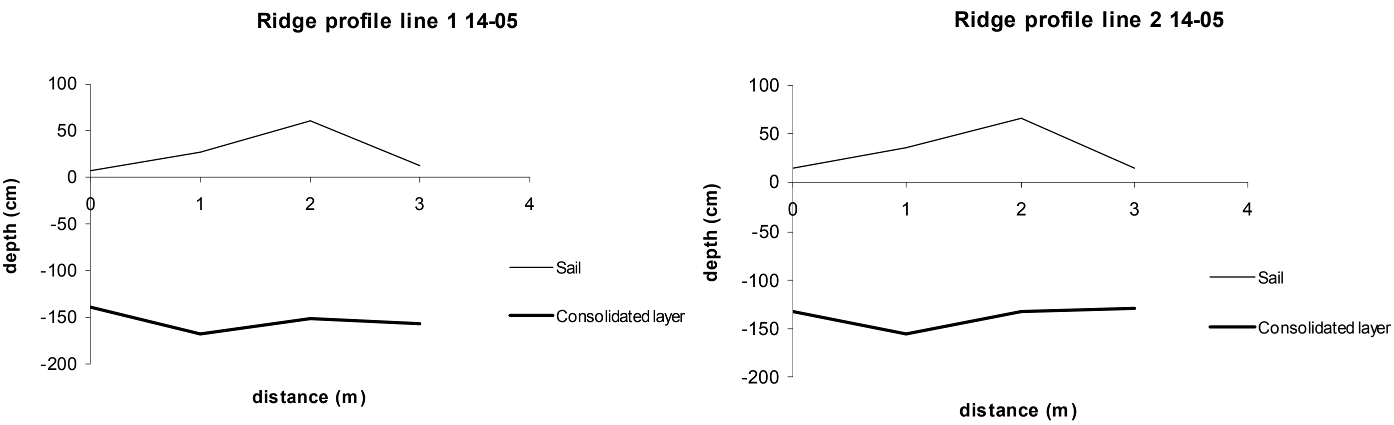

Figure 5. Ridge sail and consolidated layer thicknesses - 14 May.

The block thicknesses (h_b) of 9 pieces in the sail were measured each time the ridge was visited. At the first visit h_b ranged from 17 to 21cm with an average of 20cm. The average block thickness changed little (decreased to 18cm) until 16 April, but then it decreased to 13cm on 14 May. Figure 6 shows some pictures of the ridge. The distance between blocks 1 and 4 was zero at the two first visits, but then increased steadily up to 21cm on 14 May.

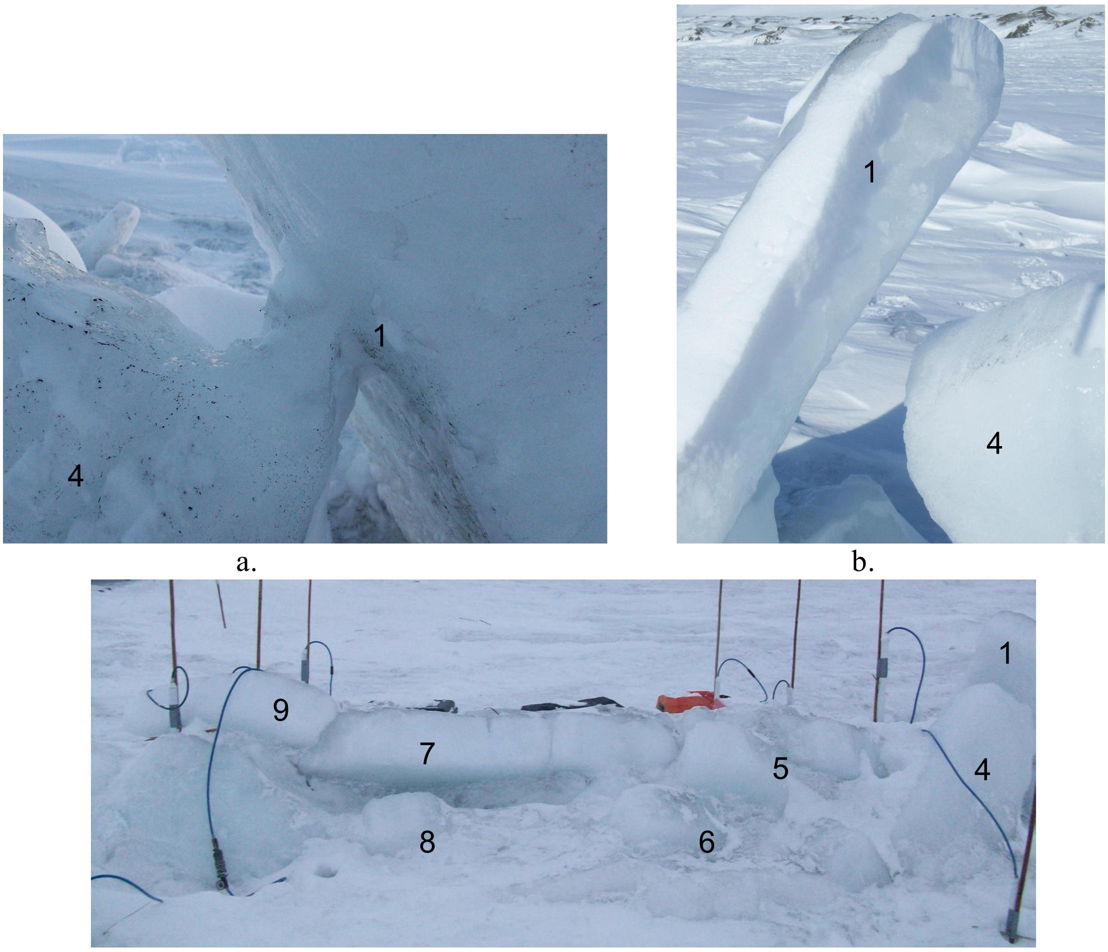

Figure 6. a) Space between blocks 1 and 4 on 4 March b) Space between blocks 1 and 4 on 16 April and c) Ridge on 4 March with numbered blocks.

Physico-mechanical properties

Both vertical profiles of TDS and uniaxial strength of vertical cores were measured as described in Table 1. Figure 8 shows salinity and porosity profiles from 1 April. The level ice salinity was less than that of the consolidated layer salinity and followed a typical c-profile whereas those of the consolidated layer were more random. The average salinity neither grew nor decreased throughout the season. It was typically 4-5psu, varying between 3.5 (16 April) and 5.5psu (14 May). The average micro-porosity of the consolidated layer varied between 9 and 15% from 4 March to 16 April and increased substantially up to 24.6% at the last visit.

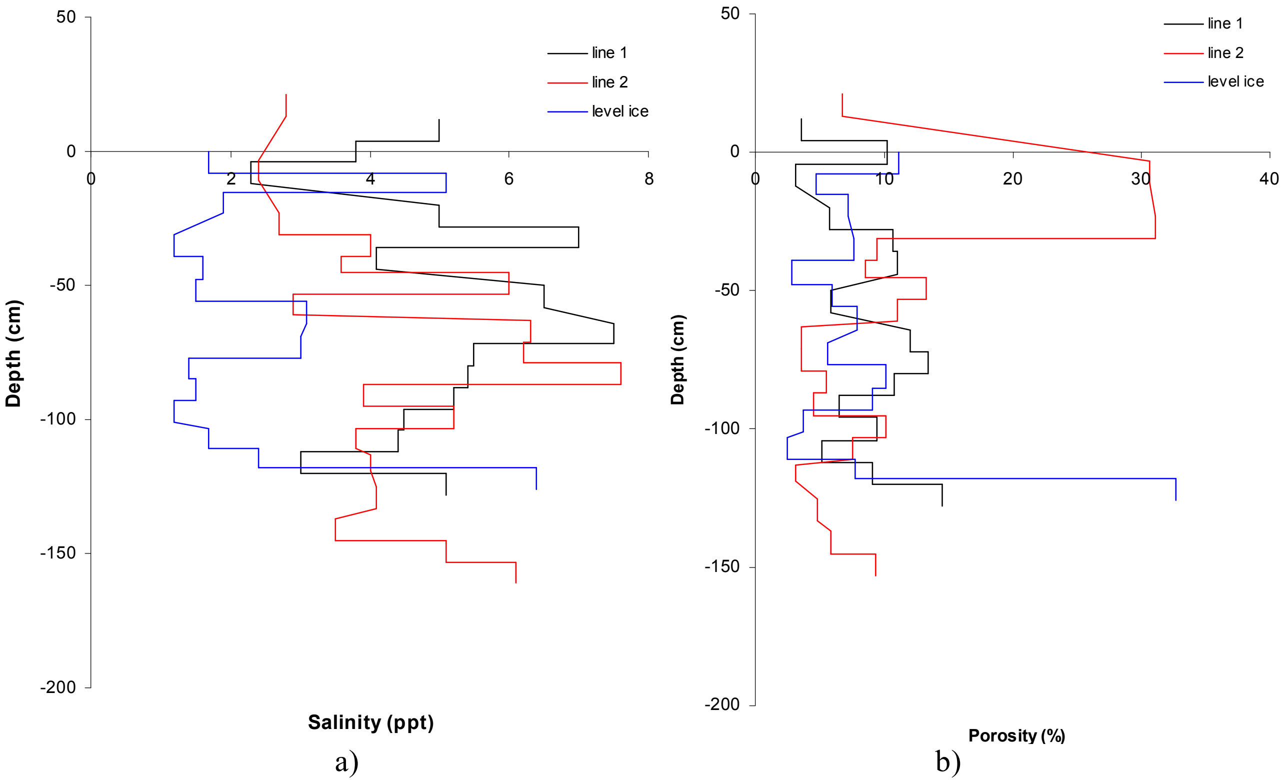

Figure 7. a) Salinity and b) Porosity profiles from April 1.

The uniaxial compression tests were done on two visits, 1 and 16 of April, and respectively 9 and 12 samples were compressed. The average strength / porosity / temperature for the two dates were 3.0 MPa / 11% / -11.3°C and 2.6 MPa / 11% / -10.6°C. All the individual tests are plotted versus porosity in Figure 10.

Ridge temperatures

Figure 8 shows the weekly temperature profile of the thermistor string 1526, placed on line 1 in the ridge. According to the four thermistor strings in line 1, the consolidated layer grew from 1.27 to 1.53m between 4 March and 16 April. Around 1 May, warm water seems to have entered the fjord and could have penetrated up into the tube in which the string was placed (Figure 8). This made it impossible to predict h_c from the strings.

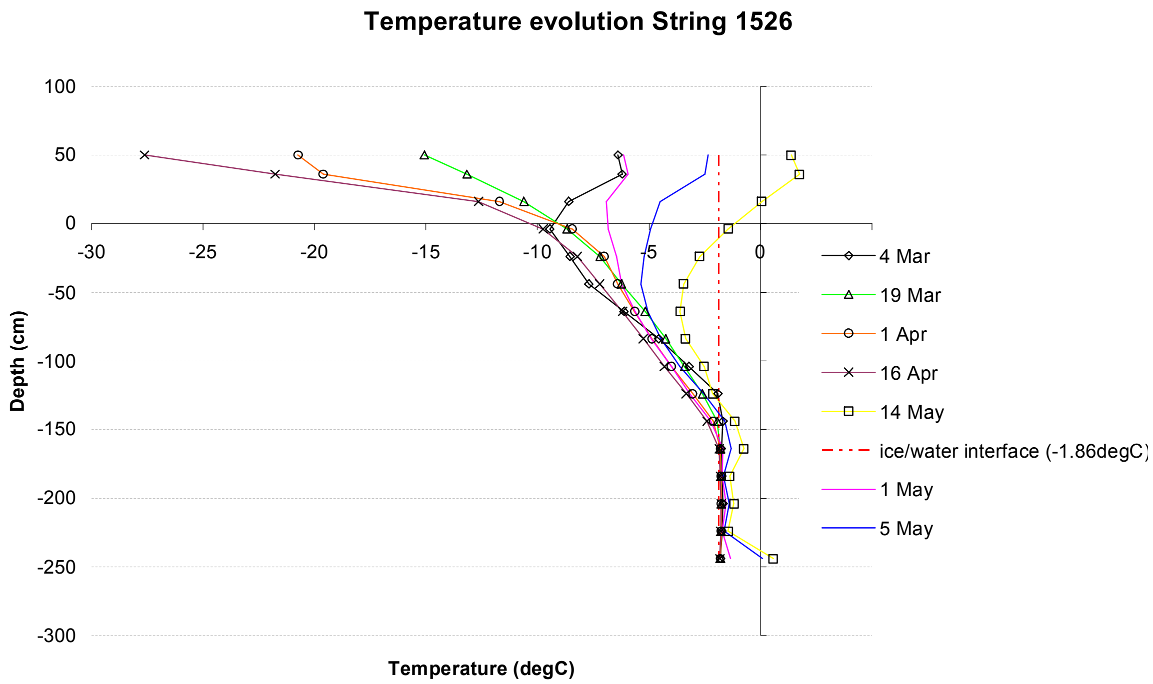

Figure 8. Temperature profiles for hole 2 in line 1 (string 1526)

Similar graphs have been plotted for all the thermistor strings. However, strings 1854 and 2157 appeared to be too short when the ridge grew up and thus its complete growth has not been recorded at these positions.

DISCUSSION

Ice growth and consolidation

We used the thicknesses of the level ice and the average thicknesses of the 4 first holes (0-3 in Figures 2, 4 and 5) in both lines in the ridge and fitted the parameters in Stefan's law. The level ice model (Eq.1) predicted the ridge surrounding level ice (*sli*) growth with ω_{sli} = 0.45 and the level ice growth in Svea bay (*SB*) with ω_{SB} = 0.33. Both are within the range estimated by Høyland (2009) for the years 1998-2006 in which the snow precipitation was modest. He also reports two different levels of level ice thickness and suggests that it is due to an early rafting event. We then combined Eqs.(1) and (2) to study the ridge consolidation and found that a combination of $\eta \cdot \omega = 0.25$ predicts the measurements for both lines. This gives a macro-porosity of 0.55 and 0.4 for respectively ω_{sli} and ω_{SB}. A combination based on the Svea Bay level ice thicknesses (ω_{SB} = 0.33 and η = 0.4) fits very well with earlier ridge consolidation measurements in the Van Mijen fjord reported by Høyland (2002). The ones derived from the surrounding level ice thicknesses may also be reasonable, but predict a relatively high rubble macro-porosity (0.55). The ratio of the consolidated layer thickness to the Svea Bay level ice thickness (*R*) varied between 1.4 and 1.57 for the two lines in the ridge. These values fit well what has been measured earlier in the Van Mijen fjord and other places (Høyland, 2002). When using the surrounding level ice thickness, the calculation of R gives then 1.2, which is somewhat lower. But if we include the date from all the holes in Figure 4, we get R = 1.33. This exercise demonstrates that

the simple version of Stefan's law (Eqs.1 and 2) is useful, but that one cannot expect an accurate prediction of the ice growth.
Figure 9 shows the measured thicknesses of the ridge and the level ice and the corresponding predictions by the Stefan's law.

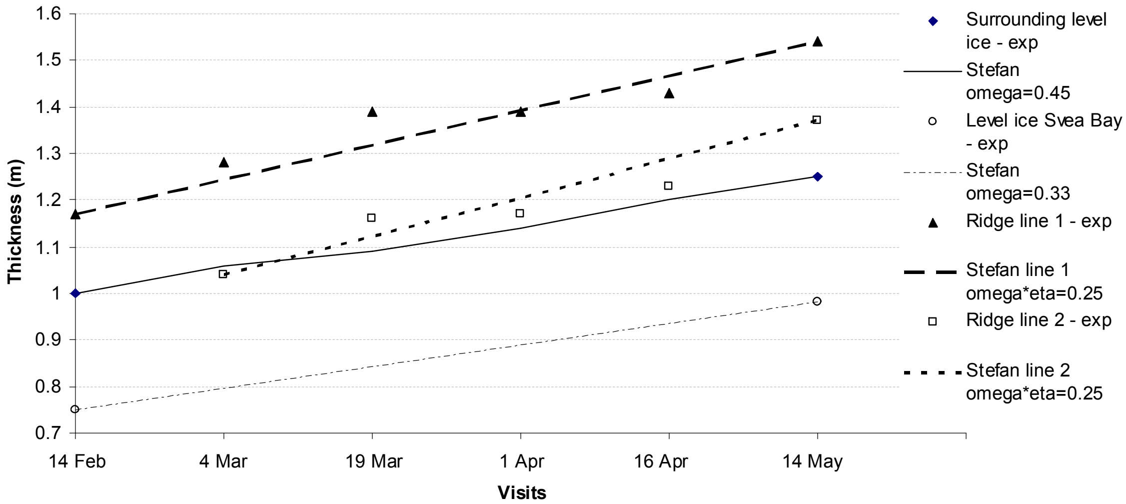

Figure 9. Measurements based on drillings and Stefan's law predictions. The thermal conductivity used in Stefan's law was k=2.1 W/°Cm.

The keel depth can crudely be estimated by empirical keel depth to sail height ratio (h_k / h_s). If we used the average value of Timco and Burden (1997) for first-year ridges (approximately 4.5) and the peak keel depth should have been about 2.2m. Using the average ratio for first-year ridges on Svalbard as reported by Strub-Klein (2011), the peak keel depth should have been around 2.3m.

Physico-mechanical properties

Very little data exists on salinities measured simultaneously in the consolidated layer and the level ice. Høyland (2007) states that the salinity of the consolidated layer was partly higher and partly lower than that of the level ice for first-year ridges in the Barents Sea investigated from 2002 to 2006. The same phenomenon was observed in further surveys of ridges (2007 and 2008) in the Barents Sea (student reports, unpublished data). In the present study, the average salinities in the consolidated layer were higher than those of level ice. Level ice salinities usually decrease through the season and are often 2-3psu in late spring. The mechanisms of desalination in first-year ice are not clear, but the different seasonal developments between level ice and the consolidated layer argue that the water below the level ice (accounting temperature, velocity and salinity) is an important factor.
The increase in micro-porosity in the final visit is basically due to increasing temperatures.

In Figure 10 the empirical formulas for level ice strength suggested by Timco and Frederking (1990) and Moslet (2007) are plotted together with our results. As the formulas gives some kind of upper limit, our ridge strengths lie as expected in between the predicted vertical and horizontal strengths of level ice, but closer to horizontal strength. This is of course due to the ice texture and argues that the consolidated layer has a more granular than columnar structure (see Høyland, 2007 for a deeper discussion and references about this). In addition to the porosity effect, it is clear that cold ice is stronger than warm ice even for the same porosity (see e.g. Cox and Richter-Menge 1988), and our ice had been slightly cooled by the air temperatures before testing and had an average about -10°C when tested. Additional tests made on an artificial ridge in 2008 have been included in the following graph.

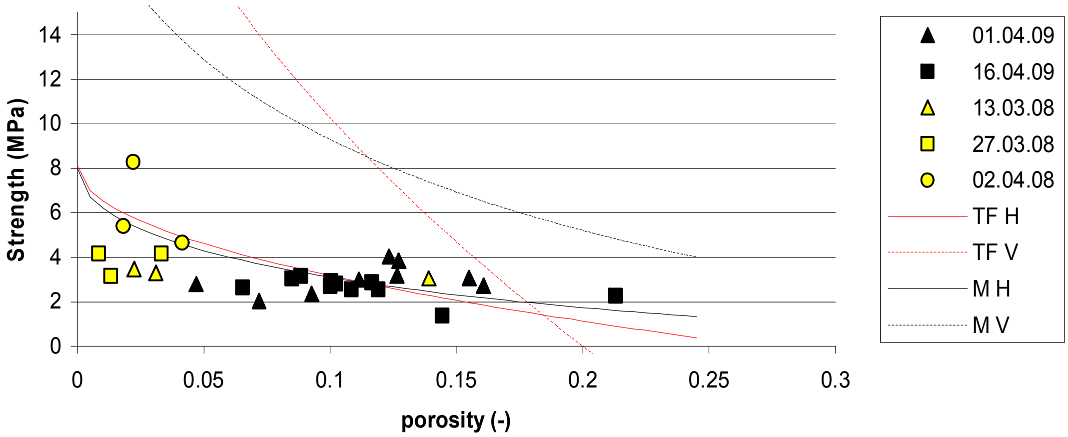

Figure 10. Comparison between the horizontal strengths measured in the field in 2009, unpublished data from 2008 (Strub-Klein 2008) and the empirical formulas for vertically and horizontally loaded samples of columnar ice developed by Timco and Frederking (1990) and Moslet (2007).

Rubble consistency

As explained earlier the rubble was so eroded and soft that it was difficult or impossible to determine the keel bottom. The calculations with the Stefan's law show that the consolidated layer grew more and faster than the level ice and this argues strongly that there was rubble beneath the consolidated layer. Earlier ridge investigations in the Van Mijen fjord (Høyland, 2002) have also reported soft and eroded rubble and in the Camp Morton case, it also became very difficult to determine the keel depth in the second half of the season. This was clearly different from the investigations done in the Northern Bay of Bothnia where the individual blocks could be easily felt throughout the season. There are important differences between these cases, with respect to both the oceanic conditions and the size and shape of the ridges. In the Van Mijen fjord there is a relatively strong tidal current, whereas there is almost no current where the ridge in the Baltic Sea was located. The second difference is that the Baltic ridge was a wide ridge field so that any oceanic flux would take more time to penetrate the ridge. It could also be that the permeability of brackish Baltic ridges is less than in saline ridges. Finally our 2009-ridge was substantially smaller than the ridges described by Høyland (2002) and thus the erosion should be much more efficient. The ratio of the oceanic flux to the conductive flux (the Biot number, see Høyland, 2007 for details) is a linear function of the size, so the effect of the oceanic flux increases with decreasing ridge size.

CONCLUSIONS

A small first-year ridge was investigated in the Van Mijen fjord, Svalbard, from 14 February to 14 May 2009. It was visited 6 times and the thickness of consolidated layer was measured by drilling along two lines across the ridge. Two lines of four thermistor strings were installed and recorded temperatures from 4 March to 14 May.

The average consolidated layer grew from 1.17 to 1.54m in line 1 and from 1.04 to 1.37m in line 2 whereas the surrounding level ice grew from 1.0 to 1.25m. The measured consolidation and ice growth fit reasonably well with the Stefan's law, but show the importance of the spatial variation of the consolidated layer. The block thicknesses in the sail were fairly constant and of 0.2m until May when they decreased due to solar radiation.

TDS profiles were done 5 times and the average salinity in the consolidated layer laid between 3.5 and 5.5psu but remained more or less constant during the season. Level ice salinity usually decreases and this suggests that the effect of the water below the level ice is significant in the desalination process.
The micro-porosity increased during the season, mostly because of increasing temperatures.

Uniaxial horizontal compressive strength was tested in field during 2 visits and the results fit reasonably well with the empirical formulas of Timco and Frederking (1990) and Moslet (2007) for horizontal strength.

The rubble consistency was very soft and eroded, even more than in previous ridge studies in the Van Mijen fjord. We suggest that this is because the ridge was small and therefore the oceanic fluxes became more important. The consistency (and consequently the mechanical properties) of the unconsolidated layer in first-year ice ridges may vary considerably, depending on their size and the oceanic conditions. Small ridges in landfast ice with tidal current should erode faster than other ridges.

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