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 analysis.

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 biochemical 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, biochemical, 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., 1988), 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, biochemical and oil-in-ice studies were conducted in 1 m³ 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 biochemical 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-

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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).
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 isotherms. 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 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%.

Fig. 4. Water temperature, freezing point, and sediment concentration of slush ice accumulating at the water surface (c) during frazil ice formation. The initial and final suspended sediment concentration in the water is indicated by '4.'
Experiments were conducted in six compartments in the Quiet Zone (Figure 1) during two freezing cycles. Dissolved organic compounds were introduced 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 (1991), sediments were added to the water for the initial 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 -10°C and with winds of 5 m/s, frazil ice was generated in the turbulent, supercooled water (Figure 4). Frazil ice enrichment could be ascribed to the presence of frazil and pancake ice. Spaceborne radar observations show that at typical air temperatures of 0-1°C, waves suffer a wavelength decrease on entry into ice. Laboratory experiments at very short periods less than 1 show a wavelength increase. Intermediate wave periods were achieved during INTEGRIST, offering a test of theory. 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/ice formation studies were complemented by experiments in a styrofoam-insulated tank placed in a wind tunnel. Sediment formation in the tank was studied, and a mechanism believed to be dominant in finewas along the Siberian coast. Langmuir circulation was successfully generated at air temperatures between -4°C and -15°C with winds of 5 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 toward the water surface. First results indicate that the slush accumulating at the end of the tank had 3 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 a given 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 processes during oil formation in ice-covered water. Preliminary results over the short period of 2 weeks there was minimal oil penetration into and within the ice could be studied, as well as processes during ice formation in oil-covered water. Preliminary results indicate that the oil was not redistributed in the ice, with the exception of some oil migration into the ice, which was not observed. These results are consistent with previous studies and show that oil is not redistributed in ice. In future studies, the effects of temperature and ice thickness on oil distribution should be investigated.

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