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Field measurements of Arctic grease ice properties and processes

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Abstract

In situ measurements of grease ice from fjords on Svalbard reveal new basic properties of the surface ice cover. New ice formation often takes place as growing frazil crystals in a surface layer of grease ice. A method for sampling grease ice is described. The grease ice layer is found to be as thick as 70 cm in places, but many of the measurements are around 10 cm. Salinity of the bulk grease ice is around 25 psu, while the drained grease has salinity around 20 psu. The grease ice congeals into a solid ice cover depending on surface cooling. Ice concentration is calculated based on the measured salinity and is around 25% for the grease, and above 60% for the new solid ice. Grease ice, or frazil ice crystals, forms in response to atmospheric and oceanographic forcing, and the salt released by the ice growth influences local hydrography. For the Storfjorden polynya, existing parameterizations for grease ice thickness in relation to wind speed are discussed. The changing wind conditions during the fieldwork partly explain the deviation from an idealized situation, but tidally driven turbulence and the effects of snow drift are suggested as important processes to include in future theoretical descriptions of grease ice processes.

Keywords: Grease ice; Polynya; Frazil ice; Brine water

1. Introduction

New sea ice formation takes place throughout the winter in the Arctic. Most efficient ice production is found in situations where dry cold winds force the sea ice cover offshore, and create a polynya (Morales Maqueda et al., 2004). The first ice that forms in a polynya are loose ice crystals called frazil ice. Depending on the level of turbulence, frazil ice will be mixed down into the upper layer, and form a surface layer of grease ice. Grease ice is thus a mixture of frazil crystals and seawater.

A coastal polynya usually forms in response to offshore winds, and the extent is governed by the balance between the export of ice and the production of ice within it. Polynyas have an important climatic role, both because they warm the atmosphere, and also because they cool and add brine, oxygen and CO_2 to the underlying ocean. The densest brine-enriched shelf water (BSW) (Schauer, 1995) transformed by coastal polynyas along the Arctic continental shelf areas, might reach the deep ocean and hence, maintains the thermohaline circulation. The less dense BSW feeds the cold Arctic halocline by settling between the cold and fresh Arctic surface water and the warm and saline Atlantic layer (Winsor and Björk, 2000). In this way, Arctic coastal polynyas decrease upward mixing of warm Atlantic water, and thus prevent the Arctic sea ice cover from melting. According to Cavalieri and Martin (1994), Arctic coastal polynyas generate about 0.7–1.2 Sv (1 Sv $\equiv 10^6$ m^3/s) of dense water, while

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Winsor and Björk (2000) estimated the flux out from the shelves to be 0.2 Sv.

The term 'grease ice' follows World Meteorological Organization (1970) nomenclature, and is consistent with the Martin and Kauffman (1981) definition as well. Grease ice differs from 'slush', where slush refers to a similar layer of ice crystals created by snow falling into seawater, a river or a lake. The two terms are related, as a layer of snow crystals being blown into a polynya will be the initiation of the grease ice layer, given a minimum level of mixing and cooling of the ocean surface.

Our knowledge about polynyas has increased over the last years. Pease (1987) defined a robust and straightforward analytical model of a wind-driven polynya, and a number of more recent studies are described by Morales Maqueda et al. (2004). Observations of polynyas are usually from remote sensing, moored instruments, or are interpreted from nearby meteorological stations. Drucker et al. (2003) describe processes taking place in the St. Lawrence Island polynya, and calculate ice growth and thickness from moored upward looking sonars and AVHRR surface temperature. Parameterizations of the depth of the frazil ice layer exist (Winsor and Björk, 2000; Martin and Cavalieri, 1989) and are applied in recent polynya modeling studies (Skogseth et al., 2004). Such parameterizations have up to now been based on as few as 5 measurements from the field and a set of laboratory experiments (Martin and Kauffman, 1981).

We here present in situ measurements of newly formed sea ice. The fieldwork was undertaken close to 78°N in the Arctic, in fjords on Svalbard (Fig. 1). We also discuss the processes that lead to the observed grease ice formation. The grease ice sampling and description builds on the experience of Martin and Kauffman (1981) and Smedsrud (2001). Results are compared to available field and laboratory data, as well as existing parameterizations.

2. Methods

Data presented here were collected in March–April 2003 and 2004. In 2003, an artificial lead of 8 m × 10 m was created in the 1.1-m-thick first year ice cover of Van Mijenfjorden. In 2004, measurements were taken from the fast ice along the polynya in Storfjorden (Fig. 1), or from a rubber boat inside the polynya within 200 m from the fast ice edge. The Storfjorden polynya occurs during northeasterly winds (Haarpaintner et al., 2001), and is found to produce 3–20% of the dense BSW in the whole Arctic (Skogseth et al., 2004). A more thorough description of this polynya is found in Skogseth et al. (2004). Fig. 1 also shows sea ice conditions during the fieldwork in 2004, sampling locations and surrounding area.

Frazil and grease ice thickness was measured using a transparent 0.7-m-long cylinder with a stick operating a rubber seal in the lower end. The basic outline is shown in Fig. 2 and we call it a 'frazil sampler'. The frazil sampler has a diameter of 90 mm and a ruler at one side for reading off the frazil/grease layer thickness. The sampler was lowered through the grease ice, and the rubber seal closed when the cylinder was fully submerged. Samples of grease ice, frazil ice and seawater, was then carefully filled into plastic bottles, either sieved through a plastic sieve, or directly as a bulk sample of the grease ice.

Accuracies on the thickness measurements of the grease ice is estimated as ± 1 cm. This is influenced by the frazil crystals whirling around in the cylinder, and that no specific lower boundary exist. There are sometimes more crystals on one side of the cylinder. Also for the first 30 s after the cylinder is lifted out of the water, small crystals keep entering the grease layer from below.

In 2003, samples of the ice from the artificial lead in Van Mijenfjorden could be transported to the cold lab at the University Centre in Svalbard in Longyearbyen for documenting ice crystal structure. Samples were cut into 5-mm-thick sections, placed on a glass plate, and a Leica microtome was used to make a thin section 0.3–1 mm thick. Samples were then photographed between crossed polarized glass to document crystal structure of the grease ice layer.

Sea ice and grease salinities were measured from melted samples stored in 1.0 or 0.5 l plastic bottles for 3–8 days. Before sampling, the bottles were well shaken to prevent any stratification, due to the gradual melting process. Salinity is calculated by the Wissenshaftlich-Technische Werkstätten (WTW GmbH, Weilheim, Germany) conductivity and temperature meter model LF 197-S with a Tetracon measuring 325 cell. Before the measurements were taken, a solution with a known conductivity of 12.39 mS/cm at 23 °C was checked to give a reading of 12.84 mS/cm. Thus the meter itself is accurate to within ± 0.3 psu. Samples of the range in salinity from 2004 (11.9, 17.3, 27.9 and 34.15 psu) were tapped on glass salinity bottles and measured on a Guildline Portasal 8410 salinometer in June at the University in Bergen with an accuracy of better than ± 0.01 psu. The average difference between the Portasal and WTW values was 0.17 psu, and a linear correction based on a least squares fit was performed so that the average difference decreased to 0.02 psu.

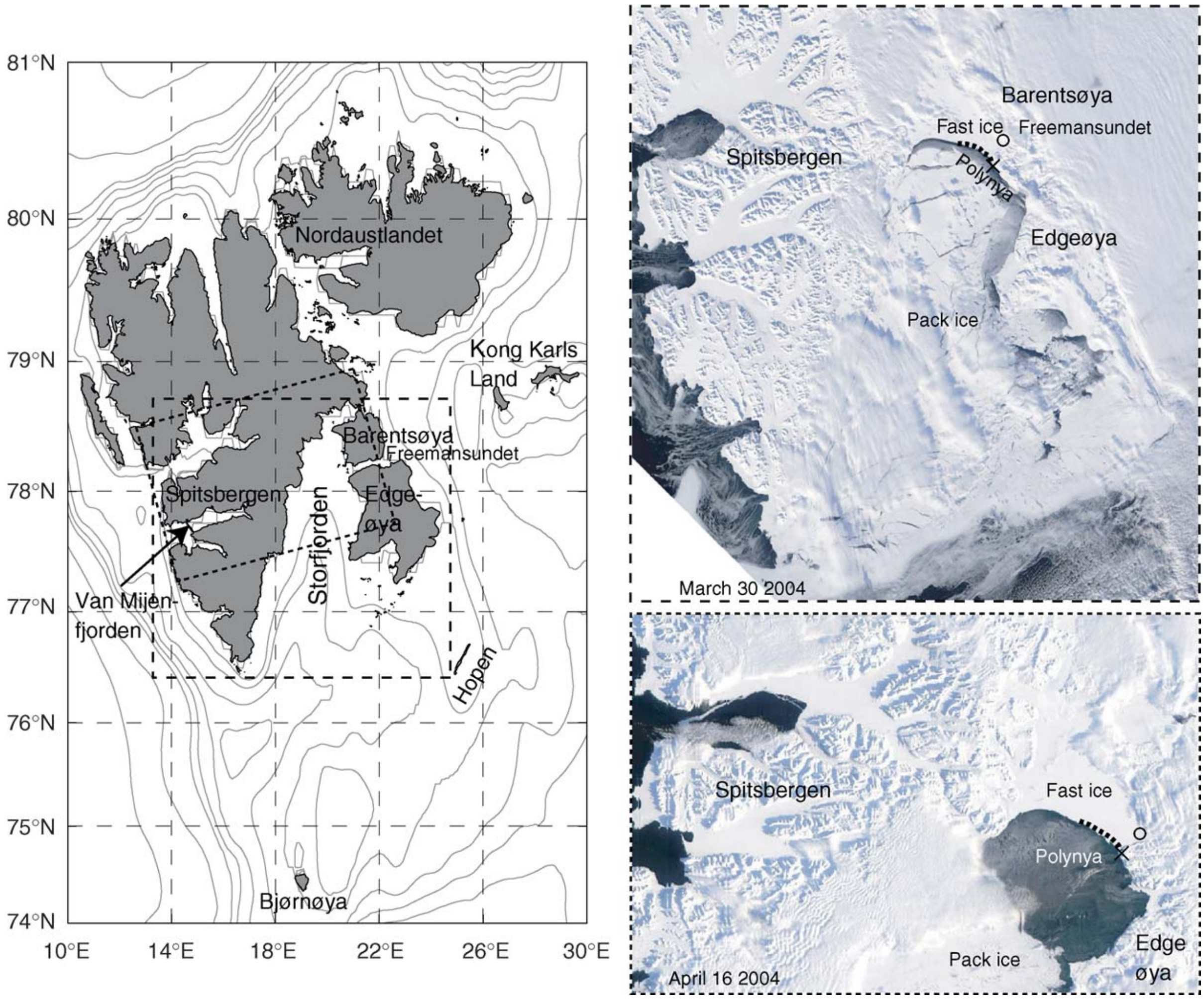

Fig. 1. Svalbard archipelago and sea ice cover on March 30 and April 16, 2004 (Optical Terra/MODIS data, copyright NASA). Frames for images are indicated on the map. Position of the meteorological station at Kapp Lee and the in situ sampling from the rubber boat is marked (×), and the grease ice sampling and CTD stations were carried out along the fast ice edge (- -). The current profiler was located in Freemansundet (○).

Melt volumes of grease and sea ice was measured using standard laboratory glass bottles for 500 ml and 250 ml, as well as a 50 ml cylinder. Melt water volumes accuracies are ± 1 ml and are used to calculate frazil ice concentrations.

Solid sea ice thickness (congealed ice) was measured with a standard tape measure with a hook at the end. Accuracies on the thickness measurements of the solid ice is estimated as ± 0.5 cm. This is influenced by the fact that thin sea ice always has a soft, or mushy, lower boundary, and sometimes loose crystals fall off when the ice is lifted out of the water. The lower boundary is never totally flat either. Samples of thin sea ice were lifted out of the water and put into larger plastic boxes for salinity measurements.

Atmospheric and oceanographic data was also recorded during the fieldwork. In 2003, this is limited to wind and temperature from the local airport in Svea (Norwegian Meteorological Institute (met.no), personal communication, Yngve Øen). In 2004, atmospheric sensors were placed in a mast at Kapp Lee, the northwestern tip of Edge Øya, current measurements were recorded from the nearby Freemansundet, and a hydrographic profile was taken along the fast ice edge (cross, circle and dashed line, respectively in Fig. 1) (Skogseth and Smedsrud, in press). The atmospheric data were converted to standard 10 m values following Smith (1988), using the measured air temperature and humidity data to approximate the stability of the atmospheric boundary layer.

3. Results

We start with a compact description of the observations that drive the ice formation processes. Tradition-

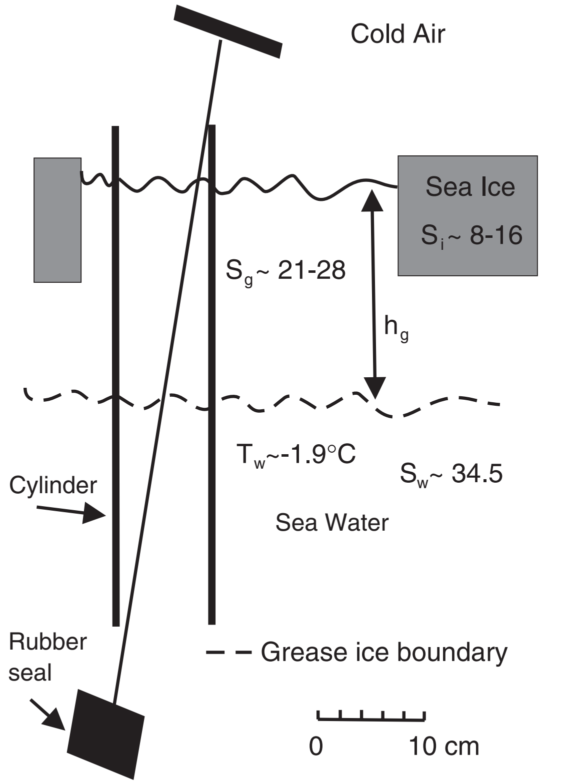

Fig. 2. The frazil sampler used to measure frazil/grease ice thickness and get salinity samples.

ally, this is taken to be wind and air temperature, but as we find that tidal currents are significant as well, this is also included. Ocean surface salinity is also needed for the ice concentration calculations, but the more detailed observations of the hydrography of the Storfjorden polynya in winter will be presented elsewhere.

3.1. Forcing conditions

In 2003, conditions were quiet and stable with −25 °C air temperature and 1.6–2.1 m/s wind speed throughout the 2 days of the artificial lead experiment in Van Mijenfjorden.

In 2004, the fieldwork lasted over 10 days, and we had a wide range of conditions. During the polynya sampling, air temperature varied between −5 and −10 °C and wind speed between 5 and 10 m/s. Just before our arrival on April 16, strong northeasterly winds had opened up a ~30-km-wide polynya in the lee of Edge Øya (Fig. 1). The strong northeasterly winds lasted until early morning April 18. This maintained the polynya for a few days. But after an initial attempt to sample within the polynya using a rubber boat in 10 m/s winds, we realized that we would have to wait for more quiet conditions.

The ice sampling was done during 2–3 days onwards from April 19. The polynya was slowly closing due to advection of ice forced by moderate southerly winds of ~5 m/s, in addition to sea ice growth. During the weak wind conditions, we also noted that the strong tidal currents in nearby Freemansundet would maintain a small polynya just off Kapp Lee where we were working.

Observations of hydrography in Van Mijenfjorden in 2003 are limited to surface salinities in the range 33.20–33.45 psu, giving a freezing temperature of −1.82 °C. In 2004, we did a number of CTD stations (Skogseth and Smedsrud, in press) indicating a water column close to the freezing point, and the stability clearly governed by a salinity increasing gradually with depth. The surface salinity varied between 34.46 and 34.58 psu with the most saline profiles close to Kapp Lee, giving a minimum freezing temperature of −1.89 °C.

The current measurements from Freemansundet show strong tidal currents up to 53 cm/s in magnitude, being controlled by the orientation of the sound. Although we do not have any measurements of ice drift, we observed that the sea ice clearly moved north or south following the tidal flow, with speeds in excess of 10 cm/s.

3.2. Ice thickness

Frazil crystals gathered in the surface to form a layer of grease ice. As individual frazil ice crystals grow, the crystals form a matrix of solids bathed by interstitial fluid called a mushy layer. There is always seawater, or brine, water with higher salinity than the surrounding water, present within the grease ice. The grease ice thickness is here defined as the lower boundary in the frazil sampler within the accuracy of ±1 cm.

The observed range in grease ice thickness, h_g, is 1.5 cm to >70 cm, and Fig. 3 shows the thickness distribution for the available measurements. The peak around 10 cm is present for both the data from the artificial 10 m wide lead in 2003 and the samples along the edge of the polynya in Storfjorden in 2004. But for the artificial lead the thickness range was much more compact at only 8–14 cm. For the 2004 data, the peak at 70 cm is a result of the length of the frazil sampler of 70 cm, so the 5 samples are of an unknown larger thickness.

The almost uniform grease ice layer around 10 cm in the artificial lead solidified with time. After 6 h, the upper 2–3 cm had started to congeal, forming a layer of flexible ice, termed nilas. World Meteorological Organization (1970) refers to this as dark nilas, as it is

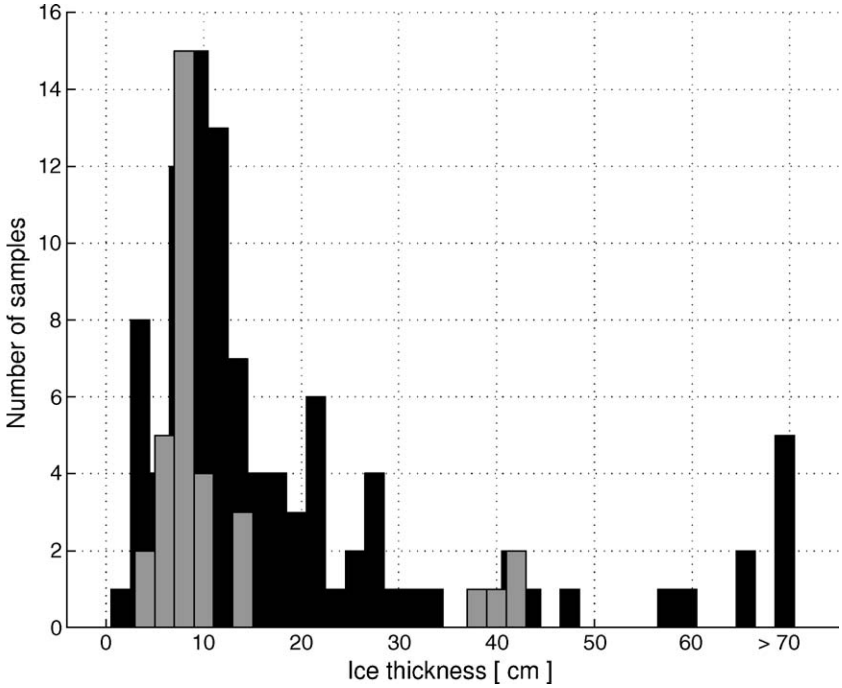

Fig. 3. Thickness of the grease ice layer (black) and solid ice (grey). Data from Van Mijenfjorden in 2003 and Storfjorden in 2004. Accuracies are estimated as ±1 cm for layer thickness.

transparent to the dark color of the ocean below. After 24 h of the experiment, a 9.5-cm-thick solid ice layer had formed. This is still nilas, now classified as light nilas (World Meteorological Organization, 1970), but would enter the grey ice category upon reaching a thickness of 10 cm. This process will also take place in a real polynya, when the waves are dampened by the grease ice layer. But then different types and stages of ice growth are mixed together, and it is difficult to follow a specific grease ice layer.

The solid new ice thickness inside the polynya, h_i, was sampled from the 1-m-thick fast ice edge in Storfjorden. The data form two groups, a group of h_i~40 cm, and one with h_i~9 cm. The thickest ice was sampled in an area that most likely had been ice covered for a longer time, and thus had frozen in with the fast ice, and not been a part of the recent polynya event. The grease ice thickness below this ice was around 30 cm, while the maximum grease ice thickness was found below 8–9 cm of solid ice.

Much of the sampled solid ice cover was 5–10 cm thick. This group of ice looked like new ice formed in the polynya that was transported northwards by the southerly winds and closing the polynya. Thinner ice was observed to be crushed against the fast ice, while the 10 cm ice had internal strength enough to withstand the moderate wind stress.

It is expected that the grease ice thickness, h_g, will increase in the direction along the wind from an open water area. Two such profiles were made in Storfjorden along the fast ice edge, and are shown in Fig. 4. They generally confirm such an increase along the wind. But the profiles also show significant difference to a theoretical "frazil wedge" thought to exist at the downwind edge of a polynya. It is thus not straightforward to define the "frazil collection depth" as used in different theoretical approaches (Morales Maqueda et al., 2004). The grease/frazil ice thickness and relation to wind forcing will be discussed in Section 4. As no value for the "frazil collection depth" stands out in Fig. 4 we suggest using two values from each profile, the first being the maximum grease ice thickness.

For the 16-m-long profile in Fig. 4, the maximum of 16 cm was found at 7 m distance. We also include a mean value of the 5 following measurements of 8.8 cm. In this profile the grease ice vanished at 12 m, and only solid ice was found further downwind. The solid ice thickness was 7 cm at 16 m. We also assume that the entire ice thickness was grease ice originally, and simply solidified during the night before. For the 25-m-long profile of grease ice at the surface, the grease ice layer persisted all the way to a thicker floe found there. The maximum value of 42 cm, and a mean value of 18.8 cm from 15 to 25 m distance

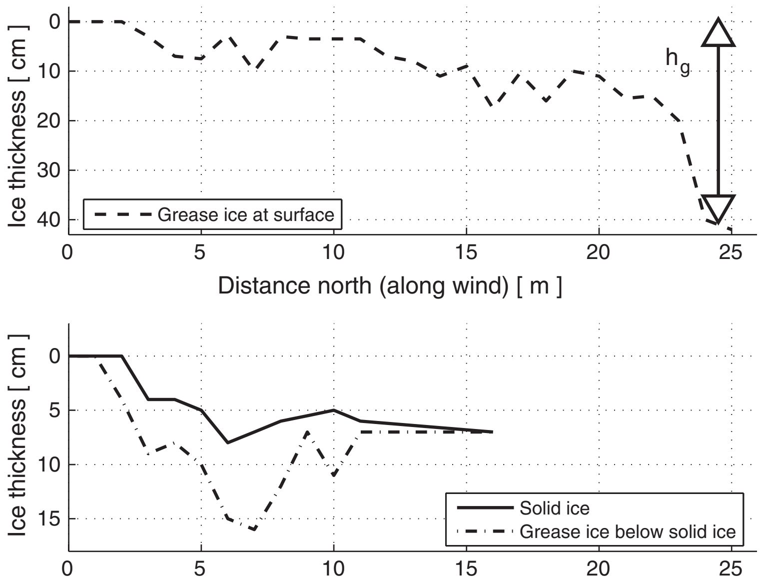

Fig. 4. Ice thickness along the wind direction in the Storfjorden polynya April 2004. Accuracies are estimated as ± 1 cm for slush ice thickness. Grease ice thickness below solid ice is found by subtracting solid ice thickness from the total thickness.

is our two suggested values for the "frazil collection depth" in this profile.

3.3. Ice crystal structure

The frazil ice crystals in the grease ice show small grain-like features when congealed and photographed through crossed-polarized light. Fig. 5 documents a grain size up to 3–4 mm and no particular orientation either in the vertical or horizontal plane. This grease ice formed in the artificial lead experiment in 2003, and looked like a homogeneous layer. The samples were taken when the grease had solidified and reached a thickness of 9.5 cm, classified as light nilas (World Meteorological Organization, 1970). The ice is thus also granular ice, with a gradual transition towards congelation ice toward the bottom.

Several bulk samples of grease ice were taken during the experiment and congealed in boxes. This was an attempt to document systematic change in size of the frazil crystals, presumably an increase with time. But all images have similar grain sizes during the 12-h-long experiment. This might be a result of the freezing of the grease ice in the boxes in the cold air after they were sampled, or just indicate that the frazil crystal size is more or less the same throughout the experiment.

Attempts to film the frazil crystals in the lead directly indicated that the actual size of the loose crystals in the water were larger than the grain sizes in Fig. 5.

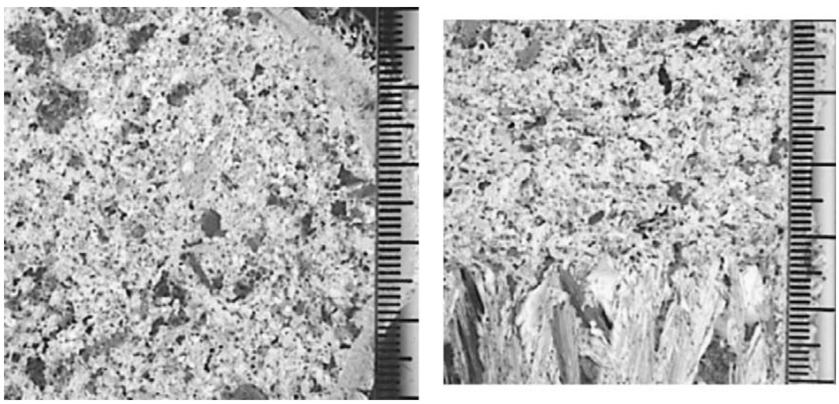

Fig. 5. Crystal structure of the congealed grease ice layer. Left image is horizontal crystal structure, and right image is vertical structure. The transition towards normal congelation ice with more elongated crystals in the vertical shows clearly. Scale in mm.

3.4. Ice salinity

The volume of a grease ice sample, V_g, consists of an unknown volume of frazil ice crystals, V_f, and seawater. Frazil ice is defined by having a salinity of zero, $S_f=0$. But a drained sample of grease ice still contains some ocean salt, meaning that there is seawater that covers the individual frazil crystals with a film that does not drain away. This seawater surrounding the frazil crystals is termed 'brine' here, in analogy with the water in the brine channels of solid sea ice. Thus, the grease ice volume is

$$V_g = V_f + V_b + V_w, \quad (1)$$

where V_b is the volume of the brine film, and V_w is the volume of water that drains away.

Sea ice salinities decrease with age, so that generally, thinner sea ice has higher salinities than thicker ice. This is also the trend for the samples shown in Fig. 6. The grease ice samples (with seawater) has a minimum salinity of $S_g=21.5$ psu, while the samples of drained grease ice has a minimum of 12.7 psu. These values are consistent in that the drained grease ice contains less seawater, and therefore has a lower salinity.

For practical reasons, it is usually more convenient to store the drained grease ice than the full grease ice sample. This means that most of the sampled salinity of the grease layer in Fig. 6 is of the frazil and brine volumes V_f+V_b. The frazil and brine salinity S_{f+b} is in the range 12.7–23.9 psu. The average values for the ocean salinity is $\overline{S_w}=34.5$ psu and for the frazil and brine salinity $\overline{S_{f+b}}=18.9$ psu. Mean grease ice salinity $\overline{S_g}=26.0$ psu, and mean solid ice salinity $\overline{S_i}=12.5$ psu.

The sea ice and grease ice samples were taken within a distance of 200 m from the fast ice edge, and show a large range in salinity. But they also overlap, and the most salty solid ice is saltier than the freshest frazil and brine. This means that there are different types of ice present at the edge of a large polynya, and that the desalinization process is complex. It also seems that the desalinization process is gradual in that the upper part of the range for S_g comes close to the surface water salinity of around 34 psu.

A sample of the seawater that drained away from the sieved grease ice in 2003 had a salinity of 34.6 psu. This is included in Fig. 6 and show an increase by 1.2 psu compared to the salinity of the surface water.

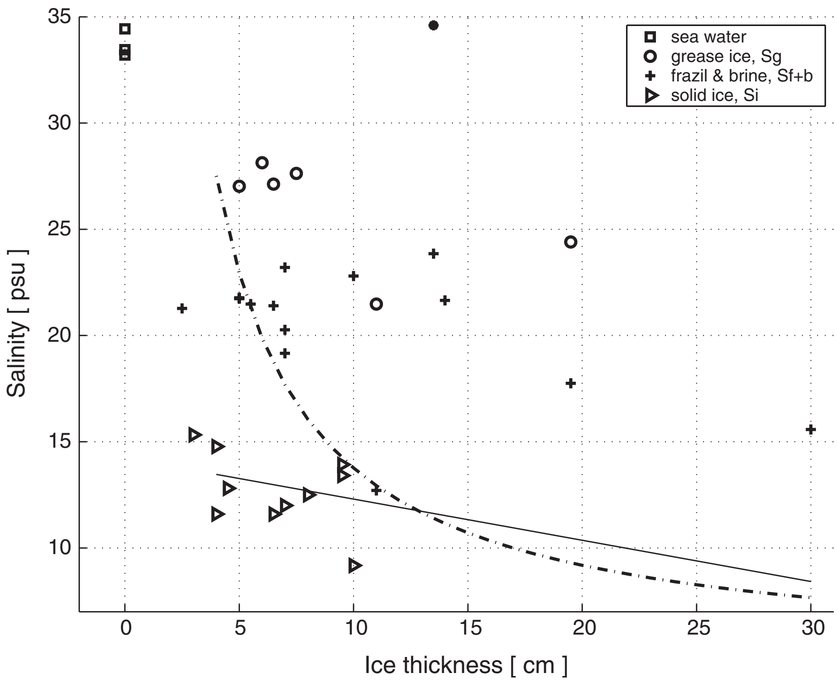

Fig. 6. Salinity of sampled ice plotted towards grease and solid ice thickness. Salinities of seawater are plotted at zero ice thickness. One sample of drained water from a 13.5-cm-thick grease ice sample is also included (•). A single $S_{f+b}=17.45$ at 70 cm thickness is outside the plotted range. Accuracies for sea ice salinities are ± 0.02 psu. A classical linear relationship for ice thickness and salinity following Cox and Weeks (1974) is shown as (—) and an empirical relationship for first year sea ice from Kovacs (1996) as (– · –).

3.5. Ice concentration

From the salinity measurements, an ice concentration may be calculated. It is a matter of definition whether the water fraction should be included in the surface ice layer, and as in Winsor and Björk (2000) the seawater is sometimes deliberately left out, and an 'effective collection depth of pure ice' is used. The seawater leaves the frozen sea ice matrix only gradually as the crystals congeal, and even thick sea ice (>1 m) contains a significant volume of seawater, or brine, in the brine channels.

The ice concentration is simply the volume of frazil ice, or "fresh" ice, divided by the volume of water, salt and ice in which it is sampled. We here adapt the % convention as in Martin and Kauffman (1981), so pure fresh ice with a salinity of zero has an ice concentration, $C_i=100\%$. In this way, we can describe the way seawater, with $C_i=0$, gradually forms a surface layer of grease ice, and compacts through the sequence of forming a layer of loose frazil ice crystals, a thicker slurry of grease ice, then freezing into solid sea ice.

$$C_i = 100\frac{V_f}{V_g}\ [\%], \tag{2}$$

It is not possible to measure V_f directly, so C_i must be calculated based on conservation of volume for water (1) and salt;

$$V_gS_g = V_f(S_f=0) + V_bS_b + V_wS_w. \tag{3}$$

V_b can be eliminated from Eqs. (1) and (3), and the frazil volume is then given by

$$V_f = V_g\left(1-\frac{S_g}{S_b}\right) + V_w\left(\frac{S_w}{S_b}-1\right). \tag{4}$$

This is a general expression, but we have to work out an expression for quantities that are measurable. The V_g in (2) may be calculated from the measured h_g in all cases. This leaves us with the different terms in (4).

The samples of grease ice brought back from the field were stored in plastic bottles, and we will term this sample volume V_s, and the sample salinity S_s. In cases where the full grease ice sample was stored $V_s=V_g=V_f+V_w+V_b$, and $S_s=S_g$. In cases where the grease ice was drained of V_w, $V_s=V_f+V_b$ and $S_s=S_{b+f}$. The sampled salinities were shown as S_g and S_{f+b} in Fig. 6. We replace V_g with V_s and S_g with S_s in (4) in order to proceed with both cases included.

For the drained samples, this means that the last term vanishes in (4) as $V_w=0$ and we get;

$$C_i = 100\frac{V_f}{V_g} = 100\frac{V_s}{V_g}\left(1-\frac{S_s}{S_b}\right). \tag{5}$$

No similar simplification may be done in the cases when the grease ice sample contains frazil ice, seawater, and brine. Because it is not possible to measure S_b we need to make some assumption regarding its value. The problem is caused by the fact that the frazil ice and brine is inseparable. If we assume that $S_b=S_w$ the last term in (4) vanishes regardless of $V_w\neq 0$.

Although this is an assumption, we know that $S_b \geq S_w$ because S_b is growing from S_w. In addition, S_b is bounded by the freezing point relation for seawater (Millero, 1978), as the brine and ice must exist in thermodynamic equilibrium. For grease ice, that still has a water surface towards the cooling air above, it is difficult to imagine a super cooling of more than 1°, so $S_b \leq 45$, as the freezing point of water with a salinity of 45 psu is −2.8 °C. We examine the effect of increasing S_b below, especially for solid ice where ice temperatures might be significantly colder. A salinity of 100 psu corresponds to a freezing point of −6.6 °C. The observed local surface salinity of the ocean is in the range 34.20–34.58 psu, much smaller than the variations in S_b or S_w noted above.

We thus assume $S_b=S_w$ from now on, and finally arrive at an expression for C_i that is useful compared to all our measurements;

$$C_i = 100\frac{V_f}{V_g} = 100\frac{V_s}{V_g}\left(1-\frac{S_s}{S_w}\right). \tag{6}$$

The solid ice C_i is a simple calculation using (6). The solid ice samples are stored in boxes, melted, and the salinity $S_s=S_i$ as plotted in Fig. 6. There is no need to measure the melted solid ice volume as V_s equals the volume of the total sample, here termed V_g.

Our frazil sampler has a diameter of 90 mm. This means that a grease ice layer of 15.7 cm thickness has a volume of 1 l, equal to the largest sample bottles. In cases where the grease ice layer is thinner than 15.7 cm we take a bulk measurement, and $V_s=V_g$. We measure the bulk grease ice salinity $S_s=S_g$, and calculate C_i using (6).

In cases where the grease ice thickness is more than 15.7 cm thick, the water fraction of the grease ice may be drained away. Then $V_s=V_f+V_b$, and we must measure this sample volume as well as $S_s=S_{f+b}$. The surface water salinity S_w is needed in all cases.

Eq. (6) is similar to (14)–(15) in Martin and Kauffman (1981) and to (2) in Smedsrud (2001). The uncertainty of ± 1 ml for the V_s value translates into ± 0.13% for C_i for the typical values h_g = 5 cm and S_s = 20 psu.

Fig. 7 shows the calculated C_i for grease ice in the range 16–32%, with a mean of 25.3%. A mean sea surface salinity from the CTD data of S_w = 34.50 is used (Skogseth and Smedsrud, in press). Several sets of measurements were performed in the same place, within only 2 min of each other. This was done to validate the two methods in draining or not draining the grease ice before pouring the samples into the plastic bottles. Fig. 7 confirms that the values are very similar, and that the two methods both give satisfactory values of C_i.

C_i based on (6) has a nearly linear dependence on S_w. With a 1.0-psu increase for S_w, the mean grease ice C_i increases to 26.4%. If S_b gets as high as 5.0 psu above S_w, the mean grease ice C_i increases to 30.2%. Supercooling of the grease ice layer has so far not been detected in the field, and laboratory experiments indicate levels of 0.05 °C (Smedsrud, 1998), indicating that $S_b \sim S_w + 0.5$.

During laboratory experiments indoors (Eicken et al., 1998), a centrifuge was used to extract as much of the brine as possible from frazil ice grown in the 1-m-deep tank (Smedsrud, 2001). When comparing these values to the two methods described above, absolute deviations were below 1% (Hajo Eicken, 2004, Personal correspondence). This indicates that for a layer of grease ice, brine salinities remain fairly low, while brine salinities in solid ice are known to increase significantly above the seawater.

Solid ice concentrations are approaching 75% in Fig. 7. This is also calculated using $S_w = S_b$ = 34.5 psu. This indicates that there is still 25% seawater in a ‘solid ice’ sample at the freezing point with this salinity. Colder sea ice temperatures will result in smaller volumes of brine with higher salinities. An ice temperature of − 6.6 °C compares with brine salinities close to 100 psu given in the numerical experiments of Oertling and Watts (2004). If S_b approaches 100 psu our solid ice C_i ends up in the 85–91% range.

An unknown portion of air will also be present in a solid sea ice sample. This air volume is likely to increase when a solid ice sample is lifted out of the water, and it has been ignored in our considerations here. Air volume will have a profound effect on the sea ice density as well. In any case does our calculated solid ice C_i (Fig. 7) show an increase with thickness. This seems natural as one would expect the solid ice to compact with age, reflecting the salinities that decrease with thickness.

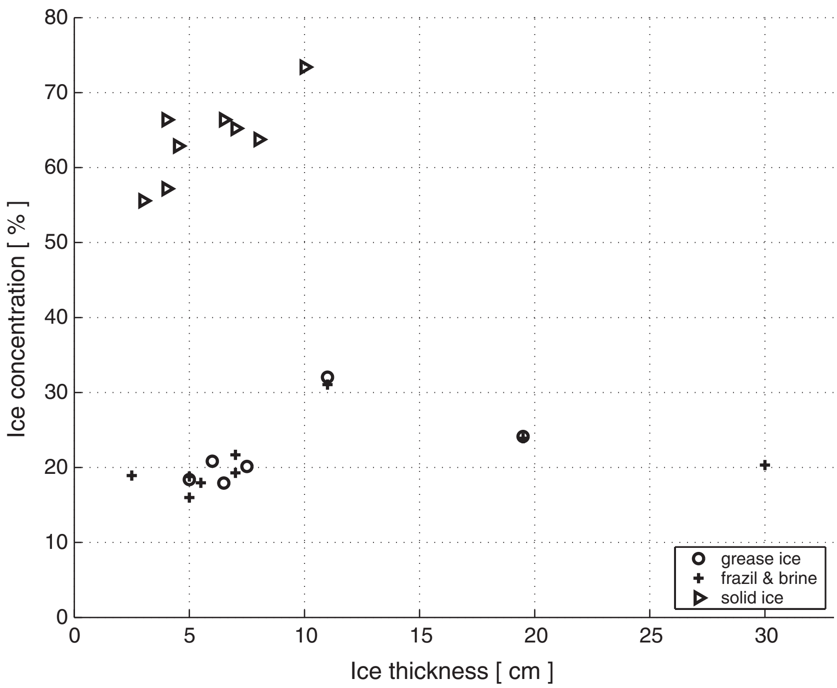

Fig. 7. Ice concentration of new ice formed in the Storfjorden polynya April 2004. Grease ice was sampled in two different ways (○ and +) and solid ice concentrations (triangles) might be significantly higher as described in the text.

4. Discussion

The presented data set is fairly small, but represent the first set of measurements of frazil and grease ice thickness and salinity from a natural polynya.

The only previously available in situ observations from a polynya (Martin and Kauffman, 1981) describe grease ice thickness along a 10-m stretch being 70, 100 and >100 cm in relation to a wind episode of 15 m/s. At another location and time, a 50-m-long lead had a wind of 10 m/s and air temperature of −16 °C producing a 8-cm layer of grease ice. The incoming waves were damped at this site, and inwards of this a region had $h_g \sim 5$ cm. The wind forcing was stronger than in our cases, but our grease ice thickness (Fig. 4) seems to be comparable.

Martin and Kauffman (1981) measured grease ice salinity from a set of laboratory experiments. They arrived at a mean salinity of the 'melted crystal sample' of 11.8 psu. This salinity compares to the S_{f+b} values presented here that are usually about twice as large. The cause of this large difference is unclear. Possible candidates are: (1) The laboratory experiment used 35.5‰ NaCl solution, and not real ocean salt, having a freezing point of −2.15 °C. (2) The processes in the laboratory driving the freezing, the heat flux, radiation and lack of snow drift are significantly different from the field processes. (3) The processes in the water are significantly different from the field: the wave engine could induce more or less turbulence than the waves and tides during the fieldwork. Until this difference can be explained, we regard our field values as being the more representative of the natural processes. Note the minimum S_{f+b} close to 12.5 psu in Fig. 6, approaching the level in Martin and Kauffman (1981), so processes in the field may also produce salinities as low as ~12 psu. A stronger wind, or larger waves, could lead to lower salinities of the drained grease, S_{f+b}, in the field as well.

The solid ice salinities may be compared to previous field and laboratory measurements. A recent numerical study confirms that initial sea ice salinities may be in the 15–20 psu range for new sea ice of 4 cm thickness (Oertling and Watts, 2004). This is significantly higher than the linear relationship presented by Cox and Weeks (1974), but lower than the empirical estimates given by Kovacs (1996) based on available solid first year sea ice samples. The Kovacs (1996) estimate increase to above 20 psu for ice below 6 cm in thickness as shown in Fig. 6. This relationship is likely to be rather approximate at these thin ice thicknesses as there is only available 4 data points below 10 cm (Kovacs, 1996). The grease ice salinities presented here are well above the earlier solid ice salinity estimates for grease thicker than 5 cm.

Oertling and Watts (2004) did not find any delay in the onset of brine drainage from their model runs, and this is consistent with the data presented in Fig. 6. Recent in situ non-destructive laboratory and field measurements of growing sea ice salinity (Notz et al., in press) also confirm that sea ice salinities above 15 psu are to be expected in solid ice. A continuous increase in ice salinity towards the ocean salinity as the lower ice boundary is approached is to be expected.

Winsor and Björk (2000) base their salt flux calculations for the Arctic Ocean on the Martin and Kauffman (1981) values, and state that the "frazil ice salinity" $S_i = 0.31 S_w$. With the terminology adapted here their S_i equals our S_{f+b}, and using $S_w = 34.5$ psu, S_{f+b} should be around 10.7 psu. This is clearly less than half of most of the salinity data presented in Fig. 6. In that respect, the new values presented here would change such an Arctic polynya salt flux estimate considerably. The similar mean relationship for the Svalbard data is $\overline{S_{f+b}} = 0.55\overline{S_w}$, based on $\overline{S_w} = 34.5$ psu and $\overline{S_{f+b}} = 18.91$ psu. The salt released from the forming ice is nevertheless important for the local hydrography, and integrated over a time period and region the total flux of salt to the ocean will be the same when the surface ice cover congeals into a solid state. But the salt release from the grease ice layer is probably more gradual than previously expected.

In addition to the average salinity of the grease ice, the ice concentration is needed to calculate released amounts of salt to the underlying ocean inside a polynya. Martin and Kauffman (1981) also calculated ice concentrations in their laboratory experiments, but they included the brine volume in the ice volume. Correcting for the 30% brine content their range in ice concentration is 14–29%, being very similar to the values from Svalbard. Winsor and Björk (2000) also states that "the pure ice fraction in grease ice" is ~30%, but they also include the brine in this ice concentration. When C_i is so similar, this indicates that some of the major processes in the laboratory and the field, like heat flux and turbulence in the water, are similar.

Winsor and Björk (2000) suggest a simple parameterization for the relationship between wind forcing and the thickness of the surface ice layer that the Svalbard data may be tested towards;

$$h_i = \frac{1}{15}(1 + 0.1U_a) \Rightarrow h_g = 0.22(1 + 0.1U_a). \quad (7)$$

Here h_i is the "effective collection depth of pure ice", and U_a is the wind speed 10 m above the surface. We find the "pure ice" terminology confusing and suggest that the measured depth of the grease ice layer, h_g, is the most intuitive value. The constant factor 0.22 appears as Winsor and Björk (2000) assume $h_i = 0.33h_g$, but as shown above, none of these values are close to constant in the field data.

The choice of h_g is consistent with the approach in Bauer and Martin (1983) and Alam and Curry (1998), and the different parameterizations of the grease ice layer are plotted in Fig. 8. Remotely sensed ice thickness, as derived from the ice surface temperature in Drucker et al. (2003) are also included in Fig. 8.

The h_g values from the 10 m lead in 2003 were taken during a period with 1.6–2.1 m/s mean wind speed. From sampling the grease ice, and as documented by the crystal structure in Fig. 5, this is clearly a layer of grease ice forming, and not normal congelation ice. It did take about 4 h into the experiment before the upper cm on the grease started to congeal, and at this stage there was still about 10 cm of grease below. After 24 h of ice growth in the experiment, the ice thickness was still 10 cm. But at this stage the lower layer started to look like congealed ice as shown in Fig. 5.

The 2003 data document that there is, in practice, no lower bounds in wind speed for frazil ice production as suggested by Alam and Curry (1998). Based on the laboratory experiments of Bauer and Martin (1983) this lower bound was set to 4.35 m/s, being the point where the different fetches in Fig. 8 cross-over into positive h_g. At least under the cold conditions of -25 °C a grease ice layer formed with winds speed as low as 1.6 m/s.

Our observations from 2004 in Fig. 8 are the maximum and mean values from the two profiles presented in Fig. 4, and h_g as sampled along the fast ice edge as indicated in Fig. 1. Wind speeds are measured at the 5 m mast locally in Storfjorden, and 10 m winds were calculated following Smith (1988). This resulted in multiplying the 5 m wind speed by a factor of 1.03–1.05, based on the observed temperature and humidity.

A recent field and model study of the heat budget of Arctic leads show that during the first 12 h the sensible heat flux influenced by the lead was 80 W/m^2 larger than the background values (Pinto et al., 2003). The thin ice cover of the lead influenced the atmospheric boundary layer more than 2 days after it refreeze, and the heat flux changed more than 60 W/m^2 once the frazil ice layer in the model congealed. During the refreezing of the lead, wind speed was 6–7 m/s and air temperature -20 °C. Unfortunately, the field study did not include any detailed frazil ice observations. The only measurement showed a congealed layer of 1 cm when the model predicted a 2 cm grease ice layer. This is somehow surprising compared to the 10 cm layer of

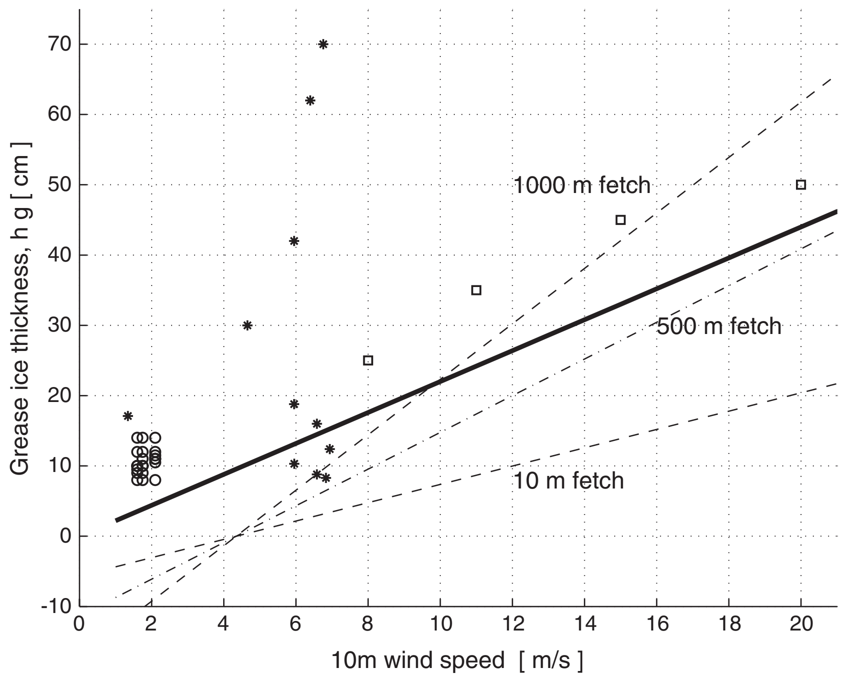

Fig. 8. Thickness of the grease ice layer as a function of wind speed. Solid thick line after Winsor and Björk (2000) as a function of wind speed, and dashed lines after Alam and Curry (1998) including a fetch length dependency. Data from Drucker et al. (2003) are plotted as squares. Our observations from 2003 are plotted around 2 m/s winds (○), and data from 2004 are plotted as (*).

grease that formed during much lower wind speed in Van Mijenfjorden in 2003.

Our measurements clearly indicate that the grease ice processes in an Arctic polynya are complex. The wind-based parameterizations used until now describe a steady state solution, but the changing wind speed and directions during our fieldwork created thicker layers of grease ice that do not compare directly with the local wind. Although we do not suggest any new ways to parameterize the processes taking place in the field here, we would like to emphasize that the turbulence in the surface layer may also be created by tides as well as wind, and this should be included in some way in future studies.

Also snowdrift could make a difference in the way that frazil could form more easily with more available ice/snow crystals. Jaedicke (2002) documented snowdrift in one valley on Svalbard, and although the snowdrift into the ocean was quite low in this valley it might be more efficient in other areas. Snow drift is a factor that seems to have been overlooked in the literature on sea ice formation up to now. We would suggest that this is an important contributor to the first frazil formation in a wind-driven coastal polynya.

Theoretical studies of polynyas often refer to "the polynya edge", where grease and frazil solidifies to normal sea ice (Biggs and Willmott, 2004). The results presented here illustrates that such a polynya edge may not always be easily detected in the field. In the Storfjorden polynya solid sea ice and grease exist interspersed with each other, and for the polynya closing event, much of the grease ice is found below solid ice. In one such case 30 cm of grease was rafted below the solid ice, and the impression of a large variety in grease and solid ice thickness was qualitatively supported by observations from helicopters when flying over the polynya.

5. Conclusion

Thickness and salinity measurements of grease ice forming under natural conditions in fjords on Svalbard are presented. As only a few scattered measurements of grease ice from the field have been available up to now, this data set marks a start in the verification of grease ice processes occurring in Arctic leads and polynyas.

The sampling technique using a transparent cylinder is described, and results show that grease ice properties vary considerably more than has been anticipated up to now. The two main parameters describing the grease ice layer is the thickness and concentration of pure fresh ice that may be calculated from the salinity of the grease ice sample. The grease ice thickness distribution has a peak around 10 cm, values as low as 2 cm, and a maximum at over 70 cm. The concentration of fresh ice within the grease ice layer is in the range 16–32%, with a mean close to 25%.

The grease ice sample may either be a bulk or a drained sample. The bulk sample incorporates the ocean water, the fresh frazil ice as well as the brine coating the frazil crystals, and has a mean salinity of 26 psu. The drained sample has no ocean water, except for the brine coating, and therefore a lower mean salinity of 18.9 psu. The salinity of the drained grease ice commonly used up to now has been 31% of the surface salinity based on laboratory experiments of Martin and Kauffman (1981). The data presented here suggest that the grease ice retains as much as 55% of the surface salinity when it forms. Later in the freezing process when the grease solidifies, salinities decrease to the 10–15 psu range, closer to the previous estimates. The salt will thus drain out at a later stage, and this process determines where the large salt fluxes to the underlying ocean will be found.

Available parameterizations of the grease ice thickness as a function of wind speed and fetch do not reflect the measurements particularly well. This is likely a consequence of shifting wind conditions during the fieldwork, but other factors that also seem to be important are snow drift and tidally induced ocean mixing.

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