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Scientific note

Laboratory experiments on frazil ice formation with application to the Arctic marine environment

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Abstract: Laboratory experiments on the frazil ice formation in the upper low saline water layer cooled from below by a more saline water layer indicate that frazil ice production is maximal when both layers are in turbulent state of motion. It is argued, that a considerable amount of frazil ice may be formed in the contact zone between fresh river water and cold marine water in the Arctic shelf zone. Frazil ice production in the fresh/salt water contact zone should be suspected as an important source of sediment incorporation into the Arctic surface ice cover.

Frazil ice is one of the important sources of sea ice in polar seas. According to Martin (1981), Weeks and Ackley (1982) frazil ice is formed:
a) in regions of open waters, called leads and polynyas, during cold and windy weather;
b) adjacent to deep ice shelves and icebergs where water with a lower freezing point due to hydrostatic pressure may be transported toward the sea surface;
c) at the interface between two water masses of different salinities, both near their respective freezing points;
d) from the drainage of cold dense brine from sea ice into the underlying water.

The first mechanism has been frequently observed and studied under both natural and laboratory conditions (Reimnitz and Kempema, 1987; Ushio and Wakatsuchi, 1993). Obviously it is an important mechanism in both Arctic and Antarctic seas. The second mechanism is not typical under Arctic conditions, because of the absence of deep ice shelves and the presence of strong density stratification that prevents upwelling of deep waters to the surface. The third and fourth mechanisms are governed by the effects of double diffusion of heat and salt (Turner, 1973). While the last one influences only ice stalactites growth (Martin, 1981), the third one is expected to be widespread in most Arctic seas where a low saline upper water layer is maintained due to strong river runoff. In spite of many observations (Cherepanov, 1972; Timokhov, 1989), it is still a question, how intensive is the frazil ice production in the contact zone between fresh and salt water under natural conditions? Does it contribute significantly to Arctic ice production and what is its impact on the Arctic marine environment?

Typically, the temperature of the low saline, or fresh, river water during the cold season in the Arctic is close to the freezing point. Entering the ice-covered sea, fresh mwater spreads over the surface of much colder saline water and a two-layer system with sharp density interface is formed.

Due to the influence of the molecular transfer properties (the molecular coefficient of the heat transfer is two orders higher than the coefficient of salt diffusivity), the heat exchange across such an interface may be much more effective compared to that of salt. Taking into account the approximately linear dependence of the freezing temperature of the sea water on salinity it is easy to consider that in such circumstances the upper fresh water layer should be supercooled from below. The rate of supercooling and thus, frazil ice formation strongly depends on the heat and salt fluxes across the density interface.

The laboratory experiments by Martin and Kauffman (1974) have shown that in the absence of mechanically generated turbulence the basic mechanism of heat and salt transfer between the fresh and salt water layers is double-diffusive convection in the "diffusive" mode. Because of the very large density step across the density interface, the stability parameter $R=b(S''-S')/a(T''-T')$ is more than 100 or even 200, where a and b are the coefficients of thermal and salt expansion of sea water, T', S' and T'', S''—the temperature and salinity of the upper and lower layers, respectively. It was show by McClimans *et al.* (1978) and Stigebrandt (1981) that in such cases the convection process is very weak. The rates of heat and salt transfer are close to molecular and typical rates of frazil ice formation under the most favourable conditions are not more than a few millimeters per day. This means that a slush ice layer with the thickness about few millimetres may be formed during one day. Moreover, freezing decreases with time due to the thickening of the density interface. Similar laboratory results and theoretical estimates were obtained by McClimans *et al.* (1978), Stigebrandt (1981) and Krylov, (1989). In natural conditions the density interface is usually thicker than in laboratory conditions, so, the rate of supercooling and frazil ice formation due to quasi-molecular heat exchange between the fresh and salt water layers in polar seas is expected to be negligible.

However, it was discovered in a laboratory experiment by Zatsepin and Krylov (1987) that the rate of frazil ice formation considerably increases if the contacting layers of fresh and salt water are turbulently stirred. Subsequently a laboratory investigation of the process of heat and salt exchange across a density interface between fresh and salt layers stirred by vertically oscillating grids was carried out at room temperature (Krylov and Zatsepin, 1992). It was found that moderate turbulent stirring of the layers greatly enhances the heat and salt fluxes between the layers, but still some difference in the effective coefficients of heat and salt exchange remains for the ranges of the main non-dimensional parameters investigated (typical for natural conditions). Estimates based on the experimental results have shown that the rate of freezing in the presence of turbulence in the contacting layers may range from a centimetre up to a meter per day. So, it may be two orders of magnitude greater than in the case of pure double diffusion and as high as in open leads and polynyas!

Later Voropayev *et al.* (1995) carried out an analogous experiment in a tank filled with two layers of water: fresh water at 0°C in the upper layer and salty (35 psu) cold water at temperature −1.9°C. The tank was placed in a large walk-in freezer at a temperature near 0°C. The turbulence induced in both layers enhanced the transport of heat across the sharp pycnocline between the layers. As time progressed the pycnocline and lower boundary of the upper layer became supercooled and small crystals of frazil ice were rapidly formed in the supercooled zone. These buoyant crystals rose to the surface and with time a sheet of slush ice was formed at the surface of the fresh water. The rate of frazil ice formation (the thickness of the slush frazil ice layer, formed in a unit time interval) was consistent with estimates by Krylov and Zatsepin (1992).

Recent field studies performed in the Transdrift-IV expedition near the delta of the Lena river in the Laptev Sea during the flood period (late May–mid of June) give new evidence of intensive frazil ice formation in the contact zone between the fresh river and cold saline water layers. Temperatures of both the upper quasi-fresh and lower saline layers were close (within 0.1℃) to the freezing point. CTD data have revealed the presence of supercooled water layers 0.05–1.5 m thick in the pycnocline between the layers. The supercooling value was as much as 0.8℃! Both layers were in a turbulent state of motion. Although the turbulence characteristics were not measured, they were estimated on the basis of semi-empirical turbulence theory (Phillips, 1977). Thus, we obtained an estimate of the integral lengthscale L of turbulence and its mean-square velocity scale U^* using the expressions $L = kH$, $U^* = kU$, where H is the thickness of the layer, U — the scale of the mean horizontal velocity in the layer and $k \sim 0.1$ — the empirical coefficient. The thicknesses of the layers were estimated from the CTD data. The scale of mean horizontal velocity produced by the river flood in the upper layer was taken as $U' = 10$–50 cm/s, while the scale of mean horizontal velocity $U'' = 2$–10 cm/s for the lower layer was taken as typical for tidal motion in the Laptev Sea. On the basis of semi-empirical formulas from laboratory studies of frazil ice formation, similarity analysis and *in situ* data, the possible rates of frazil ice formation in the river/sea water contact zone were estimated for different stages of the seasonal flood near the mouth region of the Lena river. The calculated thickness of the frazil ice layer changed from a few centimeters per day during the period prior to the flood up to more than meter per day during the flood peak. The average porosity of the slush frazil ice layer (the ratio of the mass of the ice crystals to the sum of ice crystals mass and the mass of water, trapped between them) was taken equal to 0.3 for these calculations.

Of course, the application of laboratory results for estimating rates of frazil ice formation under natural conditions can cause justified criticism. However, such high rates of frazil ice formation in the Laptev Sea fresh/sea water contact zone during the flood period do not necessarily contribute to the increase of surface ice thickness. For almost all of the CTD stations the temperature of the upper layer was slightly higher than the freezing point, so frazil ice rising from the pycnocline to the surface should be completely melted. But in winter historical hydrology data have shown, that for about 40% of the Laptev Sea area the upper layer temperature was equal or below the freezing point (Golovin *et al.*, 2000)! So, it is reasonable to suspect that frazil ice formed at the fresh/saline water contact zone may significantly contribute to the Arctic ice cover during the cold season.

However, there is direct evidence of intensive ice formation at the pycnocline level during the flood period in the Laptev Sea. At one of the stations near the Lena river delta a conglomerate of the frazil ice was found attached to a cable at the depth of the upper pycnocline part. Its weight was about 1.5–2 kg and its height — about 0.6 m. It consisted of transparent chaotically oriented crystals of frazil ice within which inclusions of sediments transported by river water were clearly seen. The cable in this case served both as a nucleus and a place where the frazil ice crystals were trapped.

The frazil ice formation mechanism plays a significant role in sediment transport to the surface of both fast and drifting ice. Laboratory experiments have shown (Reimintz *et al.*,

1993) that the concentration of sediments in frazil ice may be much higher than the concentration of suspended sediments in river water. The enrichment of frazil ice by sediments is achieved due to the scavenging action by frazil ice flocs through mechanical trapping of both biological and terrigenous matter suspended in the water. This fact was experimentally recorded during the Transdrift-IV expedition. The concentration of the suspended matter in the frazil ice agglomeration attached to the cable was 60 times higher than in river water (Golovin *et al*., 1999).

During production, growth and rising through the water column, frazil ice entraps sediments transported by river water. When rising to the surface, frazil ice crystals can be incorporated into the surface ice layer if the temperature of the upper fresh layer is equal to or below the freezing point. This condition is generally fulfilled in cold season, so the frazil ice production in the fresh/salt water contact zone should be suspected as one of the important sources of sediment incorporation into the Arctic ice cover. It may significantly contribute to the long-range transport of sediments in the Transpolar Ice Drift (Golovin *et al*., 2000).

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