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RAPID FRAZIL ICE PRODUCTION IN COASTAL POLYNYA: LABORATORY EXPERIMENTS

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Abstract: Laboratory experiments were carried out to clarify the production processes of frazil ice in a wind-generated polynya. We measured the production rate of frazil ice formed from salt water in a test tank as a function of air temperature and wind speed. The results show that the production rate increased with increasing wind speed and with falling air temperature, and was about four to five times greater than that of sheet ice growing vertically. It is found that wind blowing continuously on the open water surface plays an important role in the process of rapid ice production; that is, the wind-driven current transports supercooled water which is formed on the surface to the underlayer and much frazil ice production occurs under water as the state of supercooling is maintained, because a large amount of heat is released from the open water. Convection phenomena in the tank were observed with a Schlieren optical system. Most brine excluded on the open water surface was transported with the ice crystals downwind through the wind-driven current and then fell vigorously mixing with surrounding water near the edge of accumulated frazil ice layer.

1. Introduction

Persistent open water areas surrounded by sea ice cover are often observed in the polar ocean even during severe winters. In such open waters, called 'polynyas' or 'leads', exposed to the cold air, sea ice newly forms with a high growth rate. Particularly in a coastal region where strong wind is continuously blowing, vigorous production of sea ice and the sweeping away of it simultaneously occur. Because of a large amount of heat transfer from the sea water which is at its freezing point, sea ice forms rapidly as very small disc-shaped crystals. These crystals, which measure about 1–4 mm in diameter and 1–100 μm in thickness, are called 'frazil ice' and they accumulate at the edge of downwind ice cover (*e.g.*, MARTIN, 1981; MARTIN and KAUFFMAN, 1981; BAUER and MARTIN, 1983). It is considered that such a wind-generated open water, or coastal polynya, serves as a more efficient ice factory than ice-covered areas, where the sheet ice grows under calm conditions.

Moreover as ice forms in sea water, it excludes salt in the form of brine, which is at low temperature and has high salinity. The amount of salt exclusion increases with increasing ice production, as given by WAKATSUCHI and ONO (1983). Hence a large salt flux occurs in the open water region where ice production proceeds rapidly. We can suppose that dense saline water resulting from the brine will cause active convective mixing in the ocean mixed layer. Above all, in the Southern Ocean such a rapid ice production has been considered to contribute to the formation process of Antarctic Bottom Water (GILL, 1973). In this way large quantities of heat to the atmosphere and salt to the ocean are supplied through the processes of rapid frazil ice production, so the open waters have great influence on climate and abyssal circulation in the polar region.

Thus the ice production rate in the wind-generated coastal polynyas is one of the most important factors in the atmosphere-ocean interaction. The purpose of the present study is to obtain the dependence of ice production rate on air temperature and wind speed. From examination of the results of laboratory experiments, this paper describes the production rate of frazil ice, the factors causing rapid ice production, and the nature of the brine exclusion from frazil ice production.

2. Experiments

Figure 1 shows a schematic diagram of the experimental apparatus. For the experiments a 15 mm thick acrylic test tank with dimensions of 2 m in length, 0.4 m in width, and 0.6 m in depth was set in a large cold room. We filled the tank with salt water of about 32 per mill salinity up to a level of about 0.55 m. The sides and the base of the tank were covered with 0.1 m thick styrofoam so that the inner water would be cooled only from the upper surface.

The behavior of the excluded brine in the water was observed with a Schlieren optical system. The system is a method to visualize local differences in density gradient (corresponding to the salinity differences) as the differences in refractive index of the water body where parallel rays are passing in the tank. Thereupon we set two concave mirrors facing each other about 8 m apart so that the tank could meet at right angles with parallel rays passing between these mirrors. A xenon lamp was used

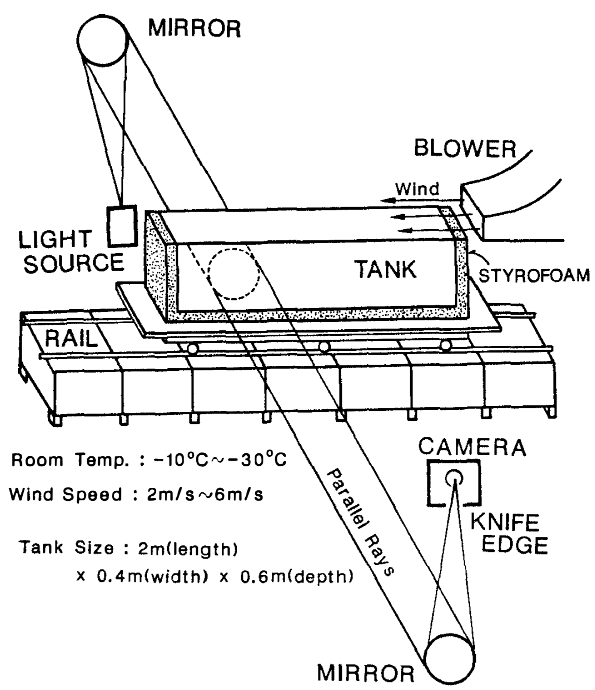


Fig. 1. Schematic diagram of the experimental apparatus set in a cold room. The size of the mirror is 0.4 m in diameter and 4 m in focal length.

for the light source and set at the focal point of the first mirror. A knife edge is placed at the focal point of the second mirror to create a contrast between light and darkness in the image. In order to observe the whole length of the tank with the mirrors 0.4 m in diameter, we moved the tank along the rail so slowly that no disturbance would occur in it. In this observation the visualized events were recorded with a video camera.

When the whole water layer cooled to its freezing point (*ca.* $-1.8°C$), the artificial wind was continuously blown over the water surface from one side with an air blower. We then observed the following phenomena: small frazil ice crystals which formed on the water surface were transported downwind by the wind-driven current; on the lee numerous frazil ice crystals accumulated in a layer, where the edge of the layer advanced upwind with the lapse of time, so the open water area slowly decreased. For the experimental conditions, the room temperature was varied from -10 to $-30°C$ and the wind speed was varied from 2 to 6 m/s. The wind speed is a value measured at a point 50 cm apart from the windward edge of the tank, 2 cm over the water surface.

In order to estimate the rate of frazil ice production, we measured the following items at regular time intervals: edge position, thickness distribution, and salinity of the accumulated frazil ice layer. And water temperature was continuously recorded with copper-constantan thermocouples.

3. Results and Discussion

3.1. Production and accumulation of frazil ice

In the open water area exposed to the cold air, frazil ice is produced, then swept downwind. Such a phenomenon repeats itself as long as the open water exists. The numerous frazil ice crystals which formed near the water surface accumulate at the downwind end of the tank, so that edge of the accumulated layer advances gradually upwind. We measured the distance from the leeward to the edge and the layer thickness every 5 cm horizontally at intervals of 5 min. The layer had roughly uniform thickness in the cross-wind direction. Figure 2 shows the cross section of the frazil ice layer accumulated on the lee. In the case of the same room temperature (*e.g.* $-10°C$), the accumulation pattern of the layer markedly changed with wind speed; the higher the wind speed, the thicker the layer (see Fig. 2a). Above all, at the wind speed of 6.0 m/s, the layer thickness increased rapidly with time. Such a rapid increase of the layer thickness was caused by underwater ice production. Besides the edge of the accumulated layer tends to advance repidly at the lower air temperature.

The open water area gradually decreased. The rate of decrease of open water area is shown in Fig. 3. The rate was obtained by the method of least squares because the advancing rate of the ice layer edge was nearly constant in all cases. The rate increased with falling air temperature, while it was independent of the wind speed. According to Figs. 2 and 3, it is considered that the production rate of frazil ice increases at higher wind speed and at lower air temperature.

3.2. The rate of frazil ice production

The accumulated frazil ice layer contains much saline water and keeps soupy con-

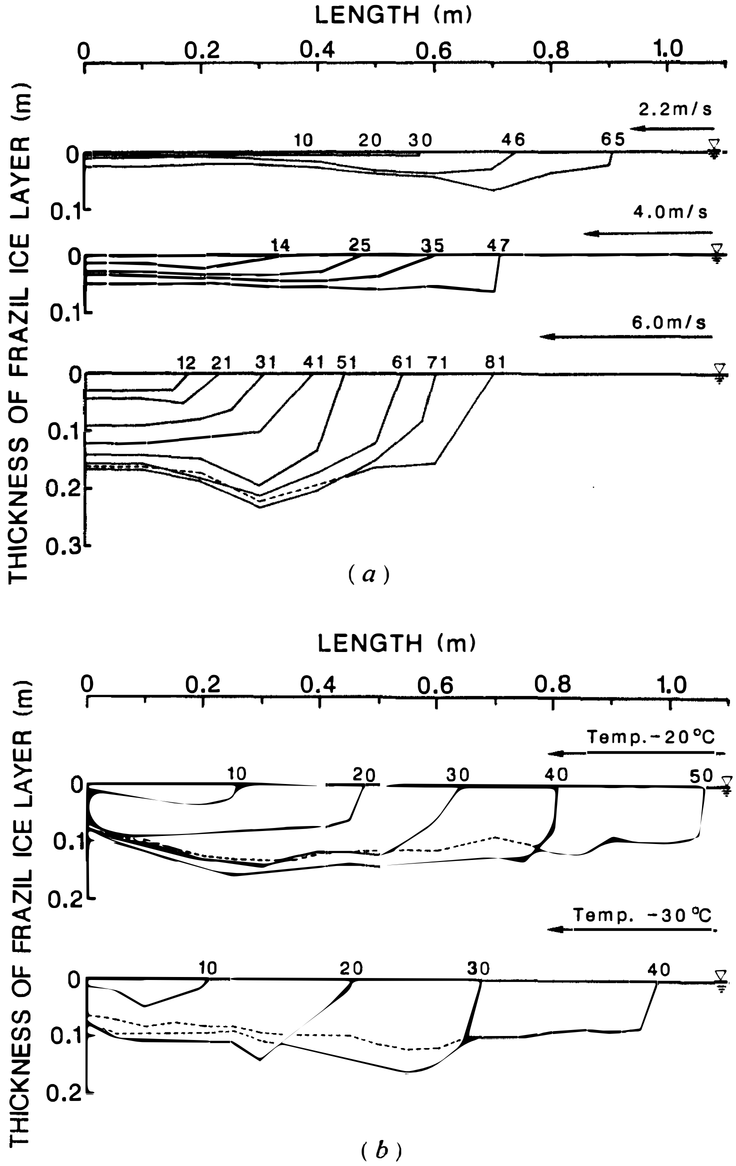


Fig. 2. Cross section of the frazil ice layer accumulated on the lee. Wind is blowing from the right side. Some figures above the water surface show elapsed time (in minutes). (a) room temperature, −10°C: (b) wind speed, 6.0 m/s.

dition which is called 'grease ice'. We estimated the total ice mass in the layer as follows.

The total mass of the layer is expressed by

$$\rho V=\rho_{\mathrm{i}} V_{\mathrm{i}}+\rho_{\mathrm{w}} V_{\mathrm{w}}\,, \tag{1}$$

where ρ, ρ_{i}, and ρ_{w} respectively represent the densities of the mean value of the layer, ice (frazil ice in the present experiment), and the contained saline water which has higher salinity than that of underlying water; V, V_{i}, and V_{w} are the volumes of the whole layer, ice, and the saline water, respectively. Assuming that the ice has no brine, an expression for the salt mass in the layer is given as

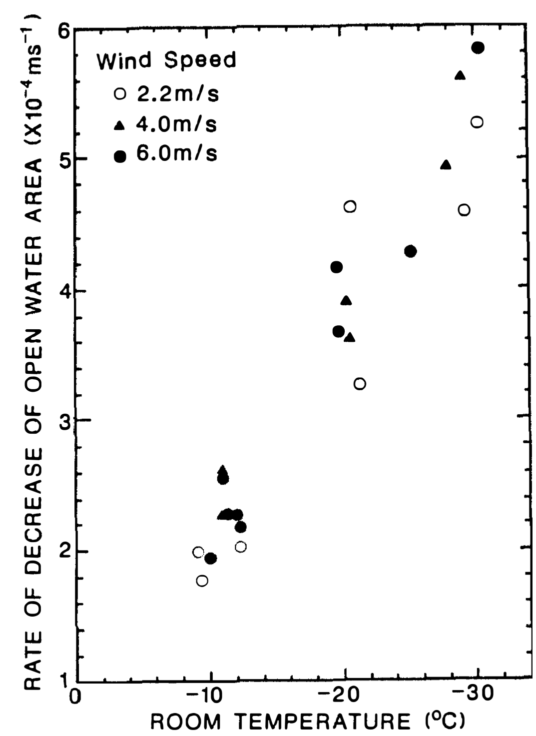


Fig. 3. Rate of decrease of open water area (per unit width of tank) versus room temperature at three different wind speeds.

$$\rho VS = \rho_w V_w S_w \,, \tag{2}$$

where S and S_w are the salinities of the mean value of the layer and the contained saline water, respectively.

If we assume that no bubbles are contained in the frazil ice layer, total volume V is expressed by

$$V = V_i + V_w \,. \tag{3}$$

Eliminating ρV from eqs. (1) and (2), we obtain

$$(\rho_i V_i + \rho_w V_w) S = \rho_w V_w S_w \,. \tag{4}$$

Further eliminating V_w from eqs. (3) and (4), we obtain

$$V_i = \frac{\rho_w V(S_w - S)}{\rho_i S + \rho_w (S_w - S)} \,. \tag{5}$$

Equation (5) multiplied by ρ_i makes total ice mass M_i

$$M_i = \rho_i V_i = \frac{\rho_i \rho_w V(S_w - S)}{\rho_i S + \rho_w (S_w - S)} \,. \tag{6}$$

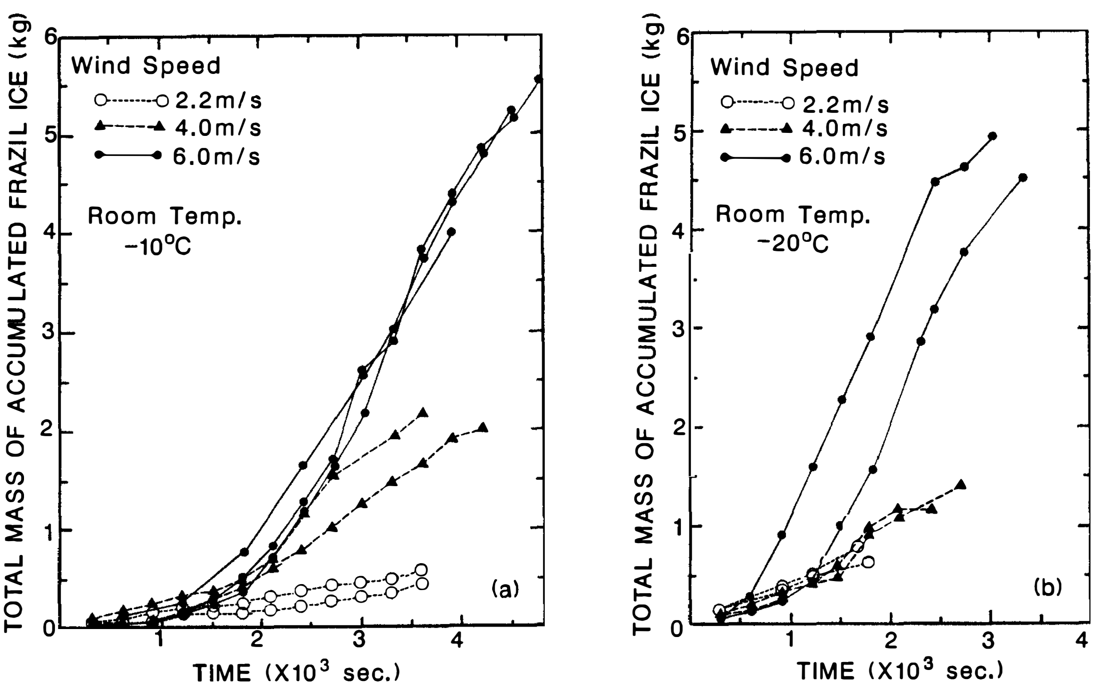
In the above equation, V, S_w, and S are measurable values; V was obtained by measuring the length and the thickness profile of the layer because we could consider the layer to be uniform in the direction crossing wind direction at right angles; S_w and S were respectively measured by sampling saline water alone from the layer with a needle (inside diameter is 0.48 mm) and by sampling the water-ice mixture. As a constant,

9.2×10^2 kg m^{-3} was used for the ice density ρ_i and the density of saline water ρ_w was determined from the following approximate formula (after ZUBOV, 1945):

$$\rho_w = (1 + 0.0008 S_w) \times 10^3 \text{ (kg m}^{-3}\text{)} .$$

So we can know the variation of ice production with time from eq. (6) by measuring V, S_w, S at different times.

The time variations of the total mass of frazil ice accumulated in the layer are



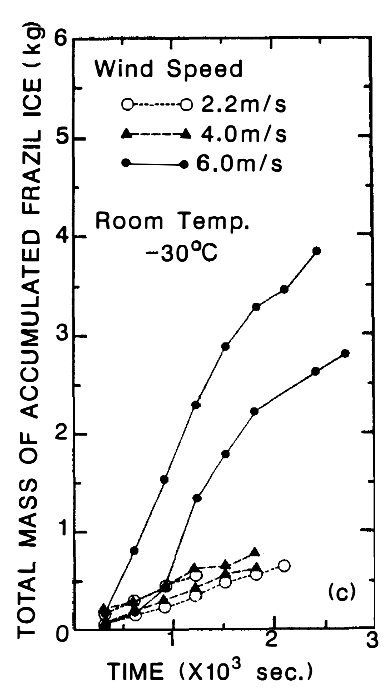


Fig. 4. Time variations of the total ice mass in the accumulated layer for room temperatures of (a) −10°C, (b) −20°C, and (c) −30°C.

shown in Fig. 4. The ice production for unit time, which corresponds to the slope of each curve in the figure, increased with wind speed and reached a large value in a short time at the lower temperaure. Therefore total ice production during the same period increases with increasing wind speed and with falling air temperature. Here we can find that in the case of the highest wind speed, 6 m/s, the curves had nearly equal slopes independently of the air temperature after the slopes reached constant values. The above-mentioned result indicates that at the lower temperature rapid ice production proceeds in the form of producing numerous frazil ice near the water surface because of the strong surface cooling, that is to say, ice crystals form before supercooled water sinks fully. This rapid ice production also leads to the fast advance of the layer edge rather than to the increase of the layer thickness (see Figs. 2 and 3).

It must be noted that despite decrease in open water area with time, accumulated total ice mass increased at the constant rate (each curve keeps a constant gradient as shown in Fig. 4); this tendency suggests that underwater ice formation contributes to the process of rapid ice production. At the lower wind speed, underwater ice formation scarcely occurred, because heat flux from the water to the air and the effect of transporting supercooled water to the lower layer were relatively small.

Next, we calculated the ice production rate for unit open water area. Figure 5 shows time variations of the ice production rate under various conditions. The rate increased as the wind speed increased and rapidly reached a large value at the lower air temperature. In the early stage, despite decrease in the open water area with time, the rate of ice production gradually increased. Such a phenomenon is explained by the production of numerous frazil ice under water as well as on the water surface. We could observe that the production of underwater frazil ice vigorously proceeded.

The rate of this rapid frazil ice production is compared with that of sheet ice growth

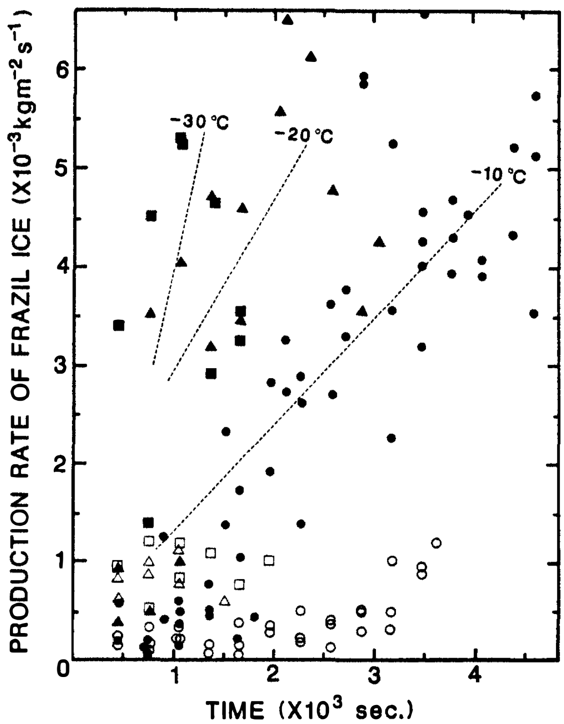


Fig. 5. Rate of ice production per unit open water area at various wind speeds and room temperatures. Closed symbols indicate the case for the strongest wind (6.0 m/s), open symbols the weakest wind (2.2 m/s); circles, room temperature −10°C; triangles, −20°C; squares, −30°C.

Table 1. Comparison of the ice production rate.

Rate of ice production ($\times 10^{-3}$ kg m^{-2} s^{-1})		
Sheet ice		Frazil ice
(Arctic)	1.20	—
(Antarctic)	1.26	—
(Lake Saroma)	0.56	—
(Laboratory)	1.31	5~6
[Data from WAKATSUCHI (1983)]		

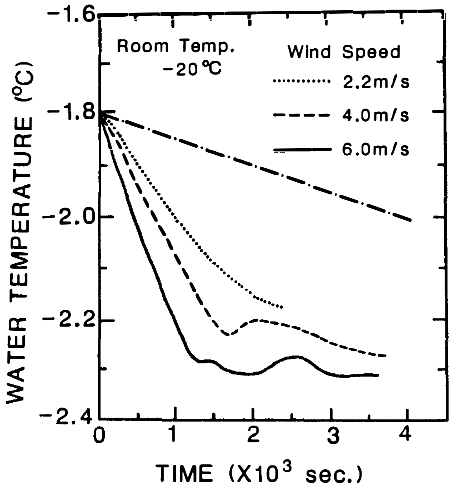


Fig. 6. Variation of water temperature at the point about 30 cm below the frazil ice layer. Dash-dotted line shows the possible maximum lowering of the freezing point.

as shown in Table 1. In the case of sheet ice growth, each production rate was calculated by making use of pure ice density for some cases in which sea ice rapidly grew during the early stage in the field and laboratory as reported before (WAKATSUCHI, 1983). The rate of frazil ice production is about four to five times greater than that of sheet ice growing vertically. Moreover, we should pay attention to the following fact that rapid sheet-ice growth is limited to the early stage when sea ice is thin, but frazil ice continues to produce rapidly while open water exists. So total ice production will increase as compared with sheet ice growth during the same period.

In the next section the factor for the occurrence of the rapid frazil ice production, in particular, underwater ice production, is given.

3.3. On the cooling of the water

Supercooling is necessary for the underwater ice production. In the experiments, we measured the water temperature to examine how the water was cooled. Variation of the water temperature is shown in Fig. 6. This record was taken at the point of about 30 cm below the frazil ice layer with copper-constantan thermocouples. During the experiments, salinization of the underlying water induced by brine exclusion with ice production certainly lowered the freezing point. However, the lowering calculated from the final salinity was less than 0.2 degrees. Therefore Fig. 6 shows that the degree of supercooling increased as time elapsed and as the wind speed increased, and that such a state of supercooling was maintained in spite of vigorous frazil ice production under water. This process can be explained as follows: at the water surface where strong winds blow, both frazil ice production and supercooling of the water occur; the frazil ice crystals which formed on the water surface are swept into the accumulated frazil ice layer by wind-driven current, while supercooled water, which is heavier than the water at its freezing point, falls to the underlayer in the water tank.

3.4. Brine exclusion with frazil ice production

When ice forms in the saline water, brine is excluded. The brine exclusion causes convective mixing in the underlying water because the brine is denser than the surrounding water. The nature of the haline convection caused by the brine exclusion from growing sea-ice sheet has been studied in the laboratory (*e.g.*, FOSTER, 1969; WAKATSUCHI, 1977). In the present experiments we used the Schlieren optical system to observe the behavior of the excluded brine from frazil ice production. The appearances of the brine were as follows. First, in the open water surface, most brine excluded by frazil ice production did not fall into water there, but was transported with the ice crystals downwind near the surface by the wind-driven current. And the brine transported with the ice downwind fell vigorously mixing with the surrounding water near the edge of accumulated frazil ice layer. Second, under water, the falling brine separated from the frazil ice crystal rising upward and eventually mixed with the surrounding water. Third, in the region of the accumulated frazil ice layer, dense water which filled interstices between ice crystals fell by the instability in density, as innumerable ice crystals are crowded within the layer by the buoyancy effect. The dense water has slightly higher salinity (32.0 to 33.0 per mill) than that of original salt water. The dense water may be not only brine newly excluded within the layer but also that transported and trapped into the layer.

4. Concluding Remarks

The processes of rapid frazil ice production in a wind-generated open water were experimentally examined with a water tank. The present study showed that the rate of frazil ice production increased with increasing wind speed and with falling air temperature. Numerous frazil ice crystals were rapidly produced under water as well as on the water surface. The rate of frazil ice production was about four to five times greater than that of sheet ice growth under calm conditions. We can suppose that total ice production will increase as compared with sheet ice growth during such a limited period as winter. In the process of the rapid ice production, the wind blowing over the water surface contributed to the maintenance of supercooling state which is necessary for the underwater ice production. From the observation of the convection phenomena by using the Schlieren optical system, it was also suggested that salt flux to the underlying water due to frazil ice production would be much greater than that for the case of sheet ice growth and that convective mixing in the water should vigorously occur.

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