THE CAUSE OF THE BREAKUP OF FAST ICE ON MARCH 18, 1980 NEAR SYOWA STATION, EAST ANTARCTICA

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Abstract: The complete breakup of the fast ice around Ongul Islands occurred on March 18, 1980. This rare event gave rise to the disaster of the loss of two airplanes moored on ice near Syowa Station. The breakup is caused by the action of swell originating from a wind-blown open sea under a strong depression. The necessary wave height for the breakup of ice plates into pieces less than 100 m length is computed from a theory based on the concept that fracture takes place when an ice plate suffers a critical strain in bending by the passage of swell under it. The critical strain is defined as the strain at which a crack of certain length at the bottom of an ice plate begin to propagate and it can be determined by both the experimentally obtained material constant K_{Ic} (fracture toughness of sea ice) and the dimension of a crack.

The computed wave height necessary to break an ice plate 1 m thick under 12 s wave period is approximately 40 cm and this coincides well with observed wave height in the tide-gauge record at Syowa Station on the day of the event. Wave analyses carried out from meteorological data obtained at Syowa Station and by satellite imagery indicate that the swell damped a little on the open sea but very much in ice-covered sea as the wave height decreased from several meters to several tens of centimeter after traveling 10 or 20 km.

1. Introduction

In the early morning of March 18, 1980, the 21st Japanese Antarctic Research Expedition (JARE-21) at Syowa Station encountered the serious disaster of losing its two airplanes moored on the coastal sea ice owing to sudden complete breakup of the surrounding fast ice. One of them (Cessna) sunk in water when the broken ice plate on which it was moored turned over near the Station. However, the other, a Pilatus Porter (PC-6), remained on a comparatively large ice plate which fortunately drifted back to the west side of East Ongul Island and was recovered by a helicopter from the U.S.S.R. research vessel SOMOV on March 26.

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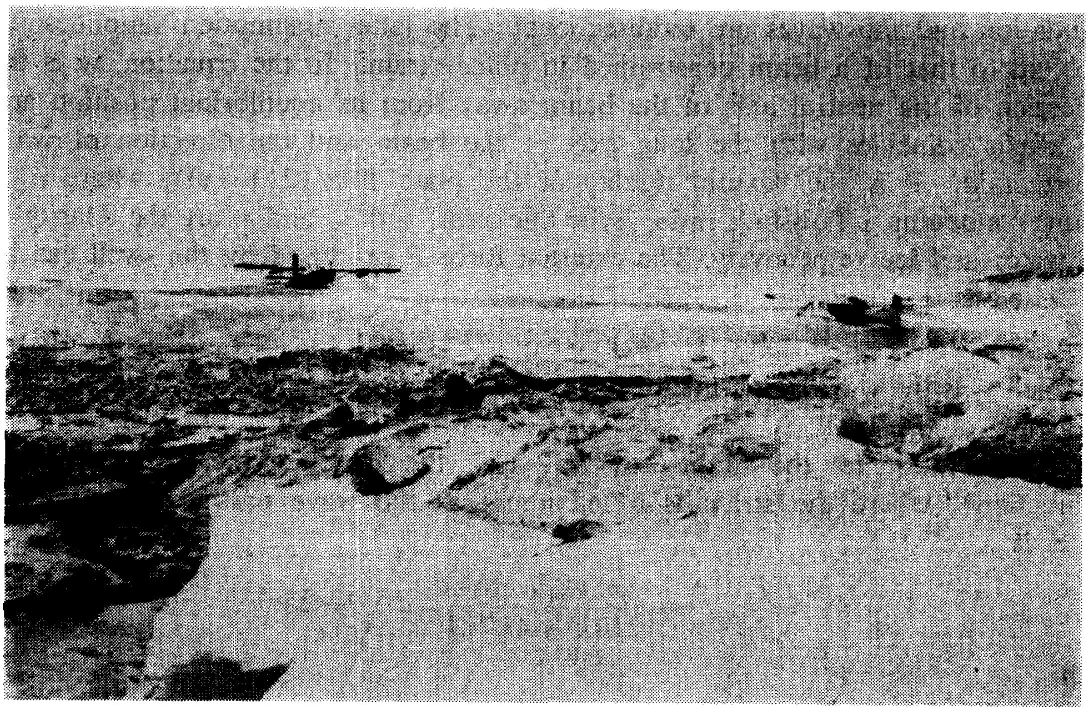

Fig. 1. Photograph of two airplanes on broken sea ice, Pilatus Porter left and Cessna right, looking northeast from Syowa Station (courtesy S. KOBAYASHI).

Continuous fast ice approximately 1 m thick used for a runway for a long time completely broke into pieces of which average length was less than 100 m (see Fig. 1).

This paper considers the cause of this breakup of the fast ice which extended around Ongul Islands by the action of swell originating in an area of strong wind over nearby open sea. The swell is a train of dissipating waves generated in a fetch area where wind waves are growing in height under influence of a strong depression. The swell-induced fracture theory of floating ice sheets in oceans was presented by one of the authors (GOODMAN *et al.*, 1980) with an application to tabular ice islands in the Greenland Sea. The theory is based upon an idea that a floating ice plates in ocean fractures when it suffers a critical strain in bending caused by passage of the swell under it. The critical strain is defined as the strain at which cracks of certain length in ice at the bottom surface of an ice plate can propagate readily due to stress concentration around them.

2. Theory

The bending strain induced in an ice sheet in response to the action of swell can be obtained by solving the equation of motion of ice plates as follows with an external force produced by the swell.

$$D\frac{\partial^4 w}{\partial x^4}+\rho_w g w+\rho_i h\frac{\partial^2 w}{\partial t^2}=P(x,\ t)\ . \tag{1}$$

This equation was derived from the general form of the equation of motion of elastic plates under the assumptions that the water behaves as a perfectly elastic foundation and the waves are unidirectional. The latter assumption simplifies the problem to that of a beam constrained in plane strain. In the equation, w is the deflection of the neutral axis of the beam away from its equilibrium position and the x-axis coincides with the long axis of the beam and the direction of wave propagation. D is the flexural rigidity of the plate $Eh^3/12(1-\nu^2)$, where E is Young's modulus, ν Poisson's ratio, h the thickness, and ρ_w and ρ_i are the density of sea water and ice respectively. The external force P produced by the swell can be expressed as

$$P(x,\ t)=\rho_w g y_0 \cdot \exp\,[i(kx-\omega t)]\,, \tag{2}$$

in which y_0 is the wave amplitude of the swell, k the wave number and ω the angular frequency of the swell.

The solution for the strain at $x=l/2$ (l is the length of the ice plate in the x-direction), where the strain is a maximum as the wave passes under the ice plate, is

$$\varepsilon\left(\frac{l}{2},\ t\right)=\frac{y_0\rho_w g k_0{}^2 h \cos\omega t}{2D(k^4+4k'^4)\Delta}[\Delta-\theta-\Sigma] \tag{3}$$

with

$$\Delta=(\sin k'l+\sinh k'l)/2\,,\quad k'=[(\rho_w g-\rho_i h\omega^2)/4D]^{-1/4}\,,$$
$$\theta=\cos(kl/2)[\sin(k'l/2)\cosh(k'l/2)+\cos(k'l/2)\sinh(k'l/2)]$$

and

$$\Sigma=\frac{k}{k'}\sin(kl/2)\sin(k'l/2)\sinh(k'l/2).$$

The critical strain ε_c at which the cracks in a solid begin to propagate is determined by the following equation,

$$\varepsilon_c=K_{Ic}\frac{1}{\Omega\sqrt{\pi c}}\ \frac{1-\nu^2}{E}, \tag{4}$$

where K_{Ic} is the fracture toughness (stress intensity factor) of the solid, c the crack length and Ω a numerical factor near unity. K_{Ic}, a measure of the stress concentration near a crack, was determined experimentally for sea ice to be approximately 80 kN m$^{-3/2}$ (URABE *et al.*, 1980). Since the value of $E/(1-\nu^2)$ is approximately 6 GN m^{-2} for sea ice, the critical strain for sea ice with $c=10$ mm is calculated as

$$\varepsilon_c{}^{\text{sea ice}}=8.0\times10^{-5}. \tag{5}$$

The crack length c is taken to be 10 mm, the usual grain size of the sea ice.

From eq.(3), we can obtain ε/y_0, the strain/amplitude ratio, as a function of various parameters such as the length and the thickness of the ice plate, and the angular frequency (or the period) of the swell. When the ice thickness and the swell period are fixed, the ε/y_0 can be expressed as a function of the length of the ice floe, as shown by the curves in Fig. 2. If the critical strain as calculated in eq.(5) is inserted, the wave height (twice the wave amplitude) with which the center bottom crack of 10 mm length begin to propagate can be obtained as in the scale of the right hand ordinate of Fig. 2. With this scale, the curves give the criterion of the stability of a floating ice plate when it is subjected to the swell:

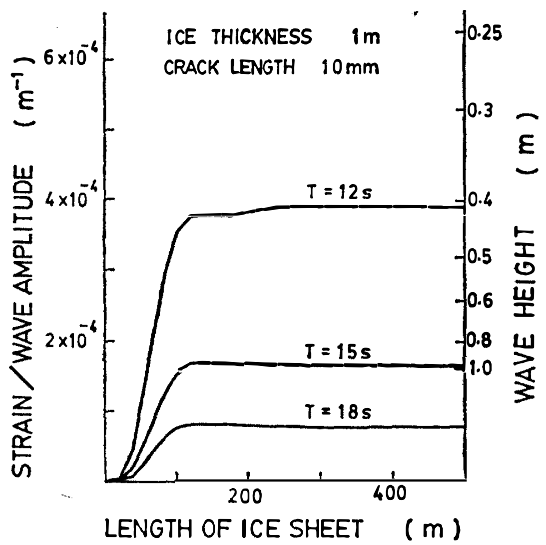

Fig. 2. Theoretical prediction of the strain/(wave amplitude), and wave height required to propagate a 10 mm crack for an ice plate 1 m thick as a function of length.

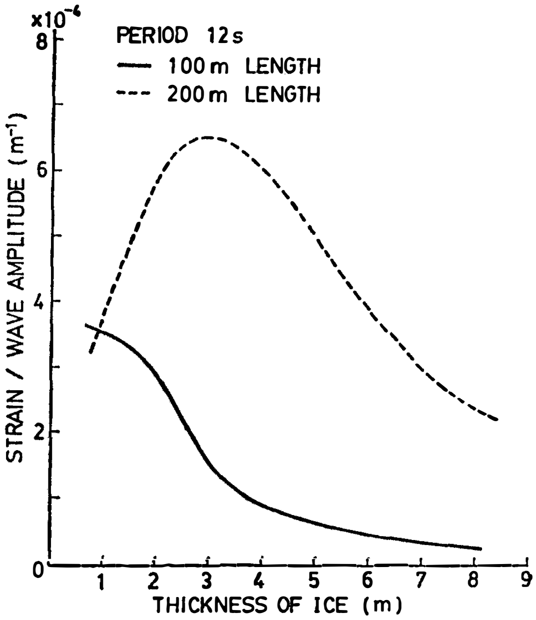

Fig. 3. Theoretical prediction of the strain/(wave amplitude) required to propagate a 10 mm crack for an ice plate of different thickness under action of swell of 12 s period.

the region above the curve is stable and below it unstable. For example, a 1 m thick ice plate of length over approximately 100 m should be broken in the pieces under the action of swell of 40 cm wave height if it has a period of 12 s, although it is stable in swell of the same wave height but of period of 15 s. However, an ice sheet over 120 m length should break when it is vibrated by swell of 50 cm wave height with the same period. It should be noted that the criterion is quite sensitive to the period.

Observations by the tide-gauge at Syowa Station indicated that the period of the swell on the day before and on March 18 was between 8 and 15 s. Therefore, the curve for 12 s period in Fig. 2 can be well utilized for the present analysis. The criterion in Fig. 2 indicates that if the swell with wave height of more than 40 cm arrives at the outer edge of fast ice or penetrates into an ice floe of 1 m thickness, the fast ice should begin to break into length below 100 m. Such disintergrated ice plates can be easily blown away to the open sea by wind action.

When the swell period and the length of the plate are fixed, the relationships between ε/y_0 and the ice thickness in eq.(3) can be drawn as Fig. 3. Although curves for $l=100$ m and 200 m are different, the ε/y_0 value is almost identical at or near 1 m of thickness. Since the actual thickness of the fast ice near Syowa Station just before the event was approximately 1 m, the use of 1 m for the ice thickness is appropriate for the present analysis.

3. Wave Amplitude Derived from Meteorological Conditions

Since meteorological data are very limited in the area around Syowa Station, it is a difficult task to estimate the wave height over the open sea at the outer edge of the fast ice at the time when the breakup occurred. The height of waves caused by wind over the ocean can be estimated by a diagram given in the WMO handbook (WMO, 1976). According to this diagram (Fig. 3.1.2 of the above hand-

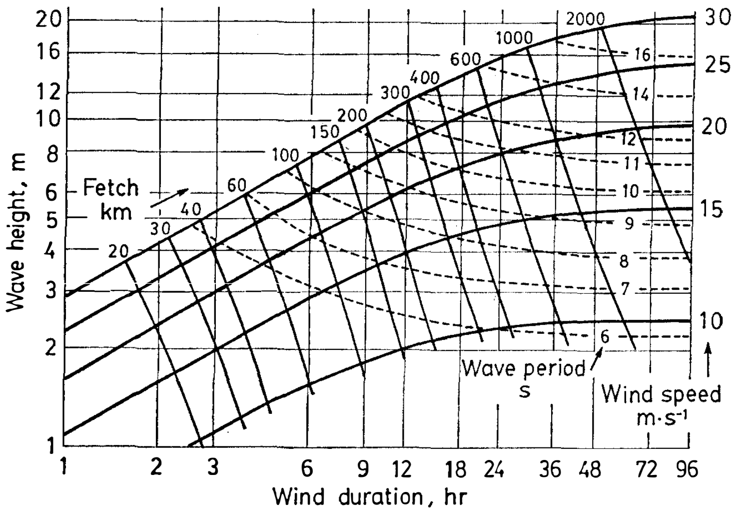

Fig. 4. Wave forecasting diagram (partly reproduced from a handbook of the WMO, 1976).

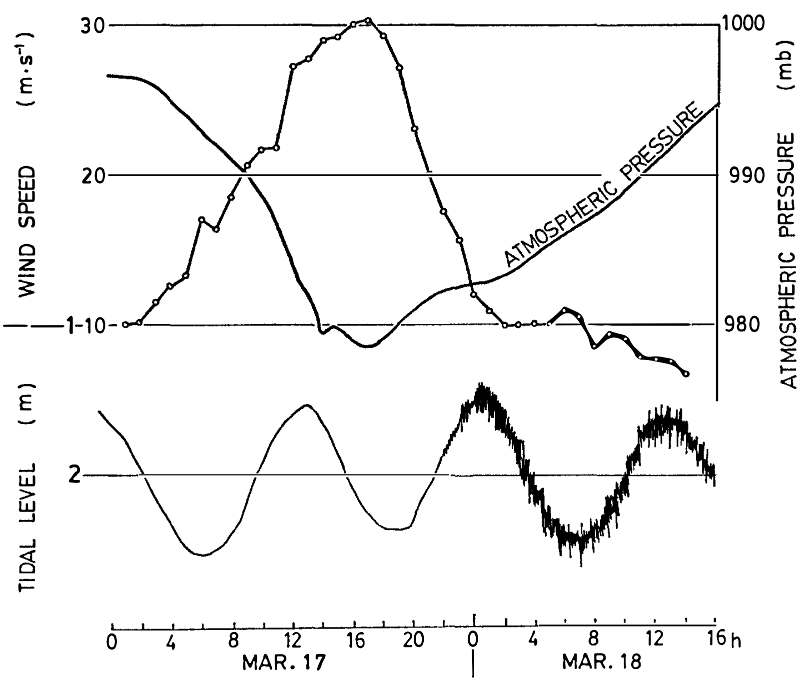

Fig. 5. Meteorological data (atmospheric pressure and wind speed) and tidal record at Syowa Station on March 17 and 18, 1980.

book), the wave height for a particular wind speed can be determined with the duration of wind of this speed or the fetch (length scale of wind-driven sea). Then, the wave period is automatically determined as indicated by broken lines in Fig. 4, which is a reproduction of the relevant part of the original diagram.

Records of the atmospheric pressure and the wind speed observed at Syowa Station on March 17 and 18, 1980 are illustrated in the upper half of Fig. 5. The record indicates that a strong wind which exceeded 20 $m \cdot s^{-1}$ continued for 12 hours. It is very likely that wind of 25 $m \cdot s^{-1}$ continued for 12 hours in the fetch area around the center of a depression. Therefore, Fig. 4 indicates that waves of more than 8 m height were generated in the fetch of approximately 250 km and the wave period was between 10 and 11 s.

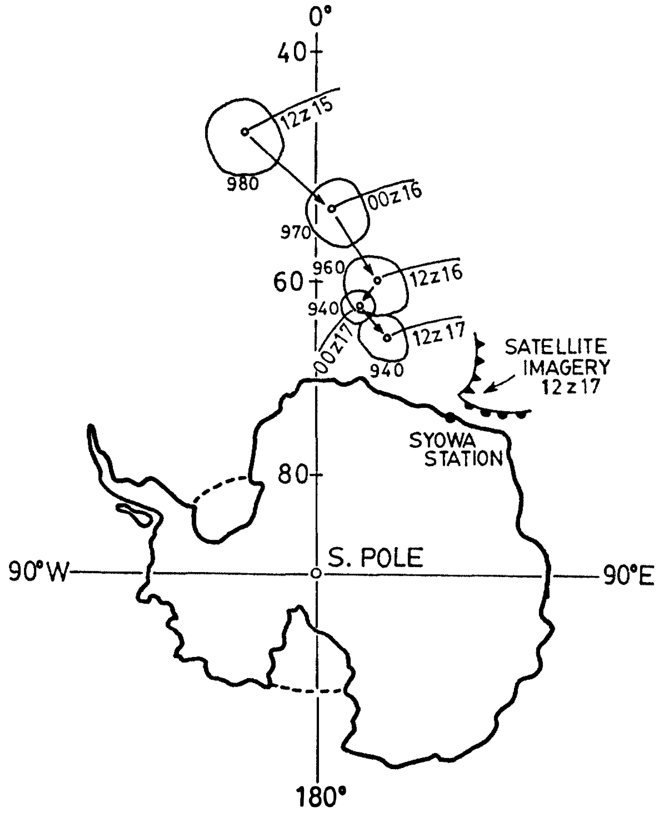

Fig. 6. Trajectory of the depression on the southern hemisphere analysis chart and the position of the depression from satellite imagery (Fig. 7) at 12 Z March 17.

The center of the depression which caused the swell was traced by both the southern hemisphere analysis chart and TIROS-N satellite imagery. The trajectory of the depression is shown in Fig. 6 from the southern hemisphere analysis chart. However, the satellite imagery shown in Fig. 7 revealed that the center of the depression was at approximately 66°S 46°E at 12 Z (1500 LT), March 17, when the wind speed was almost a maximum as shown in Fig. 5. This position is much nearer to Syowa Station than that shown in the chart, only about 400 km from the

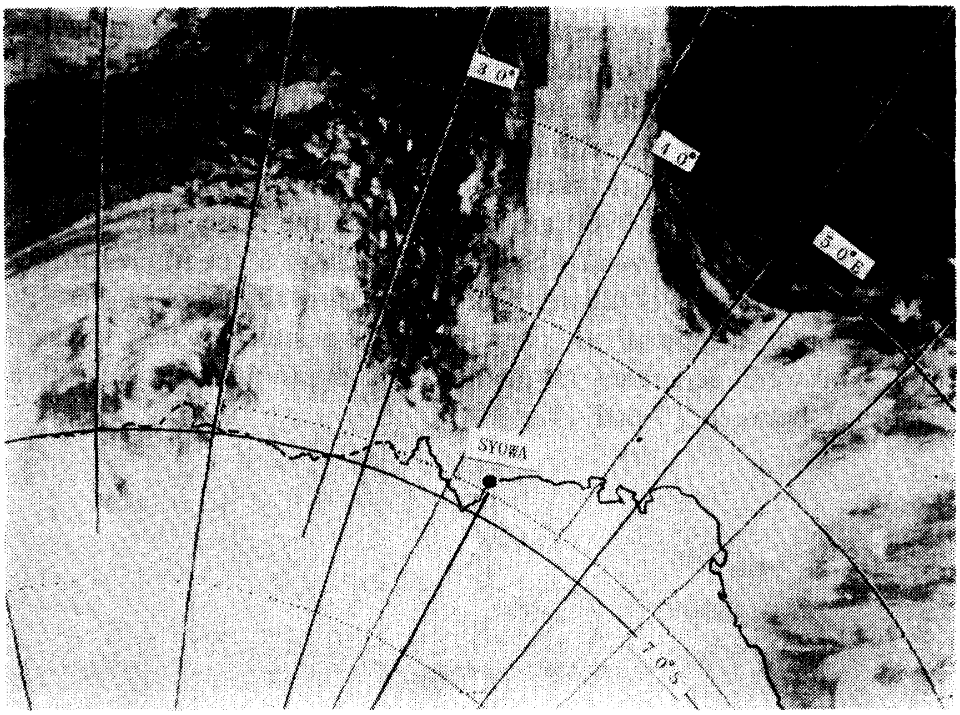

Fig. 7. A TIROS-N imagery near Syowa Station at 1412 Z (1712 LT), March 17. Circles of longitude and latitude are corrected as indicated.

area we are concerned with.

To find the actual height of swell at the outer edge of the fast ice, some 10–20 km north from Ongul Islands, we need at first to apply the angular spreading factor. This factor is related to dissipation of the energy of swell during its travel over open sea. Since the distance of 400 km in the present case is approximately twice the fetch (estimated to be approximately 250 km), the angular spreading factor for the swell energy in the same direction of the wind (prevailing in NE on March 17 at Syowa) is 30%, from Fig. 3.2.4 of the handbook cited above. This means that the wave height was at least 50% of that in the fetch area, approximately 4 m or more in this case. This is more than enough to let ice plates 1 m thick break up into pieces of length less than 50 m when the wave has a 12 s period (see Fig. 2).

When the swell begin to travel into water covered by ice floe, its amplitude should damp more rapidly than over open water. If we assume that the swell energy dissipation in an ice-covered sea occurs in the same manner as in an open sea but with 10 times larger damping factor than that for the latter, the wave height of the swell must be decreased to 10% of that at the edge of the ice pack when the swell travels under ice for a distance equal to the width of ice front perpendicular to the swell direction. Although we do not have exact information on how far the fast ice extended north from Ongul Islands, the width of the north-facing front could be estimated to be in the order of 10 km from such informations as that shown in Fig. 8. Therefore, if the front of the fast ice facing the swell was approximately 10 km from Ongul Islands, the amplitude of the swell under the sea ice near the island must have been damped to 1/10 of the swell amplitude at the

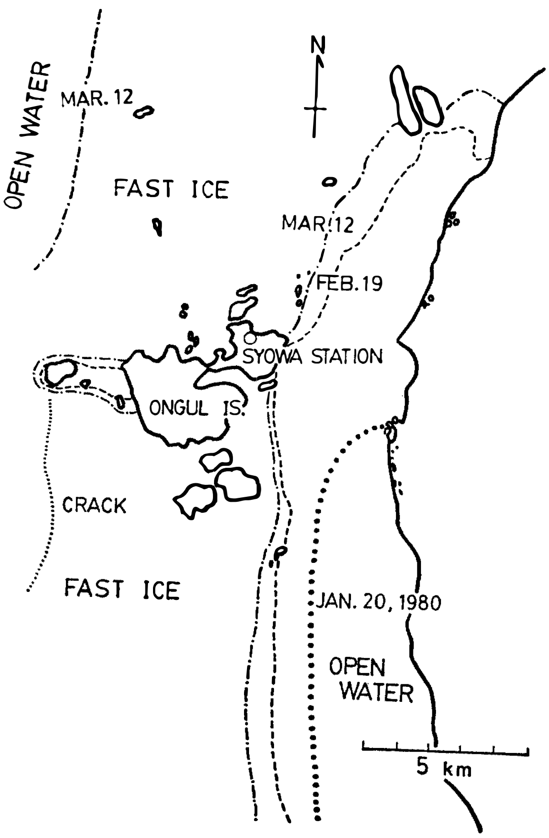

Fig. 8. Variation of the fringe of fast ice around Ongul Islands in February and March 1980.

edge of the fast ice. This estimate of the wave height, on the order of 40 cm coincides well with the necessary wave height to break the 1 m thick ice plate in the pieces of the length less than 100 m. The tide-gauge record at Syowa Station on March 17 and 18 in the lower part of Fig. 5 shows that the water level began to oscillate at 22 h on the 17th and its amplitude reached approximately 20 cm a few hours prior to the event. This value compares favorably with the above-estimated wave height.

4. Discussion and Concluding Remarks

We can now conclude that the disaster which occurred on March 18, 1980 at Syowa Station was caused by the swell-induced flexural failure of the fast ice around Ongul Islands. However, the real process of generation of swell is not so certain as described in the preceding section, because of the lack of exact data about the depression.

In the last section, we estimated the wave height at the edge of the fast ice on the assumption that the swell started from a fetch of which center was 400 km NE of Ongul Islands. However, 400 km was the estimated distance to the center of the depression, and it was found that the fetch extended 250 km from the diagram shown in Fig. 4. Therefore, it is very likely that the dissipation distance for the swell was shorter than 400 km. Since the satellite imagery showed that the depression moved eastward from Princess Ragnhild Coast to offshore of Prince Olav Coast, it is even possible that the outer edge of the fast ice was once in the fetch. Then the real wave height at the edge of the fast ice might be higher than that estimated in the last section. However, this may be compensated for if the damping factor for the wave amplitude in an ice-covered sea is higher than the assumed value. Other, improved, methods can be used for wave analysis if the trajectory and central pressure of a depression are known, but it is still very difficult to obtain such data from meteorological charts in the area of East Antarctica. In any kind of analysis, there remains the problem of determining the damping factor in an ice-covered sea.

In the last 20 years or so since Syowa Station was established in 1957, the fast ice around Ongul Islands extensively drifted away several times after severe storms, but the ice in an area very near to the north shore of East Ongul Island which was often used for a runway for airplanes never broke up until this event. Judging from the topography around the island (Fig. 8), it is conceivable that the swell which gave rise to a complete breakup of the ice in this area invaded straight from the north, breaking the fast ice. However, we cannot determine how long the invasion took to travel the distance of some 10 or 20 km through the fast ice. The complete breakup might have been caused by long duration of the swell as well as by its wave height.

Fracture of the fast ice plate was treated as a problem of the elastic strain criterion for the propagation of a crack of certain length in ice. The critical strain is dependent on the crack length as indicated in eq.(4) but is not very sensitive to it because of the inverse square root proportionality. Therefore, the assumed length of 10 mm can be well justified for expressing the real crack size in a wide range in various ice plates. However, the real process of the fracture may result from fatigue caused by repeated flexural strain due to the action of swell, and this may explain the time required for the breakup which proceeded through the fast ice area.

Nearly complete breakups of the fast ice occurred only in the late austral summer when the fast ice receded in Lützow-Holm Bay. The recession of the fast ice around Ongul Islands in February and March in 1980 is shown in Fig. 8. Precautions against the danger of breakup can be taken if we can predict the speed and duration of wind due to a strong depression approaching the mouth of the bay. Of course, the extent of the fast ice under which swell must travel is an important factor in determining whether this is really a danger or not. Statistical prediction of occurrence of such a complete breakup of the fast ice requires knowledge of how often such a strong storm visits the mouth of Lützow-Holm Bay in late austral summer. Precise investigations of the past weather record in Syowa Station in relation to the ice record are desirable, but the lack of good meteorological charts will limit feasibility of a survey of this kind.

Acknowledgments

We thank Dr. S. KOBAYASHI and other members of JARE-21 who provided us with valuable information, photographs and data. Kind arrangements by Dr. N. W. YOUNG of the Antarctic Division, Australian Department of Science for sending us copies of the southern hemisphere analysis chart are acknowledged.

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(Received May 15, 1982; Revised manuscript received July 12, 1982)