ICE TANK INVESTIGATIONS OF THE MICROSTRUCTURE OF ARTIFICIAL SEA ICE GROWN UNDER DIFFERENT BOUNDARY CONDITIONS DURING INTERICE II

Christian Haas[1]

ABSTRACT

A short overview about the EU-LSF INTERICE II project conducted in the Arctic Environmental Test Basin of the Hamburg Ship Model Basin (HSVA) in Hamburg, Germany, is given. The project team investigated physical, bio-geochemical, and sedimentological aspects of sea ice growth processes. Some features from the microstructure studies are presented. These include crystal and pore space data from a freeze-melt-refreeze cycle and from ice grown at different under-ice currents, and temperature measurements at the progressing ice water interface. The feasibility of large ice tank studies is discussed.

1. INTRODUCTION

Knowledge of sea ice is important due to its role in shaping the global climate and as an obstacle for human activities in ice covered waters. Its importance for climate processes results from a number of interactions between the atmosphere, the ice, and the ocean, which take place on many different scales. Small-scale properties of sea ice, for example the pore space structure, determine factors like salt fluxes, biological colonisation, as well as mechanical, optical and microwave properties.

The EU funded Large Scale Facility project INTERICE provided the opportunity to investigate small scale properties and processes of artificial sea ice grown under different boundary conditions in a large indoor ice tank. Two experimental phases were carried out in the Arctic Environmental Test Basin (AETB) of the Hamburg Ship Model Basin (HSVA) located in Hamburg, Germany. A three month program (INTERICE I) was performed in the winter of 1996/97 (Eicken et al., 1998), while the second, six week long set of experiments (INTERICE II) was conducted at the end of 1998, largely continuing and complementing the experiments from INTERICE I.

In this report, we give a very short overview about the INTERICE II experiments, and present some preliminary results from the microstructure studies which focused on the dependence of the pore space structure on different under-ice current speeds during ice growth.

Apart from microstructural investigations, the scope of the INTERICE team from Belgium, Finland, Germany, Norway, the UK and the USA encompassed physical, biological, bio-geochemical and sedimentological aspects of sea ice growth. The experiments contribute to fundamental research fields, for example the physical properties of sea ice, its importance for climate processes and primary productivity, as well as questions regarding sea ice as a transport agent for oil, sediments and contaminants.

---

[1] Alfred Wegener Institute, Columbusstrasse, D-27568 Bremerhaven, Germany (email: chaas@awi-bremerhaven.de)

1.1 WHY USING AN ICE TANK?

Experiments conducted in a tank environment have several advantages compared to field investigations: Because most sea-ice measurements are performed by destructive sampling techniques, a large ice area with homogeneous properties is advantageous for conducting time-series studies. This is achievable in an indoor tank, whilst natural sea ice is known to be highly variable even on the meter scale (e.g. Eicken et al., 1991). Usually, the history of a particular ice floe selected for sampling is not known. In an ice tank, air and water temperatures are easily monitored, and the temperature forcing can be controlled. Therefore, also repeated experiments are possible. For biogeochemical investigations, an ice tank provides a unique opportunity to study background chemical processes without the presence of biological activity. Therefore, it is possible to distinguish between the primary processes due to ice formation and superimposed secondary processes, e.g. algal activity. On the other hand, the development of ice communities can be continuously monitored in life experiments. Finally, the logistics necessary for tank studies are much easier than those of field expeditions. However, as tank experiments are performed without applying any scaling of the ice properties, the short time available to perform the experiments can cause problems: Temperature gradients and associated growth rates are much higher than for thicker, naturally forming sea ice, and the small achievable ice thicknesses render the comparisons with processes in older natural sea ice more complex, as will be discussed below.

2. MEASUREMENTS AND FIRST RESULTS

The Arctic Environmental Test Basin (AETB) is a 1 m deep, 30 × 6 m^2 indoor tank where ice formation can be forced by air temperatures down to -25°C. The tank was subdivided into a Quiet and a Current Zone (Fig. 1). In the latter, laterally homogeneous currents up to 0.3 m s^{-1} were generated by means of three impellers located on the opposite side of the stream channel. The basin was filled with NaCl water to an initial salinity of 35 ‰. Additionally, in the Quiet Zone, 1 m^3 PE-foil compartments filled with 27 to 34 ‰ Instant Ocean artificial sea water were installed for biogeochemical and oil-in-ice studies (Fig. 1). During experiments on frazil ice, water turbulence was generated in an open lead by currents, wind and waves.

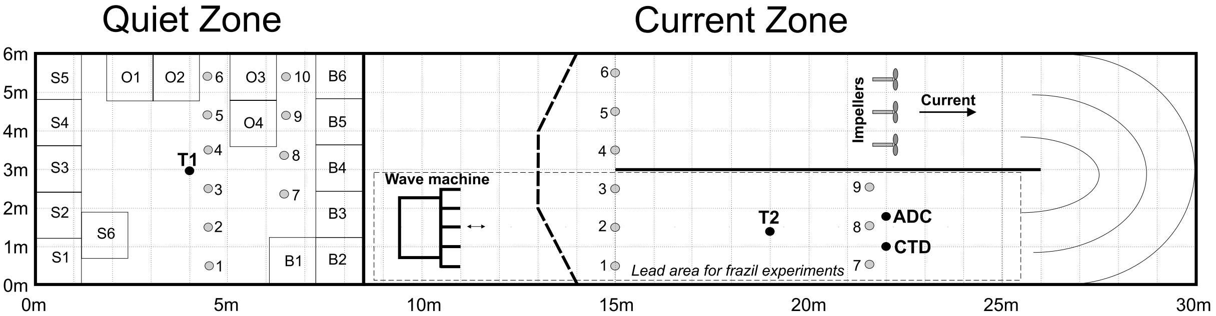

Figure 1: Map of the ice tank showing the Quiet and Current Zones, the compartments for the biochemical (B), sedimentological (S) and oil (O) studies, and the open lead area for the later frazil experiments. The latter was located in the sampling area for earlier ice sheet experiments with under-ice currents. Also the locations of two thermistor strings (T), the CTD and the Acoustic Doppler Current Meter (ADC) as well as the thickness profiles (dots) are shown.

Continuous measurements of the air and water temperature, salinity, and current were made in the Current Zone throughout the experimental phases (Fig. 1). Vertical ice temperature profiles were measured by means of two thermistor strings frozen into the ice. A daily sampling program consisted of ice thickness profiling across the tank (Fig. 1), and measurements of the bulk salinities of ice cores drilled in the Quiet and the Current Zones. Figure 2 shows the different air temperatures during the four main experiments during INTERICE II. During Experiment 1, the ice was subjected to a freeze-melt-refreeze cycle. During Experiment 4, frazil and pancake ice formation were studied.

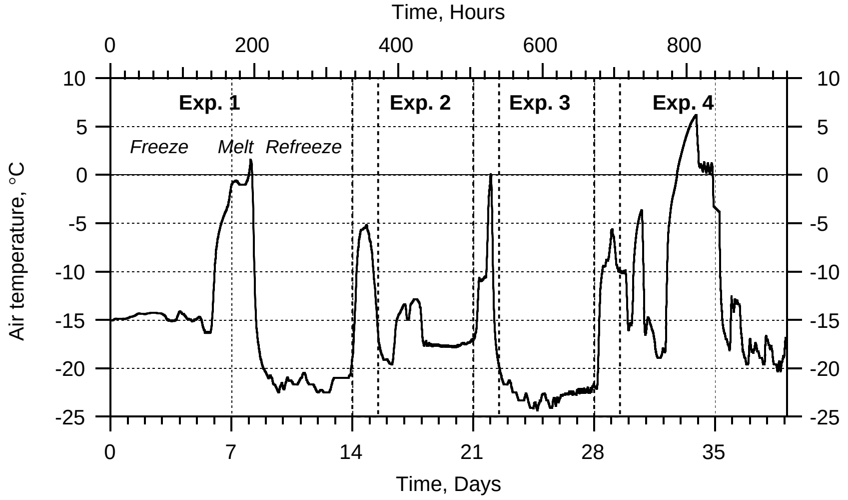

Figure 2: Air temperatures during the four main experiments of INTERICE II.

2.1 PORE SPACE CHANGES DURING A FREEZE-MELT-REFREEZE CYCLE

During sea ice formation, brine is entrapped in pores within the ice. This results in a bulk ice salinity which can be measured from melted samples. The distribution of brine is associated with a background porosity of primary pores and with brine channels, which act as conduits for vertical brine migration (Eide and Martin, 1975; Wakatsuchi and Kawamura, 1987). The structure of brine channels is illustrated in Figure 3. The bulk salinity of sea ice decreases with time and the porosity, or brine volume, is highly dependent on the ice temperature. This is shown in Figure 4 for the freeze-melt-refreeze cycle of Experiment 1 mentioned above. The cooling was switched off on Day 6 for three days, and the ice was allowed to attain an isothermal temperature profile, and even to reverse the temperature gradient on Day 8 (Fig. 4a). As a consequence, the brine volume is more than doubled in the upper ice layers on Day 8. After refreezing, the brine volume is reduced to about 40% at a depth of 0.04 m. Figure 4b illustrates the changes in the primary pore space associated with the cooling. The Figure shows photographs of horizontal thin sections of ice devoid of brine channels from a depth of 0.04 m for the warm (Day 8) and cold states (Day 11). The upper photographs have been taken with the thin sections between crossed polarizors, such that the crystals are visible by their distinct grey shade. In the lower photographs, taken with incident light, the pores have been marked with a white dye. The large differences in the primary pore volume shown in Figure 4 result in brine expulsion from the thin brine layers into the brine channels during such a temperature cycle. As was shown by Cottier et al. (1999) from his experiments during INTERICE I, this is reflected in a heterogeneous salinity distribution on the centimetre scale in cold ice, where regions of high bulk salinity are coincident with the location of brine channels. In warm ice, however, the brine is redistributed into the primary pores, creating a more homogenous small-scale salinity which is independent of brine channels.

In Figure 3b the location of the ice underside at the end of the melting phase is visible as a prominent interface. The ice underneath has formed during the refreeze phase. The brighter appearance of this ice indicates that the primary pore space in the newly formed ice is different from the primary pore space after a melt-refreeze cycle in the ice above. The brine channels seem not to be disturbed at the interface, and the structure of the drainage system is maintained over the temperature cycle.

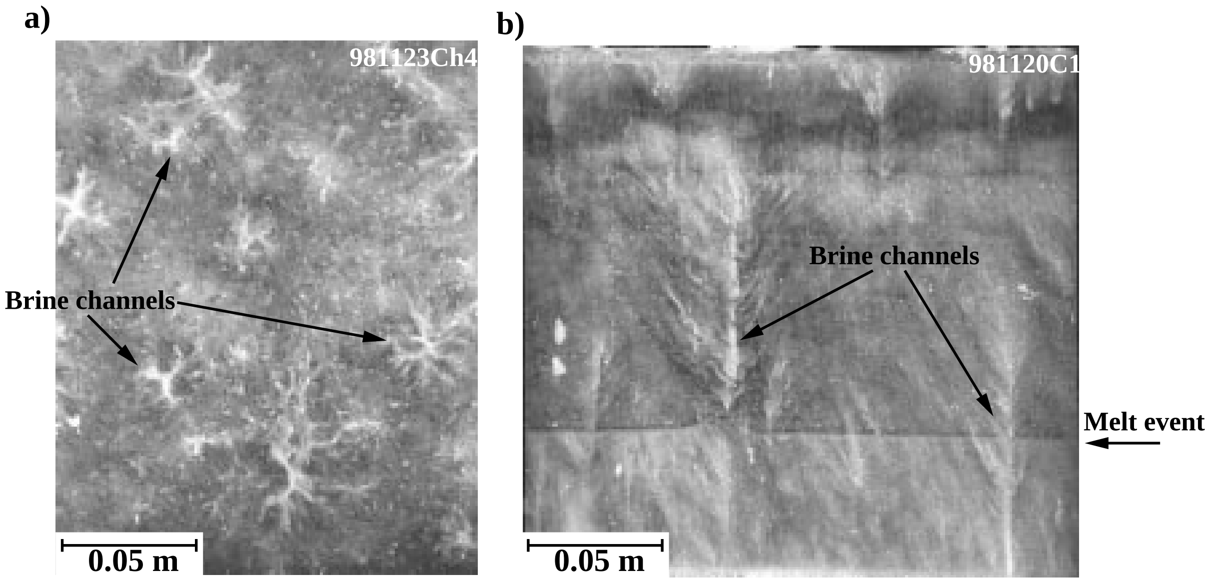

Figure 3: Photographs of ice thick sections illuminated with incident light, showing the typical structure of brine channels, which appear as bright features against the darker ice. a) Horizontal thick section from a depth of 40 mm, showing the star shaped horizontal structure. b) Vertical thick section, showing the tree like structure of the vertical drainage system. The prominent interface at 2/3 depth indicates the location of the ice underside during the melting phase.

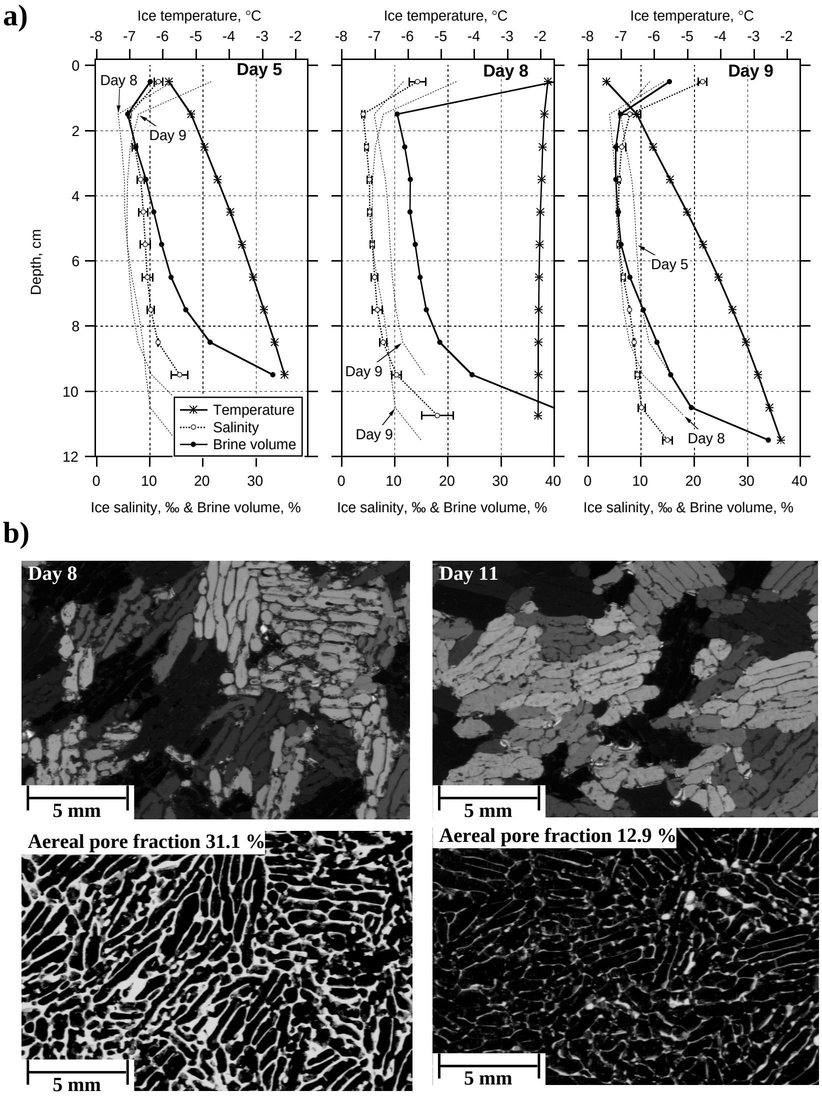

Figure 4: a) Vertical profiles of ice temperature and salinity (incl. standard deviation from 3 measured samples), and brine volume for three days representative of a freeze-melt-refreeze cycle. b) Horizontal ice thin section photographs from a depth of 40 mm, representative for the melt and refreeze states.

2.2 ICE TEMPERATURE MEASUREMENTS

Thermistor measurements of the ice temperature were performed in order to monitor brine fluxes within the ice and into the water. As was shown by Lake and Lewis (1970) and by Niedrauer and Martin (1979), down- or upward fluxes of brine or seawater can be observed by temperature perturbations at a certain depth. This is due to the vertical temperature gradients within the ice, which cause a temperature stratification of the brine as well.

Figure 5a shows a one-day record of ice temperatures measured with a thermistor string frozen vertically into the ice in the Quiet Zone. The vertical spacing between the thermistors was 0.02 m, and in Figure 5 the upper three thermistors (at 0, 0.02, and 0.04 m depth) are already frozen in. The thermistor at a depth of 0.06 m freezes in at about 7.5 hours, while the lowermost thermistor remains in the water for the whole period. Prominent brine convection events (Lake and Lewis, 1970) can not be observed in any of our data. This is probably due to the large growth rates in the cold ice, were the brine channels may soon become too narrow to allow considerable convection.

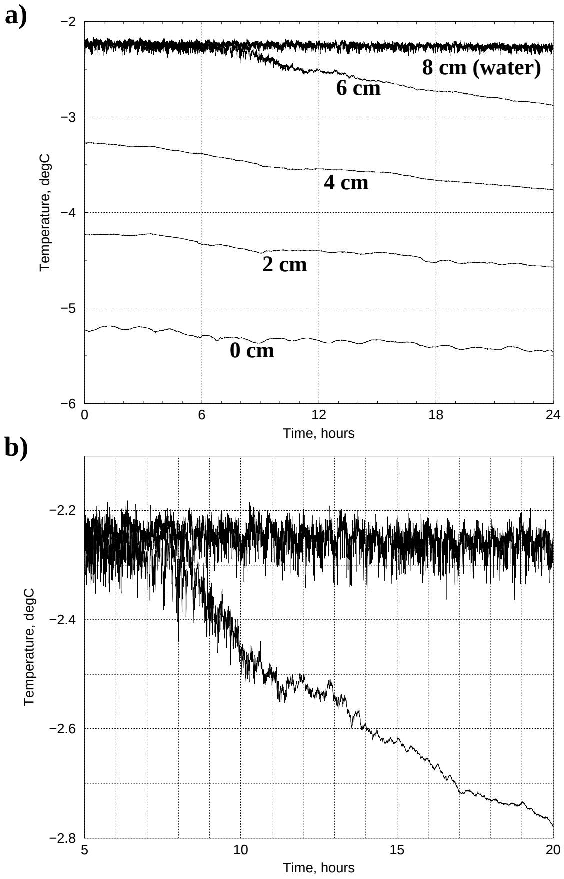

Figure 5: a) 24 hour record from 5 thermistors at different depths below the ice surface. b) Magnification from a) for the period when the thermistor at 0.06 m depth was frozen in.

In contrast to the measurements of Lake and Lewis (1970) and Niedrauer and Martin (1979), the water temperature underneath the ice is highly variable. The ice temperature however shows very little variation, apart from the general cooling trend. Figure 5b shows a magnification of Figure 5a for the passage of the ice water interface across the thermistor at 0.06 m depth. The temperature variations forced by the varying water temperature are only slowly attenuated with the progression of the freezing interface. This indicates that there is still much exchange between the pore space in the lowermost ice layer and the water. Only at about 15 hours, i.e. 7.5 hours after the thermistor was frozen in, the temperature variations are damped out. Thus, at this time the ice permeability was too low for any further rapid exchange between the water and the ice. The loosely consolidated, highly permeable, dendritic layer at the ice underside is also called the skeleton layer. From the vertical temperature gradient in the ice and from the cooling rate at a certain depth a growth rate of 0.5 mm/h can be derived from Figure 5. Thus, during 7.5 hours 3.75 mm of ice have grown, which might be taken as a definition for the skeleton layer thickness. This thickness is considerably thinner than values of 10 to 40 mm reported from natural sea ice, and might be a result of the large growth rate as well.

2.3 PORE STRUCTURE AT DIFFERENT UNDER-ICE CURRENT SPEEDS

Sea ice grows dendritically into the saline water. This is caused by instabilities of crystal surfaces at the advancing ice water interface (e.g. Weeks and Ackley, 1986; Wettlaufer, 1998). As a result, columnar sea ice crystals grown under quiet conditions have a characteristic substructure, where thin pure ice lamellae alternate with interlinked layers of brine (Fig. 4b, Fig. 6). The turbulence generated by under-ice currents modifies the boundary layer processes between ice and water, such that the development of the substructure is considerably reduced. With their experiments during INTERICE I, Eicken et al. (1998) have shown that at current speeds of 0.16 m/s grain sizes are significantly reduced, and only isolated, cellular pores develop. During INTERICE II, we generated additional under-ice current speeds to complement those observations. An example of photographs of thin sections of ice grown at different currents is shown in Figure 6. Preliminary examination of our samples indicate that the lamellar structure is gradually disturbed with increasing current speeds.

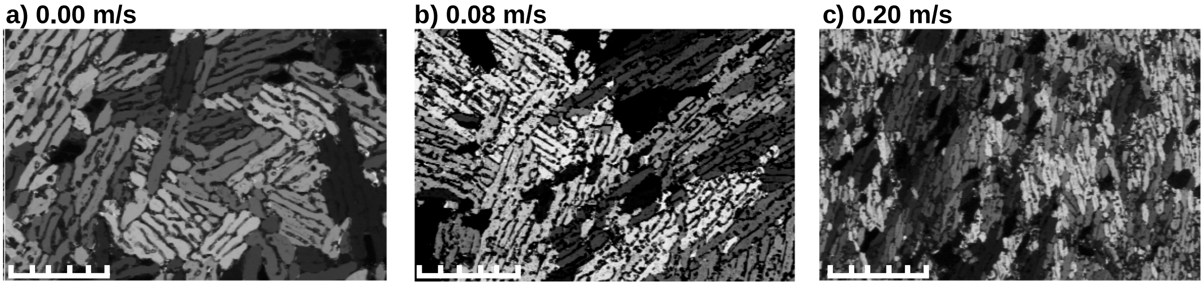

Figure 6: Photographs of horizontal thin sections (c.f. Fig. 4) of ice grown at different under-ice current speeds. Scale is in mm.

3. CONCLUDING REMARKS

We have presented some preliminary results from our microstructural investigations made during the EU-LSF project INTERICE II. They show the large potential of ice tank experiments for this kind of sea ice study, like for many other investigations during the whole INTERICE project. With respect to other HYDRALAB activities it should be pointed out that our experiments are performed on real sea ice, without any physical scaling involved at all. With this respect, there is no competition between physical and numerical modelling. However, the results of our studies can be utilised for the parameterisation of properties or processes in numerical models of e.g. salt flux or microwave scattering.

The available time for conducting the experiments is of great concern for comparisons with real sea ice. As the time cannot be scaled either, our experiments correspond to the investigations of processes in very young ice only. Natural ice, however, is much older and thicker for most of its lifetime, and studying the processes there would require much longer experiments. These would logistically become much more difficult.

One particular aspect of the INTERICE project was that all experiments were conducted simultaneously in the same, large tank. This should enable the joint and comprehensive interpretation of all gathered data sets, which is of particular importance e.g. for the biological investigations. However, for some studies smaller ice tanks might be more suitable, as certain boundary conditions are better controllable. In particular this would be necessary for the air temperature, which cannot be hold as constant as one would desire. This can be seen in Figure 2, where considerable variations are obvious during the cooling phases of Experiments 1-3. Also the rapid variations in water temperature, as shown in Figure 5, could cause problems for some investigations. Most likely, they result from temperature gradients between different side walls or the tank bottom, which cause some large scale water circulation within the tank. Finally, despite the large homogenous areas available for sampling, the development of better, non-destructive sampling techniques is highly necessary for process studies.

The INTERICE experiments were also meant as a feasibility study for further, more detailed projects focusing on particular aspects of sea ice processes, like e.g. salt release during frazil/pancake ice formation, physical/biological interactions, and the fate of oil in ice covered waters. The tank is very well suited for further projects in these fields.

4. ACKNOWLEDGEMENTS

We are very grateful for the hospitality at the Hamburg Ship Model Basin (HSVA) and the technical support by Kalle Evers and his team at the Large Scale Facility ARCTECLAB, and appreciate the collegiality within the INTERICE team. Rainer Laudien is thanked for his great help with the sampling and cold lab work. The experiments benefited largely from intensive discussions with Hajo Eicken, Johannes Freitag, and Fernando Valero Delgado based on their work and experiences during INTERICE I. The study was granted by the European Union TMR Programme through contract N°ERBFMGECT950081.

5. REFERENCES

Cottier, F. R., H. Eicken, and P. Wadhams, in press: Linkages between salinity and brine channel distribution in young sea ice. *J. Geophys. Res.*, in press, 1999.

Eicken, H., M.A. Lange, and G.S. Dieckmann, 1991: Spatial variability off sea-ice properties in the northwestern Weddell Sea. *J. Geophys. Res.*, 96, 10603-10615.

Eicken, H., J. Weissenberger, I. Bussmann, F. Cottier, K.-U. Evers, C. Krembs, H. Kuosa, R. Hall, P. Jochmann, G.H. Leonard, F. Lindemann, M. Reisemann, H. Shen, L.H. Smedsrud, S.F. Ackley, J. Freitag, R. Gradinger, J. Ikävalko, W. Schuster, F. Valero Delgado, and P. Wadhams, Ice-tank studies of physical and biological sea-ice processes, *IAHR, Proceedings of the 14th International Symposium on Ice,* edited by H.T. Shen, pp. 363-370, Balkema, Rotterdam, Potsdam, New York, 1998.

Eide, L. I. and S. Martin 1975: The formation of brine drainage features in young sea ice. *J. Glaciol.*, 14, 137-154.

Lake, R.A., and E.L. Lewis, 1970: Salt rejection by sea ice during growth. *J. Geophys. Res.*, 75, 583-597.

Niedrauer, T.N. and S. Martin, 1979: An experimental study of brine drainage and convection in young sea ice. *J. Geophys. Res.*, 84, 1176-1186.

Wakatsuchi, M. and T. Kawamura 1987: Formation processes of brine drainage channels in sea ice. *J. Geophys. Res.*, 92, 7195-7197.

Weeks, W.F. and S.F. Ackley, 1986: The growth, structure, and properties of sea ice. In *The geophysics of sea ice*. N. Untersteiner (Ed.), NATO ASI series, Series B, Physics, **146**, 9-164.

Wettlaufer, J.S., 1998: Introduction to crystallization phenomena in natural and artificial sea ice. In: M. Leppäranta (Ed.): *Physics of ice-covered seas*. Lecture notes from a summer school in Savonlinna, Finland, 6-17 June 1994. University of Helsinki, Dept. of Geophysics, Helsinki University Press, ISBN 951-45-8226-8, 105-194.