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SEA-ICE RECONNAISSANCE BY RADAR*

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Abstract. To observe the distribution of pack ice off the coast of the Okhotsk Sea coast of Hokkaido, a radar network consisting of three radar stations was constructed during 1967–69. It covers an area about 70 km wide and 250 km long. The stations are remote-controlled by radio from the Sea Ice Research Laboratory and the information obtained is transmitted back to the laboratory and observed there. Radar has the great advantage of being able to make continuous observations of ice. Usually several special features can be seen on the radar screen, and they are used as markers for the observation of movement. It is ascertained that the average pattern of drift in this area is from north to south-east along the coast line and the ice field undergoes internal deformation during its drift. To get some information on the surface topography of ice from A-scope radar, the intensity of echo signals is classified into 16 steps by computer. To obtain the movement of an ice field from the numerical radar information, a modified two-dimensional cross-correlation method was tested.

Résumé. *Reconnaissance par radar de la glace de mer.* Pour observer la distribution de la glace côtière le long de la côte de la mer d'Okhotsk bordant Hokkaido, on a construit en 1967–69 un réseau radar comprenant trois stations. Il couvre une surface d'environ 70 km de large sur 250 km de long. Les stations sont télécontrôlées par radio depuis le laboratoire de recherche sur la glace de mer et les informations obtenues sont retransmises au laboratoire où elles sont observées. Le radar a le grand avantage de pouvoir assurer une observation continue de la glace. D'ordinaire, plusieurs détails spécifiques de forme peuvent être vus sur l'écran radar et on les utilise comme repère pour l'observation du mouvement. On a constaté que la direction moyenne du déplacement dans cette région se produit du nord vers le sud-est le long du rivage et que le champ de glace subit des déformations internes pendant qu'il est poussé. Afin d'avoir quelques informations sur la topographie superficielle de la glace à partir du radar A-scope, les intensités des signaux échos sont divisées en 16 classes par l'ordinateur. Pour obtenir le mouvement d'un champ de glace à partir des données numériques du radar, on a essayé une méthode à corrélations croissées bi-dimensionnelle modifiée.

Zusammenfassung. *Meereiserkundung mit Radar.* Zur Beobachtung der Vertailung des Packeises in der Okhotskischen See vor der Küste von Hokkaido wurde zwischen 1967 und 1969 ein Netz aus 3 Radarstationen eingerichtet. Es erfasst ein Gebiet von etwa 70 km Breite und 250 km Länge. Die Geräte sind durch Radiosignale von SIRL aus ferngesteuert; die Signale werden zu SIRL übertragen und dort beobachtet. Radar hat den grossen Vorteil der Möglichkeit zur durchgehenden Beobachtung von Eis. Gewöhnlich sind auf dem Radarschirm einige besondere Erscheinungen sichtbar, die als Festpunkte für die Beobachtung der Bewegung dienen. Es ist bekannt, dass die mittlere Eisdrift in diesem Gebiet von Nord nach Südost entlang der Küstenlinie zieht und dass das Eisfeld während dieser Drift innere Deformationen erleidet. Zur Gewinnung einiger Informationen über die Oberflächentopographie des Eises aus dem A-Bereich des Radar wird die Intensität der Echosignale durch einen Rechner in 16 Schritte eingeteilt. Zur Bestimmung der Bewegung eines Eisfeldes aus den digitalisierten Radardaten wurde eine modifizierte zweidimensionale Kreuzkorrelationsmethode erprobt.

Introduction

The Okhotsk Sea coast of Hokkaido, the northernmost island of Japan, is covered with sea ice approximately from the beginning of January to the end of March. The maximum thickness of flat shore-fast ice in this area is about 50 cm. The height of hummocked ice sometimes reaches more than three metres above sea-level.

In order to observe in detail the distribution of pack ice off the coast of the Okhotsk Sea and to carry out basic research on its movement, the author constructed a radar network during 1967–69 (Tabata, 1969, 1972[a], [b], [c]). It consists of three radar stations, installed on the mountain tops along the coast in Esashi, Mombetsu, and Abashiri; the radar stations are called by the names of these locations for instance, Esashi radar. The heights of antennas are 440 m, 300 m, and 200 m above sea-level and the radii of actual coverage are approximately 80, 70, and 60 km respectively. The sea area covered by the total system is about 70 km in width and 250 km in length along the north-eastern coast of Hokkaido. The radar stations are remotely controlled by radio from the Sea Ice Research Laboratory (SIRL) in downtown Mombetsu, part of the Institute of Low Temperature Science, and the information obtained is transmitted back by radio to SIRL.

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This land-based radar network has the shortcoming of affording only a limited coverage. However, it has the fully compensating advantage of being able to provide continuous observations of ice distribution or movement.

Specification of radar

When pack ice is distributed over a wider area than the spread of antenna beams, and the cross-section σ of a target increases in proportion to the distance R, the receiver power P_2 will be expressed by the so-called radar equation:

$$P_2 = \frac{P_1 G^2 \lambda^2}{(4\pi)^3 R^3} \frac{\sigma_0}{R_0} \left(2 \sin \frac{2\pi h_1 h_2}{\lambda R}\right)^4,$$

where P_1 is the transmitted power of the radar, G the power gain of the antenna, λ the wavelength, R the distance to the target, σ_0 the scattering cross-section of the target at the distance R_0, h_1 and h_2 the heights of the antenna and target from sea-level respectively.

The frequency of the radar wave used was 5 540 MHz; this frequency is nearly the same as that of a normal weather radar. Considering the maintenance benefit, we chose a relatively small output, 40 kW, and a high antenna gain, 39 dB. The antenna is the cage type, 4.0 m in diameter and 1.3 m in height. The actual beam width was 1° in horizontal and 3° in vertical. Because the height of sea ice is very small as compared with that of the radar antenna, the effective distance mainly depends upon the height of the antenna. As the theoretically expected maximum coverage for pack ice of our radar network is about 90 km, the repeating frequency was fixed as 1 kHz for a pulse width of 1.0 μs. The radar had two pulse widths, 1.0 and 0.2 μs. The pulse width has a close relationship with the sensitivity and effective coverage. As seen in Figure 1, we could have a more detailed picture with a narrow pulse width than with a wide one. However, because the repeating frequency of the former

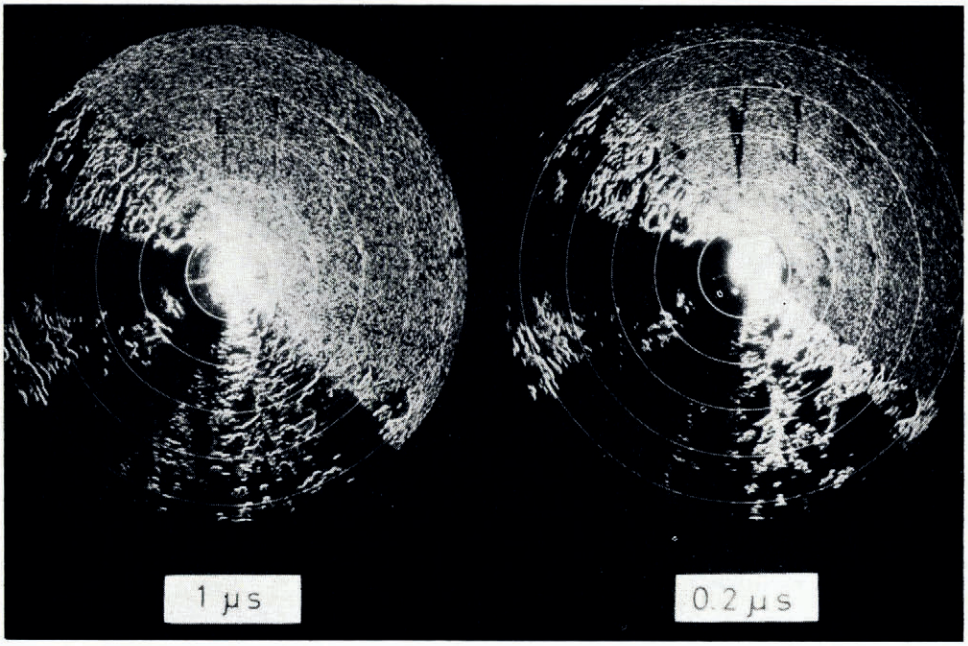

Fig. 1. Radar images observed with two different pulse widths, 0.2 and 1.0 μs. Coverage is 10 nautical miles (18.5 km).

was 2 kHz, its effective coverage was reduced to less than half of the latter. The minimum receiver power of the radar system was -100 dB m. Observed σ_0 at $R_0 = 10$ km was 0.24–0.76 m².

For remote control a VHF radio signal in the 70 MHz band was used; the radar information obtained was transmitted back to SIRL by a radar relay system in the 7 GHz band.

Each unmanned radar station on a mountain had a monitor with a 10 inch (25 cm) screen. Observations were usually made using the two screens of the main indicator at SIRL. It was constructed as a console table incorporating a 16 inch (40 cm) screen. The two screens showed the same picture. Since the two screens of the main indicator pick up only one radar station, they were switched to the desired station whenever necessary so as to obtain the pack ice information from that station. A 35 mm still camera and a 16 mm movie camera were used to photograph a radar screen. The cameras were operated automatically or manually to take successive pictures of a screen at a desired time interval. The sketching of an ice–water boundary on a translucent sheet of paper attached to the screen was another effective method.

A small electronic computer was introduced in 1972 to process the radar information so that an interpretation of the surface topography of ice was provided.

Observation of the movement

In the radar image of pack ice, several distinctive features were always seen. They were, for instance, black spots (polynyas), bright spots (very high pressure ridges) and special features of the ice–water boundaries, etc. Some of these features conserved their characteristics

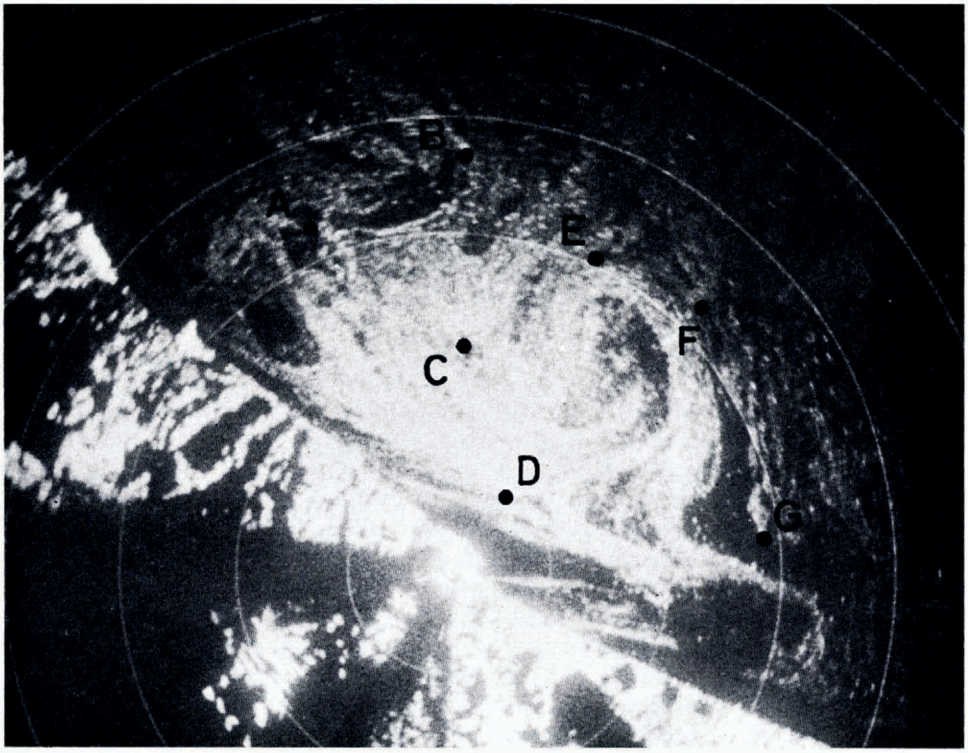

Fig. 2. Pack ice distribution off Mombetsu (05.20 h, 25 February 1973). Circles are located every 5 nautical miles (9.1 km).

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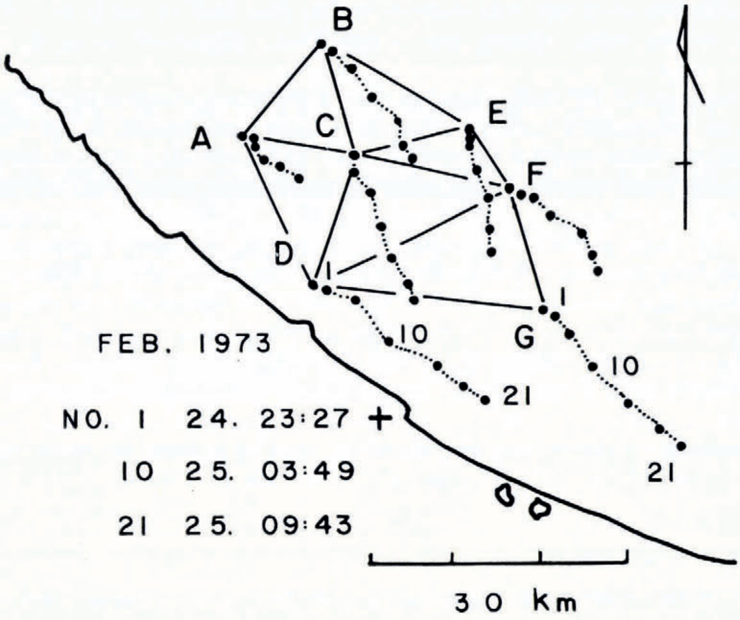

Fig. 3. Movement of pack ice off Mombetsu (25 February 1973).

for a considerable time interval, sometimes several days, so well that we could easily identify them in successive photographs of the radar screens taken at suitable time intervals. Hence, using these features as landmarks, we could easily study the movement of an ice field.

From observations of this movement on calm days when wind effects were negligible, it was estimated that in this area a sea current generally runs from north-west to south-east in winter, that is, parallel to the coast line, with an average speed of about 0.5 km/h (Tabata, 1970).

The prevailing seasonal wind in winter is north-westerly; hence the ice fields generally move from north-west to south-east along the coastal line. The drift speed was 0.5–2.5 km/h, giving a wind factor of 0.01–0.08. Though the wind factor varied through such a wide range, it was found that changes of the drift speed were rather sensitive to changes of wind speed (Tabata, 1970).

Figure 2 shows an ice pattern observed by Mombetsu radar at 05.20 h, 25 February 1973. The white pattern in the upper right portion is pack ice and the black area is open water or polynyas. It is clear from the picture that the ice undergoes a turbulent movement.

Seven landmarks as seen in the figure were selected for a movement study. Their positions were traced every 30 min during 10 h; they are shown in Figure 3. As seen in the figure, as a whole, ice was drifting south-eastward along the coast line; this is the average pattern of drift in this area. However, the velocity of movement of each landmark was different from the others, showing that the ice field underwent internal deformation during its drift. The average speed of all landmarks was 1.7 km/h. The minimum and the maximum drift speeds were observed in landmarks A and D and were 1.1 and 2.3 km/h respectively. During the measurement, the wind velocity observed at the Mombetsu meteorological observatory was 1.0 to 4.8 m/s, the direction was SW before 01.00 h, W before 06.00 h and S until 10.00 h.

The deformation of an ice field could be studied with the aid of a set of three landmarks (Tabata, 1971). Six triangles, as seen in Figure 3, were made by connecting the landmarks with each other. Applying the theory of homogeneous strain, we can obtain the strain of an

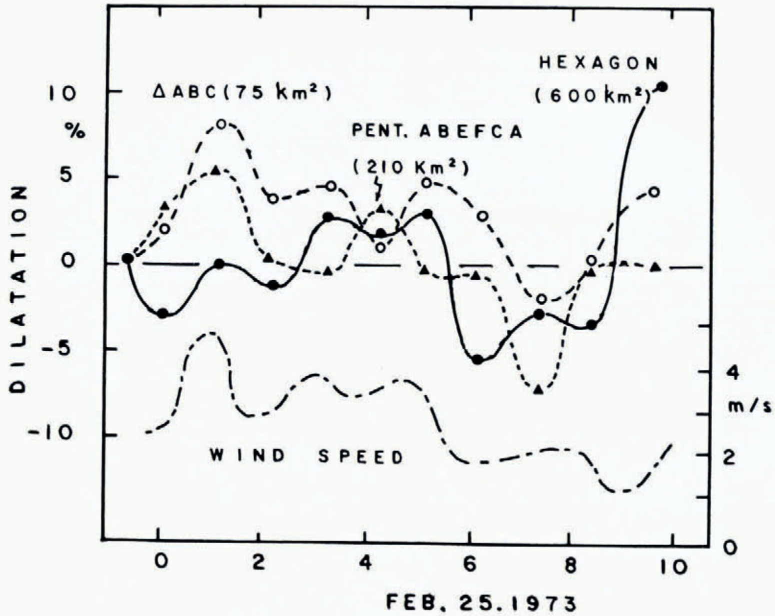

Fig. 4. Dilatations of an ice field in successive hourly deformations off Mombetsu (24–25 February 1973).

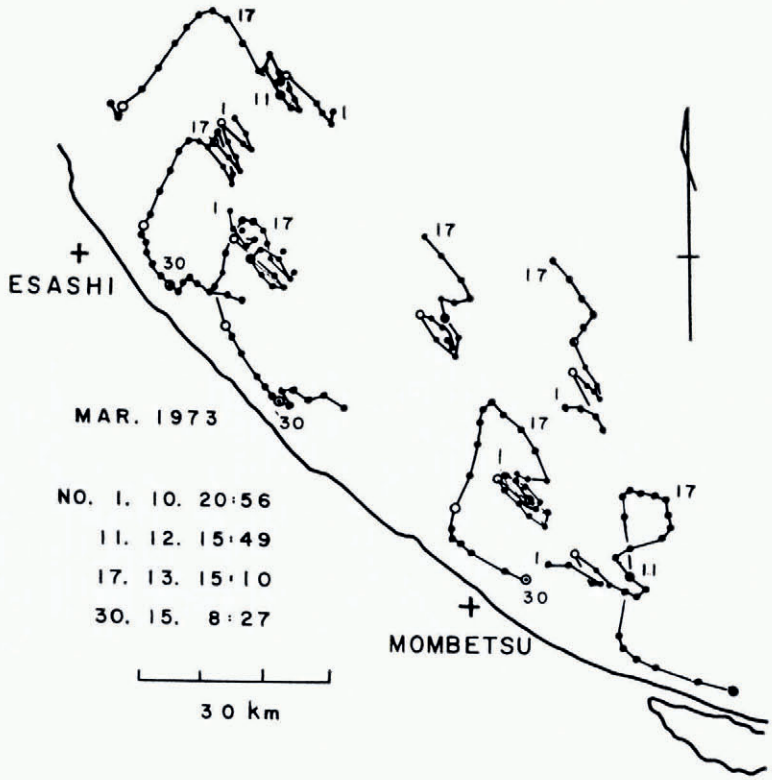

Fig. 5. Movement of pack ice off the Okhotsk Sea coast of Hokkaido (10–15 March 1973).

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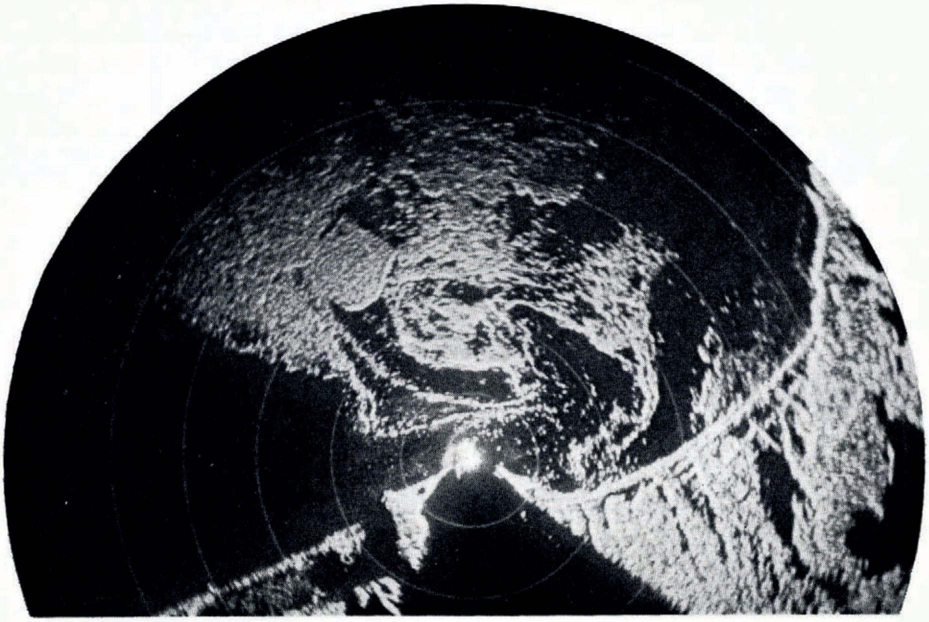

Fig. 6. Pack ice distribution off Abashiri (10.00 h, 5 March 1974).

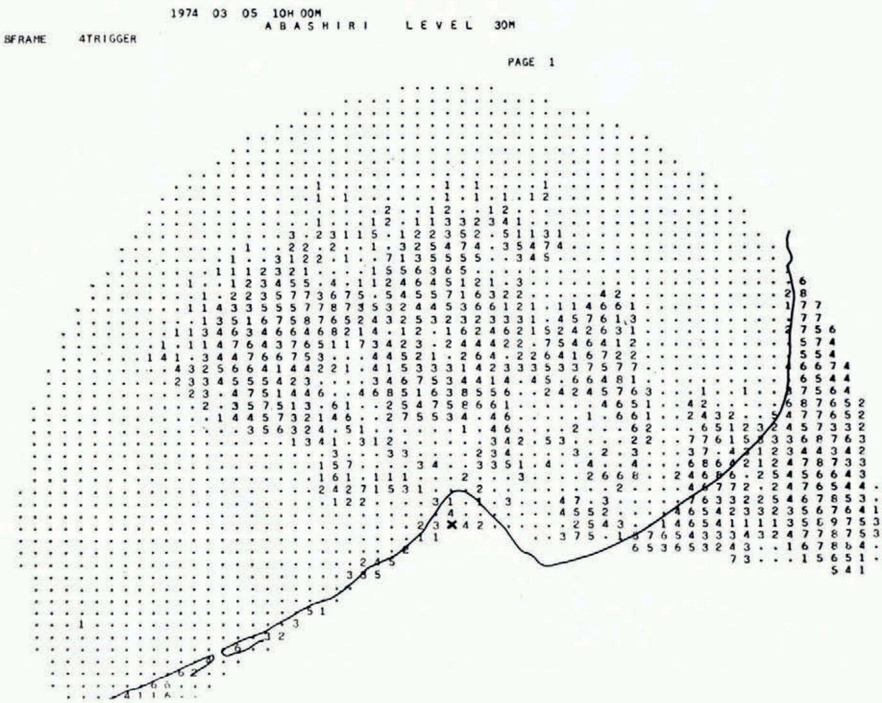

Fig. 7. Computer processed chart from Figure 6.

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ice field from the movement of a set of three landmarks. The obtained strain of an ice field for each set, that is for each triangle seen in Figure 3, showed little correlation with each other. The time sequence of dilatation of triangle ABC (initial area: 75 km²) calculated from the data obtained every hour, and the changes of area of pentagon ABEFCA (initial area: 210 km²) and a hexagon (600 km²) were plotted in Figure 4 along with the wind speed. Though each dilatation (change of area) especially that of the hexagon, shows some correlation with the wind speed, correlations among the dilatations are rather poor, showing that the internal deformation of an ice field varies from place to place and also from time to time and that we must be careful in interpreting the strains obtained from the deformation of triangles.

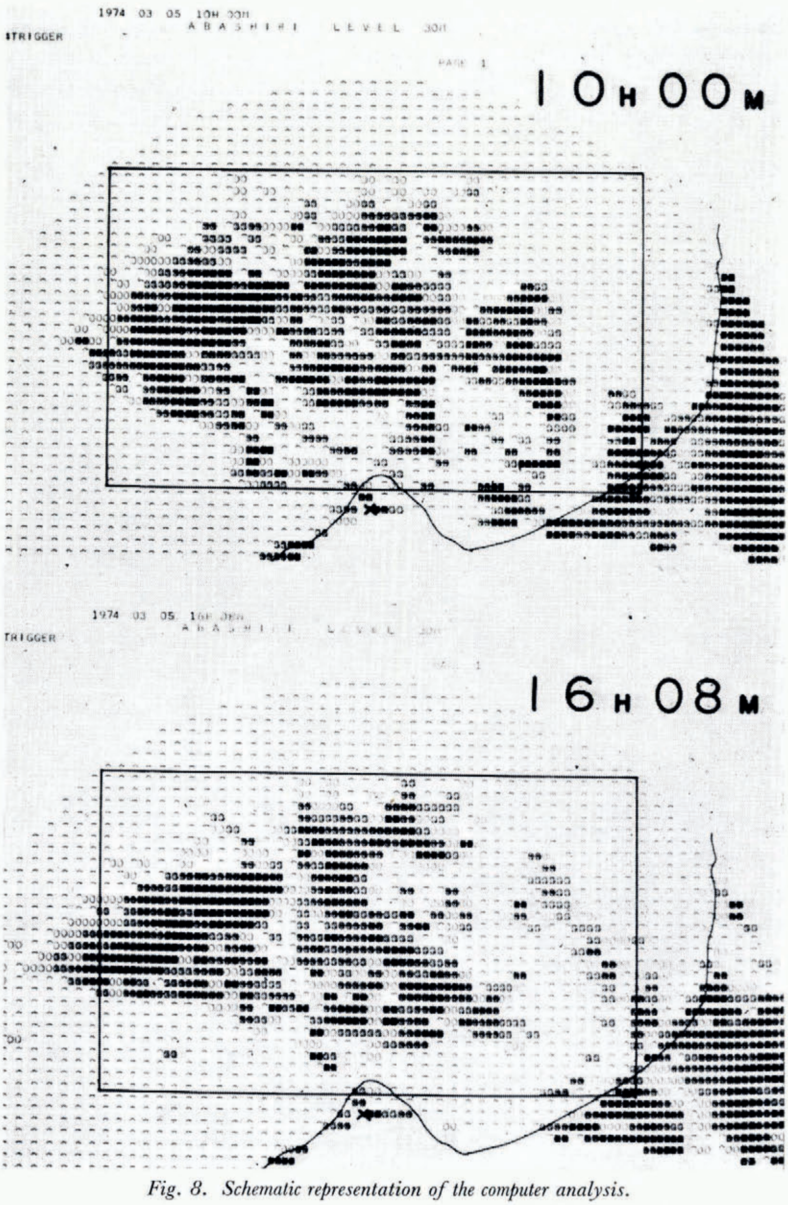

Fig. 8. Schematic representation of the computer analysis.

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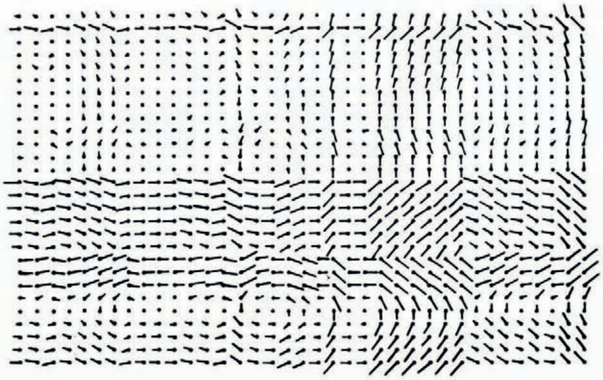
The movement of pack ice shown in Figure 3 is rather simple as compared with that shown in Figure 5, which was observed 10 to 15 March 1973.

The complex movement and violent internal deformation of an ice field are best, and only vividly, seen in time-lapse movies of a radar screen. In 1974, four movies were made: they covered from 8 January to 31 March at Mombetsu radar; from 8 January to 13 March at Abashiri radar; from 21 to 27 February at both Mombetsu and Abashiri radars.

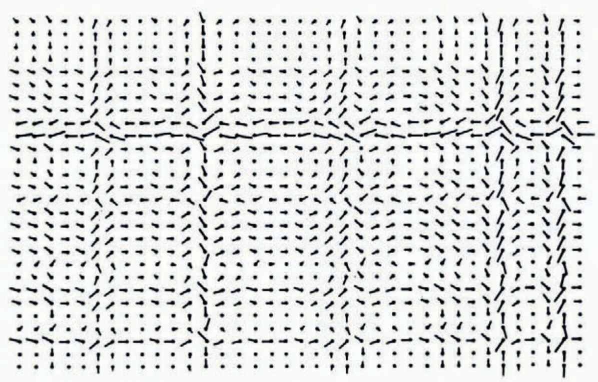
Computer processing of radar information

The complex pattern of deformation of an ice field is probably caused by the local differences of the surface and bottom features of ice-floes as well as by the wind and current patterns. As to the surface features, analyses of an A-scope image seem to give some information on them (Ishida and Ono, 1969; Ishida, 1971). A small computer was installed in 1972 to provide topographical information on ice by processing the A-scope images (Tabata and Ōi, 1972).



(a)

10·00 to 16·08



(b)

16·08 to 20·57

Fig. 9. Movement of pack ice calculated by cross-correlation.

Figure 6 represents an ice distribution off Abashiri observed on 5 March 1974 at 10.00 h; Figure 7 is a computer processed chart, where the intensity of echo signals is classified into eight steps from 1 to 8. These numbers have some correlations with the ice topography. The solid line is the coast line and the total coverage is 30 nautical miles (56 km). The radar station, represented by a "star", is in the center.

In Figure 8, these eight numbers are replaced by eight kinds of graded shade to make the figure more vivid. To show the differences of ice patterns during six hours the pattern obtained at 16.80 h the same day is also shown in the figure. In these figures, the bigger the number, i.e. the darker the shade, the rougher the ice surface.

The movement of ice during these six hours will be obtained from the calculation of the two-dimensional cross-correlation of these patterns (Ishida, 1974). The rectangular part surrounded with a solid line is taken for this calculation; the area is 68 km × 42 km. As a preliminary test and also to avoid a difficulty in calculating the two-dimensional cross-correlation, we calculated the cross-correlation of a horizontal line of the two rectangles from Figure 8. The lag which shows the maximum value of correlation may be assumed to be the displacement of ice along this line. Such a displacement was calculated along each line. Next, in the vertical direction to the line, the displacement along each column was calculated.

The vector summation made at each intersection shows the movement of the ice field during six hours and is seen in Figure 9(a). The movement of ice in the following period from 16.08 to 20.57 h obtained in the same way is shown in Figure 9(b). This is just a preliminary test to calculate the movement of an ice field from the digitized radar information. Although much elaboration is necessary, the method of two-dimensional cross-correlation may be one of the most useful for obtaining ice movement.

Acknowledgements

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REFERENCES

Ishida, T. 1971. Ryūhyō kansoku rēdā no jōhō no sūchika [Data processing of sea ice radar]. *Teion-kagaku: Low Temperature Science*, Ser. A, [No.] 29, p. 185–89.

Ishida, T. 1974. Mensōkanhō ni yoru sogunpyō no ryūdō-bekutoru no keisan [Calculation of flow vector of open pack ice by two-dimensional correlation method]. *Teion-kagaku: Low Temperature Science*, Ser. A, [No.] 32, p. 221–28.

Ishida, T., *and* Ono, N. 1969. Ryūhyō jōkyō to rēdā-zō to no taiō [On the correlation of sea ice construction to radar pattern]. *Teion-kagaku: Low Temperature Science*, Ser. A, [No.] 27, p. 317–25.

Tabata, T. 1970. Rēdā ni yoru ryūhyō kansoku. II [Observations of drift ice movement by the sea ice radar network. II]. *Teion-kagaku: Low Temperature Science*, Ser. A, [No.] 28, p. 301–10.

Tabata, T. 1971. Hokkaidō-engan no ryūhyōya no hizumi no sokutei [Measurements of strain of ice field off the [Okhotsk Sea] coast of Hokkaidō]. *Teion-kagaku: Low Temperature Science*, Ser. A, [No.] 29, p. 199–211.

Tabata, T. 1972[a]. Observations of deformation and movement of ice field with the sea ice radar network. (*In* Karlsson, T., *ed. Sea ice. Proceedings of an international conference. . . . Reykjavík, Iceland, May 10–13, 1971.* Reykjavík, National Research Council, p. 72–79.)

Tabata, T. 1972[b]. Radar network for drift ice observation in Hokkaido. (*In* Karlsson, T., *ed. Sea ice. Proceedings of an international conference. . . . Reykjavík, Iceland, May 10–13, 1971.* Reykjavík, National Research Council, p. 67–71.)

Tabata, T. 1972[c]. Sea ice reconnaissance with the radar. Means of acquisition and communication of ocean data. *Report on Marine Science Affairs*, No. 7, p. 67–75. (WMO Publication 350.)

Tabata, T., *and* Ōi, M. 1972. Ryūhyō kansoku rēdā zyōho shori sōchi ni tsuite [Data processing system of sea ice radar]. *Teion-kagaku: Low Temperature Science*, Ser. A, [No.] 30, p. 175–81.

Tabata, T., *and others*. 1969. Rēdā ni yoru ryūhyō no ugoki no kansoku [Observations on the movement of drift ice with the sea ice radar]. [By] T. Tabata, M. Aota, M. Ōi [and] M. Ishikawa. *Teion-kagaku: Low Temperature Science*, Ser. A, [No.] 27, p. 295–315.

DISCUSSION

W. F. WEEKS: Please comment on your present understanding of the appreciable coastal current near your radar stations. How does it affect your analysis of the drift information as collected by the radar array?

T. TABATA: Analysis of ice movement on a calm day shows the existence of a current running south-eastward at 0.3–0.5 knots (0.6–0.7 km h^{-1}). This current is limited to 10–20 km off the coast. It is believed to be a principal cause of anti-clockwise ice movement. However, much more information about the current is required for a full understanding of this point.

T. HUGHES: Were the clouds in your film low enough for cloud velocity vectors to be used to calculate a wind-stress field over the sea ice that could be compared with ice deformation?

TABATA: In our film the cloud movement is usually one-dimensional, while ice movement is usually two-dimensional. Therefore the cloud velocity vector could only be useful in special cases.