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Multidisciplinary Ice Tank Study Shedding New Light on Sea Ice Growth Processes

A multidisciplinary ice tank study, involving an international team of scientists, is shedding new light on sea ice growth processes. New findings have been made on brine distribution, on the fate of dissolved organic compounds during ice growth, and on sediment entrainment through frazil ice formation. For example, it was found that there is considerable brine migration out of and into brine channels during a freeze-melt-refreeze cycle. The study, known as INTERICE II, also is providing quantitative data for future modeling and analyses.

Sea ice is one of the most important and most variable geophysical materials on this planet's surface. The sea ice cover is fundamental to ocean circulation, air-ocean exchange, and long distance transport of sediments, pollutants, and oil, and also governs the ecology of such regions. Because of this, it plays a key role in shaping global climate, and climate changes in turn can affect the extent, thickness, and other properties of the ice.

In past decades there have been extensive field studies to understand the processes of ice formation, consolidation, and subsequent melt. Among the most intriguing questions have been how brine distribution, as a function of the evolution of the pore space and grain structure, affects the albedo and microwave properties of sea ice, and how these properties are related to the biogeochemical processes and primary productivity within the ice. Also, the potential for and processes of entrainment of sediments and pollutants have been of great interest, because sea ice may be an effective agent in transporting them from remote areas back to inhabited regions.

For INTERICE, the ice tank offered the possibility of refining field measurements by carrying out experiments under fully controlled environmental conditions. Work on physical, biogeochemical, and sedimentological aspects of growth processes of artificial sea ice using the large indoor tank complemented observations from both the Arctic and the Antarctic.

The 6-week experimental program was the second part of a Large Scale Facility project, funded by the European Commission, involving biologists, chemists, geologists, geophysicists, and physicists from Belgium, Germany, Norway, the United Kingdom, and the United States. INTERICE II built on experiences from a first set of experiments conducted 2 years ago *[Eicken et al.*, 1998], and part of it was designed to complement aspects of INTERICE I.

Ice was grown in the 30-m-long Arctic Environmental Test Basin of the Hamburg Ship Model Basin in Hamburg, Germany. The indoor tank, where ice formation can be forced by air temperatures down to -25°C, was 1 m deep and 6 m wide. The tank was subdivided into Quiet and Current Zones (see Figure 1). Laterally homogeneous currents up to 0.3 m/s were generated in the Current Zone. The basin was filled with NaCl water to an initial salinity of 35‰. In the Quiet Zone, biogeochemical and oil-in-ice studies were conducted in 1 m^3 compartments filled with artificial sea water. During experiments on frazil ice, water turbulence was generated in an open lead by currents, wind, and waves.

Tank experiments have several advantages over 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, while natural sea ice is known to be highly variable even on the meter scale. Usually, the history of a particular ice floe selected for sampling is not known. In an ice tank, air, ice, and water temperatures are easily monitored, and temperature forcing can be controlled.

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 primary processes caused by ice formation and superimposed secondary processes, such as algal activity. Also, 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 for 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 more complex the comparisons with processes in older natural sea ice.

Continuous Measurements

In the INTERICE II experiments, continuous measurements of the water temperature, salinity, and current were made in the Current Zone (Figure 1) throughout the experimental phases. 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 and measurements of ice salinity profiles. Figure 2a gives an example of these measurements, showing the general increase in water salinity caused by salt rejection from the growing ice sheet, and then a decrease in salinity because of ice melt during a warming phase (Days 6-8).

Brine Trapped in Pores

During sea ice formation, brine is trapped in pores within the ice. This results in a bulk ice salinity which can be measured from melted samples. The bulk salinity of sea ice decreases with time and the porosity, or brine volume, is highly dependent on the ice temperature.

Figure 2b shows the evolution of the vertical brine volume profile before, during, and after the melt event during the freeze-melt-refreeze experiment in Figure 2a. 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.

During INTERICE I it was shown that the brine content is heterogeneous on the centimeter scale and that regions of high bulk salinity are precisely coincident with the location of brine channels [*Cottier et al.*, 1999]. Warming resulted in a substantial brine redistribu-

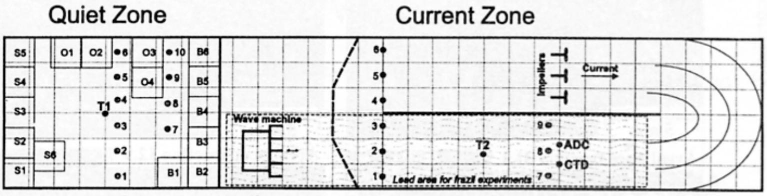

Fig. 1. Map of the ice tank showing the Quiet and Current Zones, the compartments for the biochemical (B), sedimentological (S), and oil (O) studies, and the open lead area for the later frazil experiments. Also shown are the locations of two thermistor strings (T), the conductivity-temperature-depth profiler (CTD), and the acoustic Doppler current meter (ADC) as well as the thickness profiles (dots).

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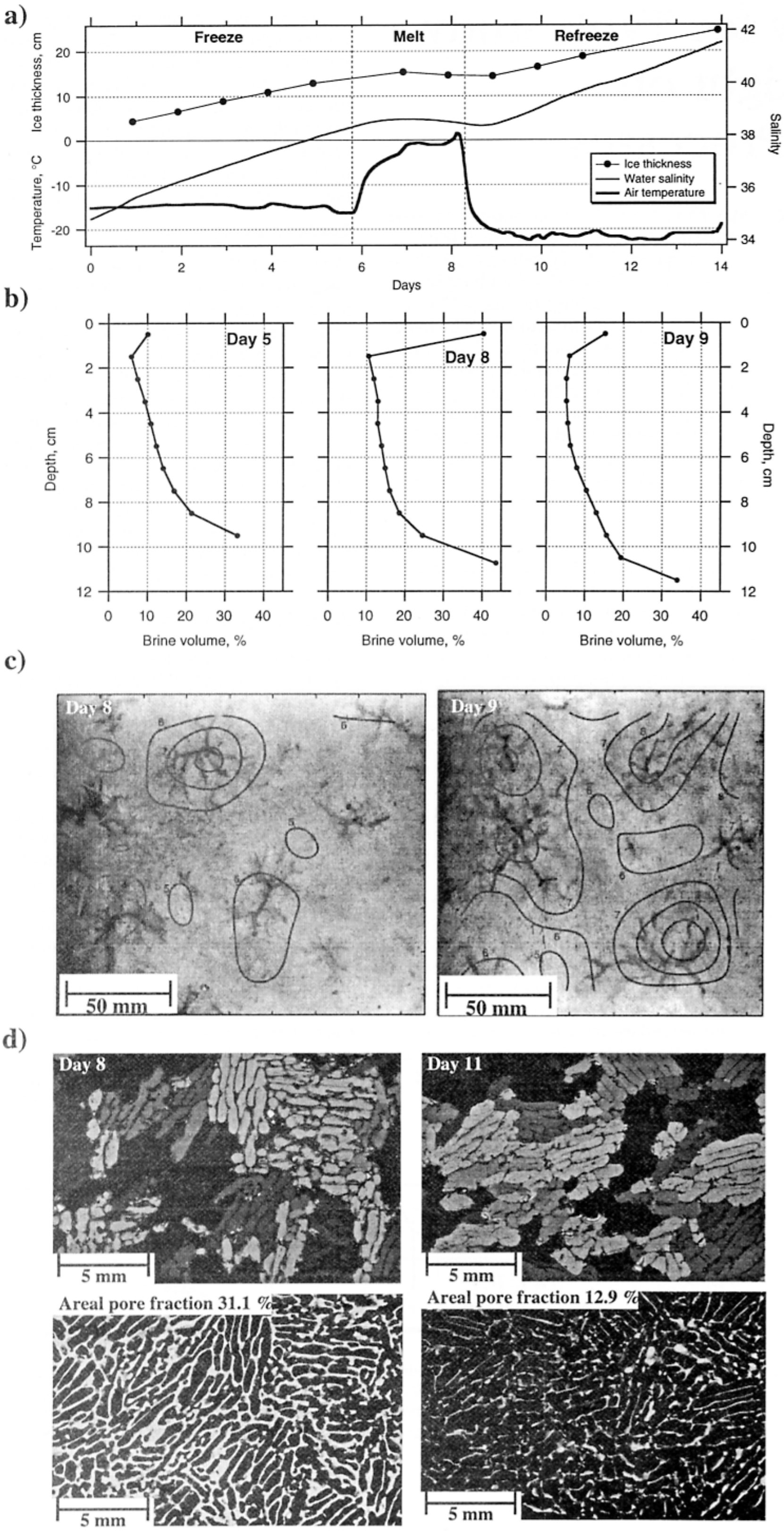

Fig. 2. a) Time series of air temperature, ice thickness, and CTD measurements of water salinity during a freeze-melt-refreeze experiment. b) Vertical brine volume (porosity) profiles for 3 representative days of the freeze-melt-refreeze cycle in (a). c) Photographs of two horizontal ice plates, 20-40 mm deep, from the melt and refreeze phases, with superimposed isohalines. d) Horizontal ice thin section photographs from a depth of 40 mm, representative of the melt and refreeze states. The upper photographs show the crystal structure (different gray shades) and were taken with the samples between crossed polarizers. For the lower pore area photographs, the pores have been marked with a dye.

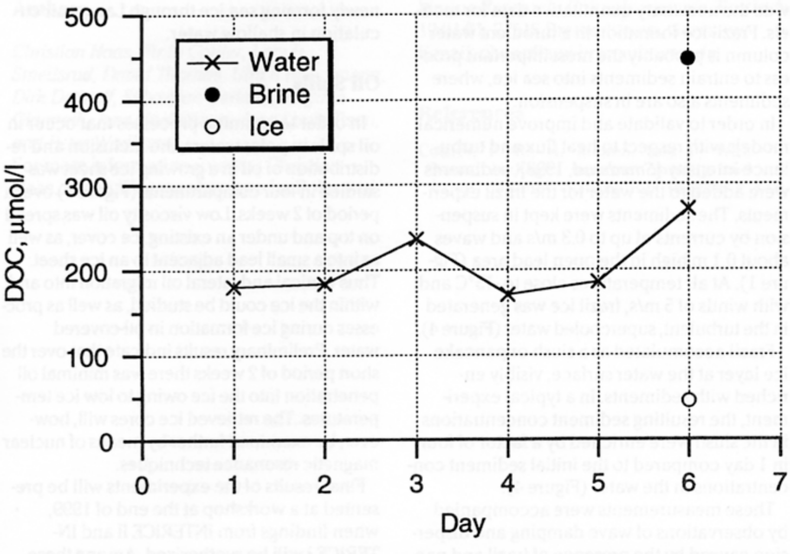

Fig. 3. Mean daily dissolved organic carbon (DOC) concentration in the water over 6 days of freezing. The tank contained added algal dissolved organic matter. Also shown are DOC concentrations of centrifuged ice cores obtained at the end of the experiment, and of the extracted brine. The 95% confidence intervals range from 4.9 to 34% of mean sample DOC concentration, with an average value of 10%.

tion, creating a more homogenous small-scale salinity independent of brine channels.

During INTERICE II these observations were extended to ice that had been refrozen. Figure 2c shows photographs of horizontal ice plates with superimposed isohalines of bulk salinity determined from a matrix of subsamples. Brine channels appear as dark, branched structures against the lighter ice.

Prior to refreeze (Figure 2c, Day 8), with the ice in an isothermal state, the brine is uniformly distributed throughout the sample regardless of the presence of brine channels. In contrast, the brine distribution in refrozen ice is more variable (Figure 2c, Day 9). With the decrease in porosity resulting from the cooling, brine is forced back into the brine channels, creating large salinity gradients across the sample.

The strong porosity decrease of up to 40% shown in Figure 2b is also visible in the photographs in Figure 2d, showing horizontal thin sections of ice areas devoid of brine channels for the isothermal (Day 8) and refreeze (Day 11) states. This confirms that the volume gain of ice forming in the pores during refreeze expels brine from the primary pore space toward the brine channels, causing the increased salinity gradients shown in Figure 2c.

Another study looked at changes in pore and crystal structure associated with different under-ice currents. Ice growth under calm conditions results in large columnar crystals composed of thin pure ice lamellae alternating with interlinked layers of brine (Figure 2d). It was shown during INTERICE I that this substructure does not develop if under-ice currents of about 0.16 m/s exist during ice growth, modifying the boundary layer processes at the crystal surface [*Eicken et al.*, 1998]. The new experiments employed different current speeds to complement those observations. Preliminary results indicate a gradual disturbance of the lamellar structure with increasing current speeds.

The varying pore structure, caused by differing growth conditions, also affects the optical properties of the ice. This modifies the ice surface energy balance and the ice ecosystem. Ice cores were extracted for spectral radiation attenuation measurements in a wavelength range of 350-2500 nm. These measurements will be linked to the pore structure results and will be compared with radiation studies performed on natural Arctic fast ice at Svalbard.

Biogeochemistry

The pool of oceanic dissolved organic matter (DOM) results from biogenic sources such as algal and bacterial exudation, viral lysis, grazing, and excretion by-products. Therefore DOM may be an available substrate to trophic flows in the food web, supporting sea-ice communities.

Dissolved organic carbon (DOC) concentrations up to 1000 µmol/l have been measured in ice cores from Antarctic perennial pack-ice and Arctic multiyear ice. INTERICE II looked at the fate of DOM and specific biochemical compounds (algal-derived DOM, lipid, amino acid, and carbohydrate) in seawater when ice forms and consolidates without the presence of any biological activity.

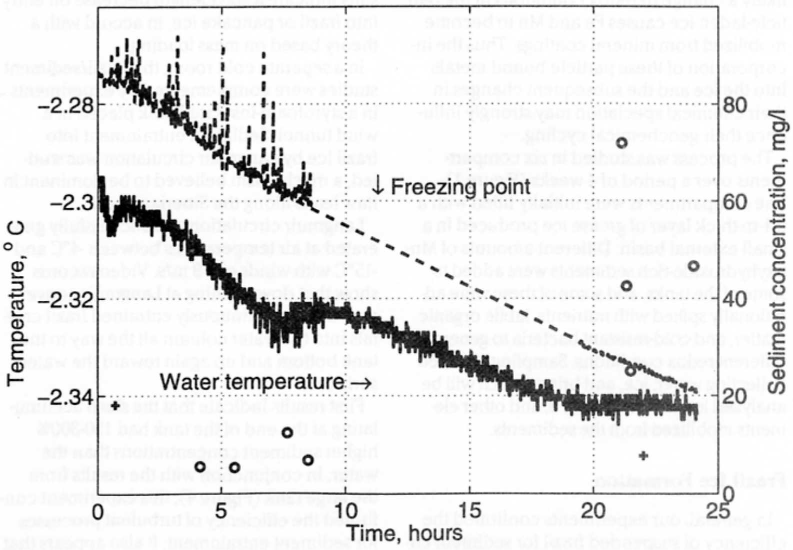

Fig. 4. Water temperature, freezing point, and sediment concentration of slush ice accumulating at the water surface (o) during frazil ice formation. The initial and final suspended sediment concentration in the water is indicated by '+.'

Experiments were conducted in six compartments in the Quiet Zone (Figure 1) during two freezing cycles. Dissolved organic compounds were introduced into the experimental tanks before freezing. DOC concentrations in one tank are shown in Figure 3. The initial concentration of DOC in the water was 200 μmol/l. Over the weeklong experiment there was uniform mixing of DOC throughout the water column.

At the conclusion of the experiment the 0.1 m thick ice had very low DOC levels in the ice matrix, and enriched levels in the brine, obtained from centrifuging the ice cores. The brine from the top half of the ice core was more enriched in DOC than the brine from the bottom half section, which was also less saline. This indicates that DOC behaves similar to inorganic ions in seawater as it freezes.

Cores also were extracted from the biologically uninhabited ice for measurements of the total gas content and the CO_2, O_2, N_2 composition. Data sets on total gas content and gas composition of natural sea ice are extremely scarce. There are considerable discrepancies with compositions that would be expected from equilibrium with dissolved gas concentrations in seawater. Undoubtedly, this results from biological activity in the brine and gas pore spaces.

Newly formed sediment-laden grease ice off the Lena delta in the Laptev Sea showed a seven-fold enrichment of dissolved Fe, Mn, and other trace metals compared to the Lena freshwater. The highest Fe concentrations in the Arctic Ocean occur in the water column underneath sediment-laden ice floes. Very likely a change in redox conditions in the particle-laden ice causes Fe and Mn to become mobilized from mineral coatings. Thus the incorporation of these particle-bound metals into the ice and the subsequent changes in their chemical speciation may strongly influence their geochemical cycling.

The process was studied in six compartments over a period of 4 weeks (Figure 1). The compartments were initially filled with a 0.1-m-thick layer of grease ice produced in a small external basin. Different amounts of Mn-oxyhydroxide-rich sediments were added to some of the tanks, and some of these were additionally spiked with nutrients, labile organic matter, and cold-resistant bacteria to generate different redox conditions. Sampling involved collecting water, ice, and brine, which will be analyzed for dissolved Mn, Fe, and other elements mobilized from the sediments.

Frazil Ice Formation

In general, our experiments confirmed the efficiency of suspended frazil for sediment entrainment in a turbulent flow and can provide the necessary quantitative data for models. Frazil ice formation in a turbulent water column is probably the most important process to entrain sediments into sea ice, where sediments also are in suspension.

In order to validate and improve numerical models with respect to heat flux and turbulence intensity [*Smedsrud*, 1998], sediments were added to the water for the frazil experiments. The sediments were kept in suspension by currents of up to 0.3 m/s and waves about 0.1 m high in the open lead area (Figure 1). At air temperatures close to -15°C and with winds of 5 m/s, frazil ice was generated in the turbulent, supercooled water (Figure 4).

Frazil accumulated as a slush or pancake ice layer at the water surface, visibly enriched with sediments. In a typical experiment, the resulting sediment concentrations in the slush were enriched by a factor of four in 1 day compared to the initial sediment concentrations in the water (Figure 4).

These measurements were accompanied by observations of wave damping and dispersion caused by the presence of frazil and pancake ice. Spaceborne radar observations show that at typical ocean wave periods of 6-12 s, waves suffer a wavelength decrease on entry into ice, while laboratory experiments at very short periods less than 1 s show a wavelength increase.

Intermediate wave periods were achieved during INTERICE II, allowing a test of theory over a new frequency range. A line of three pressure transducers was placed near the bottom of the tank at 2-m intervals to determine the dominant wavelengths. Preliminary results indicate a wavelength decrease on entry into frazil or pancake ice, in accord with a theory based on mass loading.

In a separate cold room, the frazil/sediment studies were complemented by experiments in a styrofoam-insulated tank placed in a wind tunnel. Sediment entrainment into frazil ice by Langmuir circulation was studied, a mechanism believed to be dominant in flaw leads along the Siberian coast.

Langmuir circulation was successfully generated at air temperatures between -4°C and -15°C with winds of 5-9 m/s. Video records show that downwelling at Langmuir convergent zones continuously entrained frazil crystals into the water column all the way to the tank bottom and up again toward the water surface.

First results indicate that the slush accumulating at the end of the tank had 150-300% higher sediment concentrations than the water. In conjunction with the results from the large tank (Figure 4), this experiment confirmed the efficiency of turbulent processes for sediment entrainment. It also appears that frazil may directly entrain bed material into newly forming sea ice through Langmuir circulation in shallow water.

Oil Spills

In order to examine processes that occur in oil spills in polar waters, the inclusion and redistribution of oil in a growing ice sheet was studied in four compartments (Figure 1) over a period of 2 weeks. Low viscosity oil was spread on top and under an existing ice cover, as well as into a small lead adjacent to an ice sheet. Thus vertical and lateral oil migration into and within the ice could be studied, as well as processes during ice formation in oil-covered water. Preliminary results indicate that over the short period of 2 weeks there was minimal oil penetration into the ice owing to low ice temperatures. The retrieved ice cores will, however, be examined further by means of nuclear magnetic resonance techniques.

Final results of the experiments will be presented at a workshop at the end of 1999, when findings from INTERICE II and INTERICE I will be synthesized. Among these are the dependence of optical properties on different pore and grain structures developed under different boundary conditions and the amount and composition of gases and organic compounds as a function of different growth rates and water compositions. Based on the project, it is hoped that more detailed tank studies on particular aspects of sea ice growth will be developed. One needed study involves the question of salt release during frazil-pancake ice formation, a topic of importance in assessing the role of sea ice in oceanic convection. Other future experiments might address physical and biological interactions and oil-in-ice processes in more detail.

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