Summary of Drift Ice in the Okhotsk Sea*

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Abstract

Owing to the dominance of cold northerly winds in winter and to the thinness of the thermohaline convection layer in the sea due to the very low saline surface water in the northwestern half of the Okhotsk Sea, ice formation begins at its northwestern corner roughly in the middle of November. As the season advances, the ice area extends southeastwards reaching the northern tip of Sakhalin around the beginning of December, then southward along the east coast of the island. It usually reaches one of its southern tips at the end of the month and in the middle of January it reaches the northeast coast of Hokkaido, at the southernmost corner of the sea.

Such southward extending of ice coverage in the western region of the sea is facilitated by the combined action of the persistent northerly wind and a notable flow of the low saline surface water in the same direction, namely the East Sakhalin Current. In other words, the current carries southward not only the ice-forming water of low salinity but also carries a large amount of icefloes with a mean thickness of 1 m. These movements are further accelerated southward by the action of northerly winds.

After reaching its maximum extent over a greater part of the sea around early April, the ice coverage gradually recedes toward the northwestern corner owing to the warming of both the air and surface water in spring.

These figures on ice behaviour are summarized under some oceanographical considerations using available ice data from surface, from air and from space.

I. Introduction

Every winter an enormous amount of sea ice is formed on a greater part of the Okhotsk Sea and develops to slightly over 1 m in mean thickness by the severe winter climate from the cold Siberian continent which acts upon the sea having a markable flow pattern and on a broad expanse of low saline surface water. Because of the existence of ice drift in a cyclonic way along its surrounding coasts, especially along the east coast of Sakhalin, a strong packing of drift ice occurs in the southwestern region of the sea. This is accompanied by heavy pressure ices which scene is superficially like the ones in the polar regions, in spite of the fact that this region is situated around 45°N latitude.

In spite of such a striking ice phenomena, only an incomplete picture of the extend of ice was available for the whole region of this sea until several years ago, because ice data were confined mostly to the coastal areas. However, our knowledge on the Okhotsk Sea ice-cover is gradually increasing through aerial ice reconnaissance, which however

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is still confined to the Hokkaido area. Our highest gain on ice data comes from recently developed meteorological satellites covering the whole region of the sea. Here, the present author has attempted to summarize a general profile of the drift ice in the Okhotsk Sea using available ice data.

II. Sea Conditions and Climatic Situations Related to the Ice Formation and the Ice Drift

In the surface layer of the Okhotsk Sea, there is a broad extension of the very low saline water as illustrated in Fig. 1 which plays the main role in ice formation and distribution. The mean extent of the low saline surface water for the warmer season in the left chart of the figure is made by spacially averaging iso-lines of 18.0‰ in chlorinity observed in 9 summer seasons from July through to September during 1935 to 1965 (Watanabe, 1966). The one in the right chart for the cooler season is drawn in a reasonable assumption from oceanographic data in the southern half region of the sea which were obtained in the late autumns of 1936, 63, 64 and 65, and the ones in the larger portion of the sea were obtained during 6 springs from 1937 through to 1965. The fact that a noticiable variation in the flow pattern in the sourthern Okhotsk Sea usually in late autumn every year was taken into account (Watanabe, 1963 a, b). The

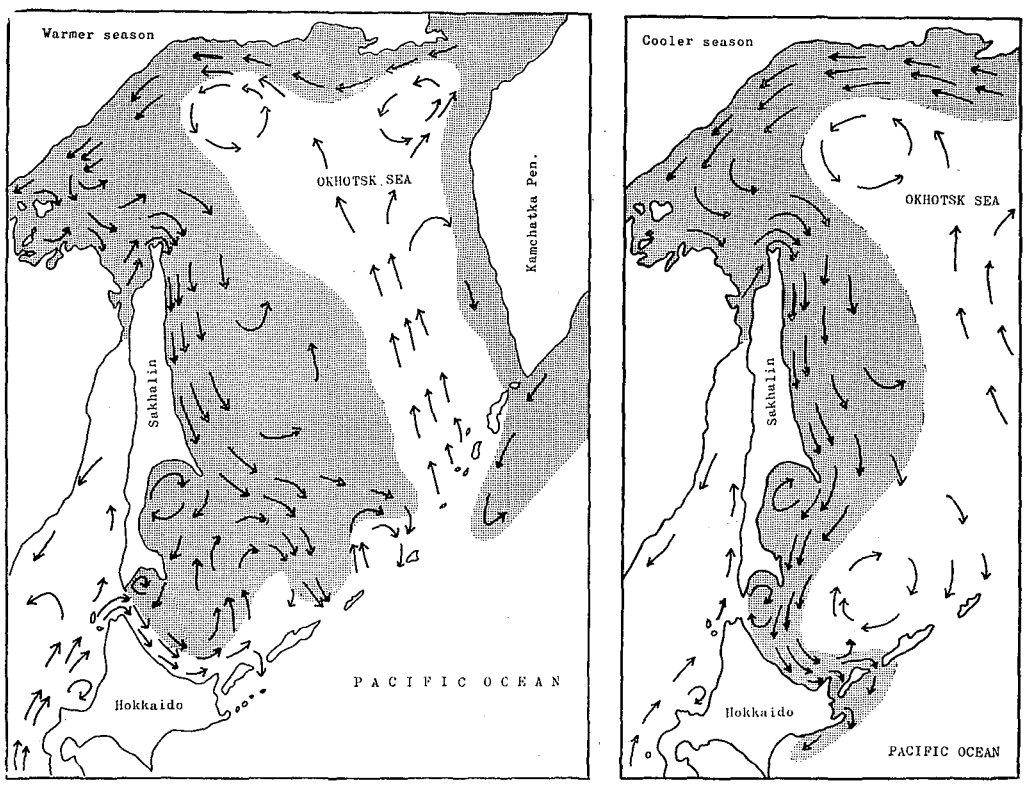
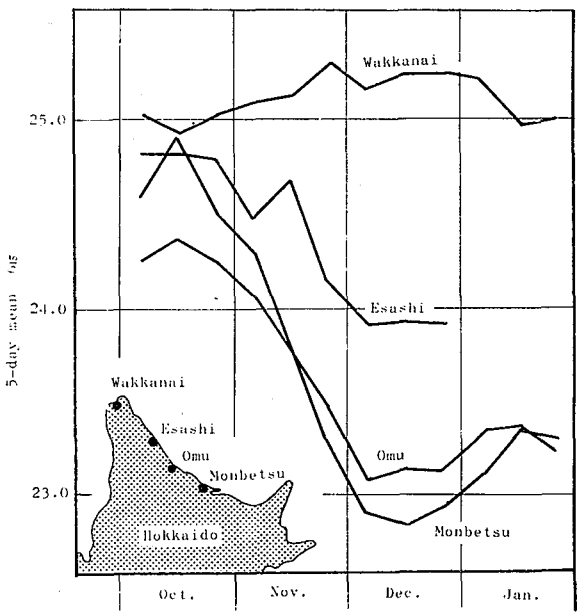


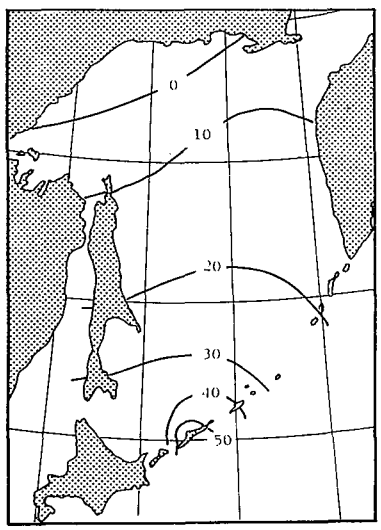
Fig. 1. Mean extent of low saline surface water (shaded areas) less than 18.0‰ in chlorinity and current systems (with small arrows) for the warmer (left) and the cooler (right) seasons

flow patterns schematically shown by small arrows in these charts are extrapolated from the extending patterns of the low saline surface water mentioned above, together with other oceanographic data including that by GEK. In the left chart for the warmer season the flow pattern in the northern half is roughly copied from that presented in the text book by Leonov (1960).

In the warmer season the very low saline surface water widely extends over the central region of the sea along the East Sakhalin Current which flows southward along the east coast of the island turning to a still easterly direction near central Sakhalin and then towards the central Kurile Islands and further partly back to the north. This mixes with a more saline water flowing in from the Pacific through the straits of the northern Kurile Islands. Most of the low saline surface water widely extending over the southern Okhotsk Sea is that coming from the melting ice in the previous season. It also includes a small part suppled by a weak branch of the East Sakhalin Current (Watanabe, 1966). Though the low saline surface water reaches to about 20 nautical miles off Hokkaido, a strong sea current of higher temperature and higher saline water which is the end flow of the Tsushima Warm Current flowing up in the Japan Sea, runs closely along the northeast coast of Hokkaido. This turns northward and extends up towards the central region to about 48°N parallel in summer mixing with the low saline surface water. Such an inflow of the Tsushima Warm Current and the northward extension of the higher temperature and higher saline water are completely cut off by an intensified southward flow of the East Sakhaline Current at about the end of autumn.



(a)



Mean precipitation (mm) for February after A. K. Leonov (1960)

(b)

Fig. 2. Left: Five-day mean water density at four coastal stations averaged for 10 years from 1951 through 1960 except for Mombetsu which has been averaged for 7 years from 1957 through 1961. Right: Mean precipitation (mm) over the Okhotsk Sea (after Leonov 1960)

Hence, the E. S. C. flows southward along the whole east coast of Sakhalin reaching the northeast coast of Hokkaido in the cooler season. The E. S. C. carries low saline surface water of easily forming sea ice and also heavy pack-ices both of northern origin. In Fig. 2 a zigzagging curves represent the variation of 5-day mean density (σ_{15}) at four coastal stations on Hokkaido from October through to the succeeding January, where each amount of σ_{15} indicates the one meant for individual 5-day period in these 10 years. Except for Wakkanai on the strait between the northern tip of Hokkaido and one of the southern tips of Sakhalin, the other three curves deeply drop in November clearly illustrating the fact that the low saline surface water reaches the coast precluding the flow-in of the higher saline water of the Tsushima Warm Current from the Japan Sea (Watanabe, 1963 b). Figure 2 b is a chart for mean precipitation (mm) over the Okhotsk Sea in February (after Leonov, 1960) which shows that the deep drop of σ_{15} is not caused by the precipitation in the cooler season, but by the southward flow of the low saline water of northern origin strongly influenced by the Amur River.

The surface layer of the low saline water strongly characterizing the conditions in the western half of the sea is rather thin as seen in Fig. 3, where the vertical section of temperature (°C) and chlorinity (‰) structures at the end of November, 1963 is presented along an observation line crossing the tongue-like protrusion of the low saline

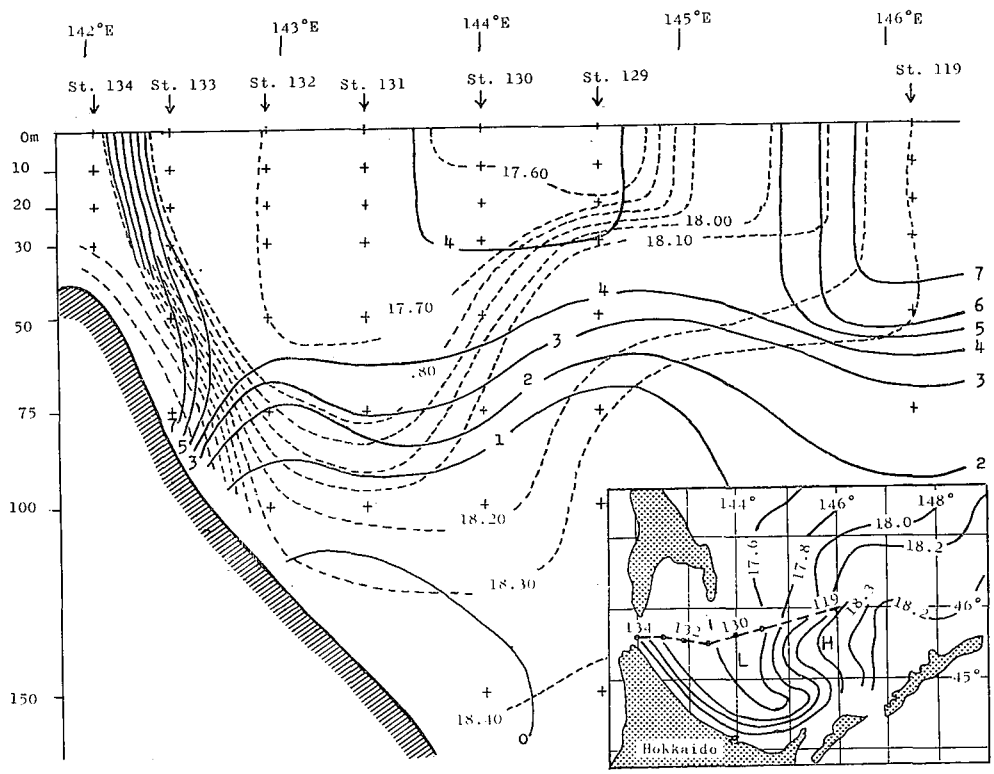


Fig. 3. Vertical structures of water temperature (°C) by solid lines and of chlorinity (‰) by dashed lines along the observation line shown by a broken line in the inserted chart observed at the end of November, 1963. Contour lines in the inserted charts show the surface chlorinoty (‰)

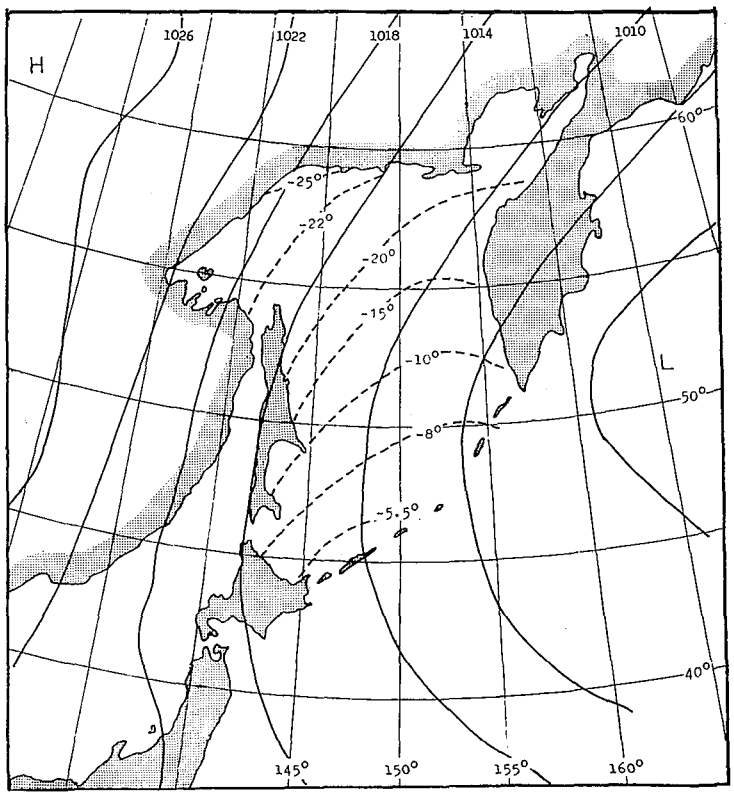


Fig. 4. Mean surface air temperature (°C) in the Okhotsk Sea (after Leonov) and mean atmospheric pressure (mb) at sea level, both for January

surface water shown by a broken line in the inserted chart. Such a thin layer of the low saline surface water is the same as the thermo-haline convection layer which develops in cooler season. Hence, the water in the surface layer is easily cooled to its freezing point under the action of the severe winter climate without reaching the thermo-haline convection layer to the bottom of the sea.

The severity of the winter climate over the Okhotsk Sea is illustrated in Fig. 4, where the mean air temperature (°C) at sea level is copied again from Leonov's text book (1960) and the mean surface pressure pattern (mb) is drawn both for January. As seen in the figure the cold climatic situation over the sea deflects in a northwesterly direction. In other words, there is a persistent and strong northerly wind in the western half of the Okhotsk Sea and the air temperature is much colder there than in the eastern half.

Thus, the sea conditions and climatic situations in cooler seasons are very favorable for the ice formation and the ice drift in the western half of the Okhotsk Sea which are very striking as will be mentioned in the succeeding sections.

III. Behaviour of Ice Cover in Its Advancing Period

There are already two reports on the mean ice limits in the Okhotsk Sea by Weaver (1947) and by Suda (1948) who presented rough patterns made from ice data mostly observed

at coastal stations and a few off-shore observations. Another two reports were made for estimating ice areas in separate months theoretically by Fukutomi (1950), Tabata (1958) and Sawada (1960). Based on these reports we have a general picture of the ice area extending or retreating with time. However, it is too rough to discuss the ice behaviour in the sea, because these reports were made under conditions in which ice data is scanty. Hence, most of our effort were centered on collecting ice data or finding a substitution for actual ice data.

Under such circumstances a trial was made for estimating the ice-forming area, *i.e.* the area where the freezing takes place, using temperature data of the surface water included in the synoptic weather data reported from Russian ships (Watanabe, 1962). Figure 5 is an example of 5-day mean surface water-temperature charts successively

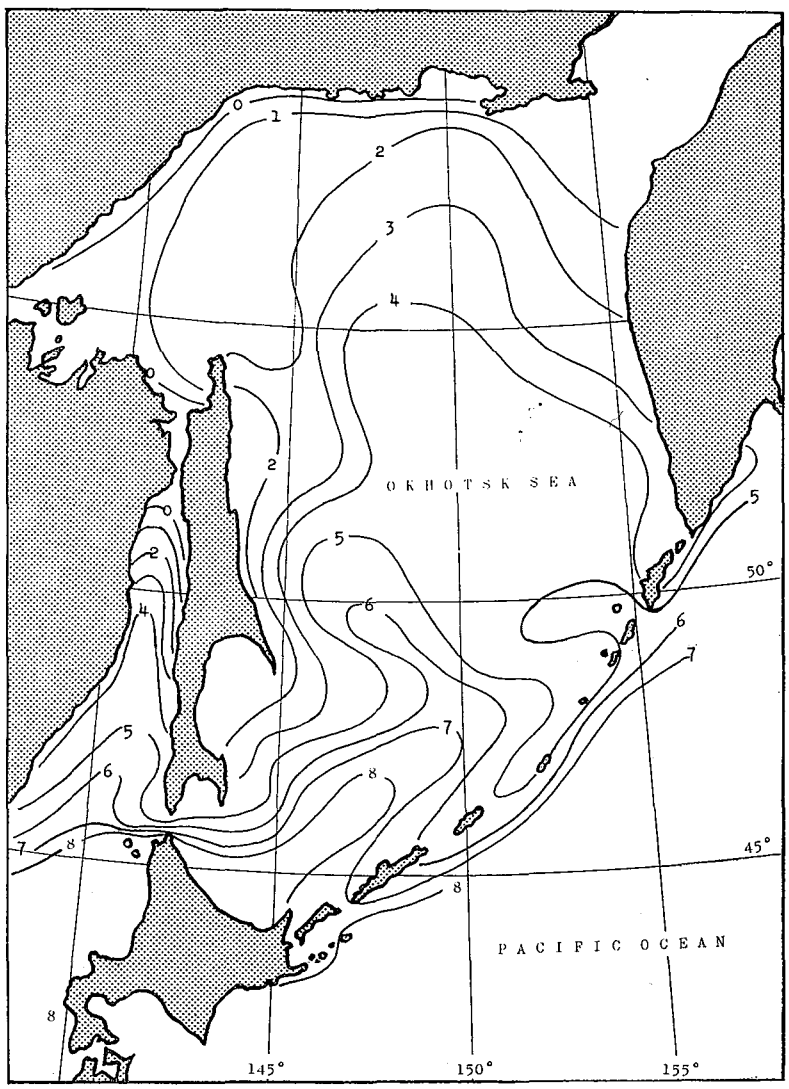


Fig. 5. Surface water temperature (°C), in November 21–25, 1963

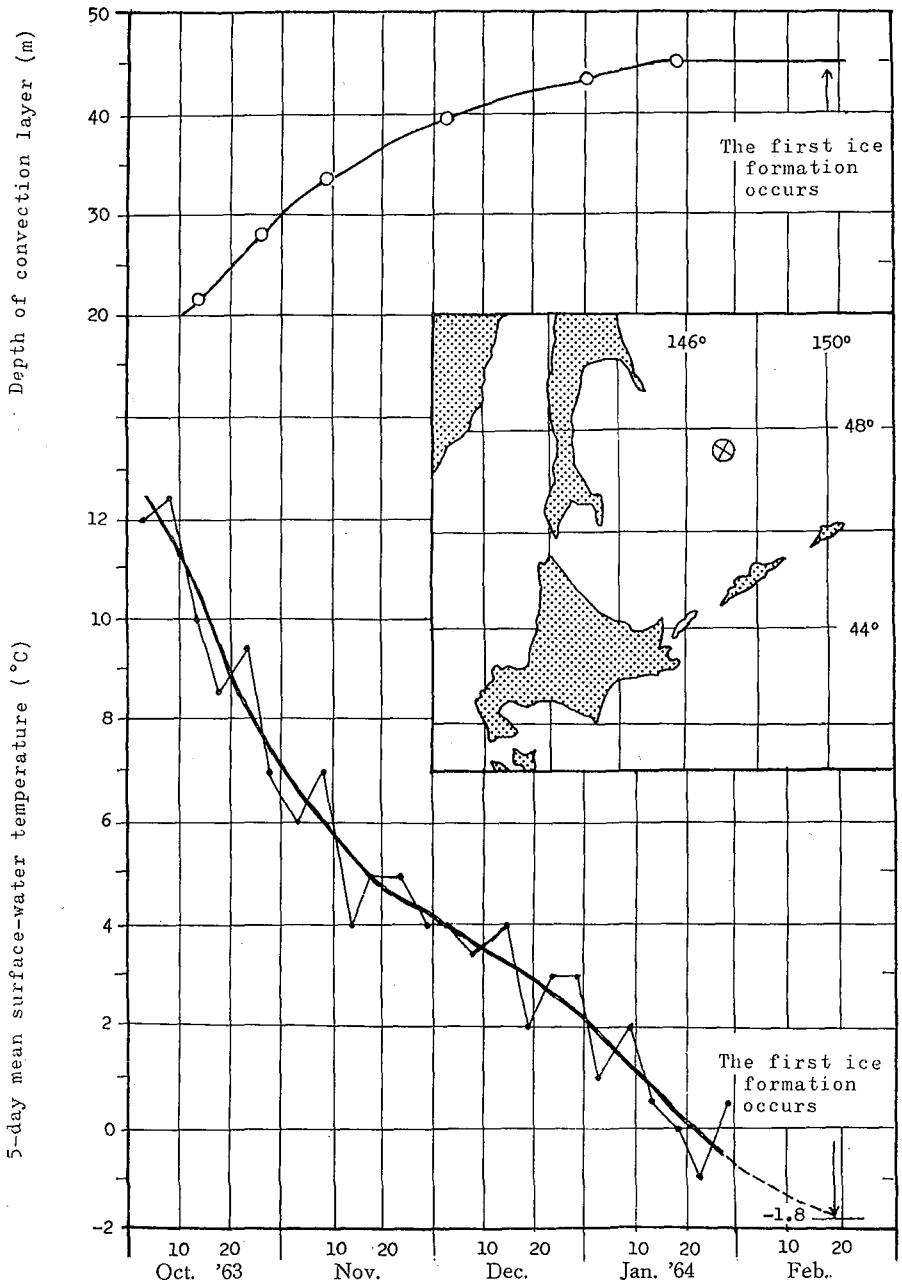


Fig. 6. Five-day mean surface-water temperature from October in 1963 through to January in 1964 shown by a thin zigzagged curve with dots and its smoothed curve by thick line, and the depth (m) of thermo-haline convection layer estimated for the same period (upper), both at the location shown in the inserted chart

made from the reported data referred to above. By means of plotting each amount of the surface water temperature read at adequately selected locations on these charts, we have a zigzagging curve of changing water temperature concerning each location such as given in the example in the lower part of Fig. 6 for the location shown by a circled cross in the inset chart. Though the smoothed curve shown by a thick solid one for the original zigzagging curve ends at around the end of January, 1964 due to the termination of ship's reporting at just the end of January, 1964, we can find the date when the surface water temperature is assumed to have reached its freezing point, about −1.8°C there, by extrapolating the smoothed dropping curve given by a thick broken line. From this we get an estimated date of the first ice-formation which is February 18, 1964 for the location. Such extrapolation is apt to have errors to some degree due to the inaccuracy in the original charts of the 5-day mean surface water temperature as

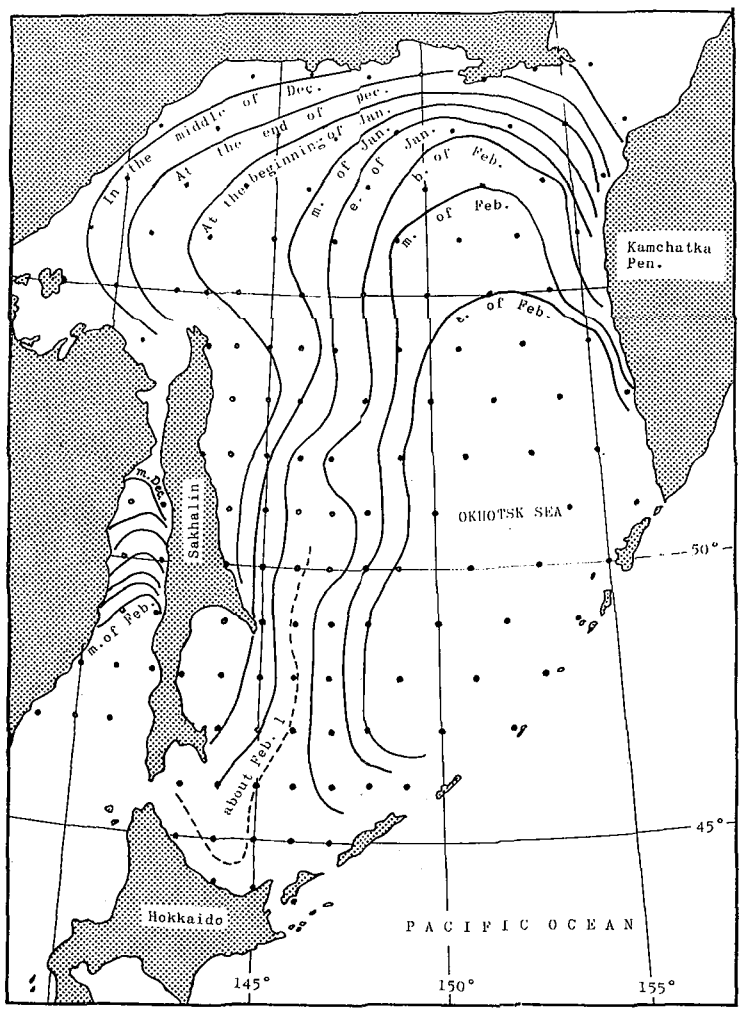


Fig. 7. Distribution of estimated dates of the first ice formation, or estimated ice-forming areas, for the 1963–64 ice season

shown in Fig. 5, but at the same time it is understood not to have such a large error caused by the developing character of the thermo-haline convection layer, when we consider the gradually rising curve of the layer depth seen in the upper part of the figure. The curve is made based on a consideration on depths of the developing thermo-haline convection layer estimated by a graphical method by Zubov (1945, Chapter III. Mixing of ocean water) together with the dropping curve of the surface water-temperature in the figure. Following such a procedure on longitude-latitude grids (dots in Fig. 7), a distribution chart of the first ice-formation dates is made for the ice-advancing period in the 1963–64 ice season as shown in Fig. 7, where each iso-line shows each approximate date of the first ice-formation, or the respective limit of ice-forming area. In the chart it is estimated that at the northwestern corner of the Okhotsk Sea the first ice-formation occurred in the middle of December, 1963, or that in the area between the coast and the first iso-line from the northwest the ice was forming at that time. The estimated ice-forming area extends southward and eastward as the season advances, reaching the northern tip of Sakhalin at about the end of December, 1963 and one of the southern tips of the island in the middle of January, 1964. Then, it touches the northeast coast of Hokkaido at about the beginning of February, 1964, which is half a month late in comparison with its mean date there. Such advancing of ice-forming area for the 1963–64 season was much later than usual winters.

Another effort has been made for collecting ice data for the whole area of the sea by analyzing satellite photographs. Shortly after the launching of the first meteorological satellite, TIROS-I, two ice charts in the Okhotsk Sea in the beginning of April, 1960

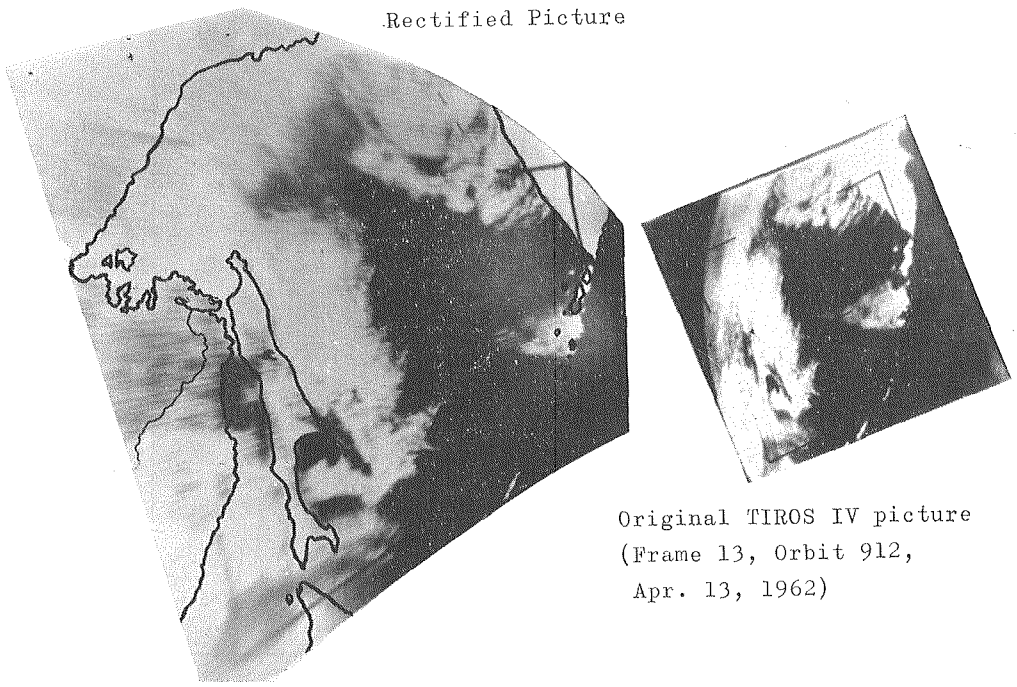


Fig. 8. An example of TIROS pictures (right) and its optically rectified picture (left)

were made from two sheets of TIROS-I photographs with a manual process of wide range photogrammetry (Watanabe, 1960, 1961). Then, after the end of 1964, many photo-charts of sea ice have been made directly from available photographs taken by successively launched TIROS satellites by an optical method of picture rectification (Watanabe, 1965). Figure 8 is an illustration of the method of picture rectification in which each negative picture and each sensitive paper are tilted at a suitable angle and furthermore each paper is bent at a suitable curvature. As seen in the figure a rectified picture made from its orignal one on the right hand appears on the left hand where several land features of Kamchatka Peninsula, Sakharin Island, Kurile Islands, the northern half of Hokkaido, and the coast of Siberia cointides with the map sufficiently well. In this photo-chart the bright area extending along the Siberian coast and along the east coast of Sakhalin is the ice cover on April 13, 1962, and a group of rather complex patterns

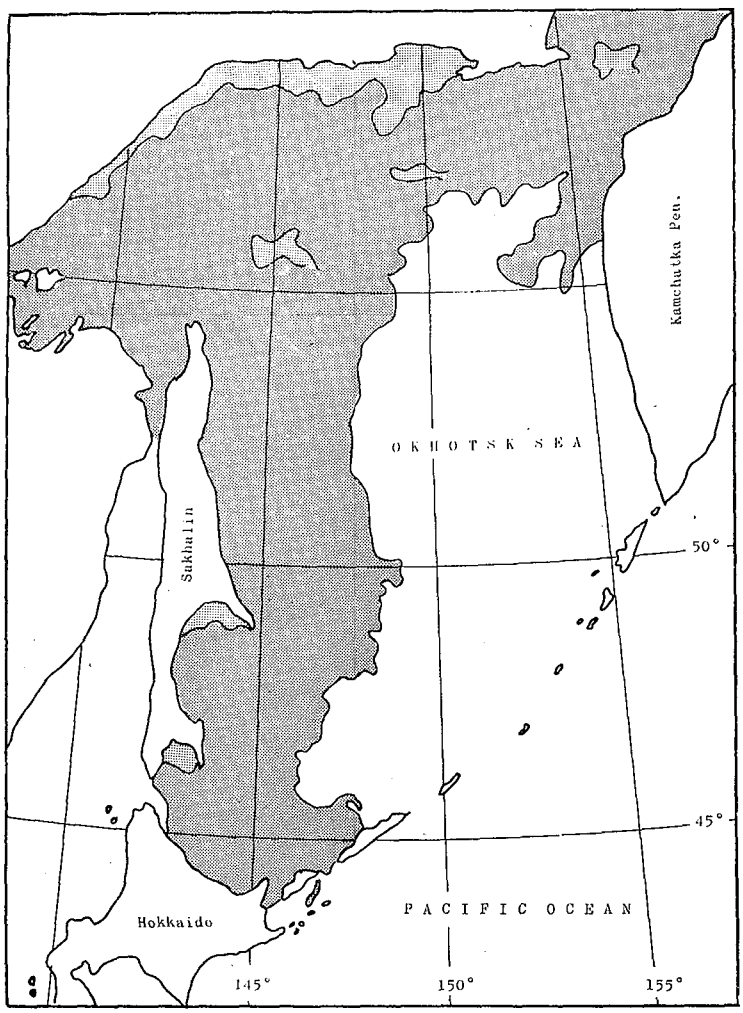


Fig. 9. Ice chart interpreted from rectified pictures taken by TIROS-VII on February 23, 26 and 27, 1964

west off Kamchatka Peninsula are clouds associated with a cyclone, and the small bright patch seen near the northern Kurile Islands is inferred as a sea fog area. The flat bright pattern in the northern Japan Sea is assumed to be a cover of low cloud or sea fog. Such an interpretation of bright areas on satellite pictures is easily made when successively taken pictures in a given short period are available, by defining almost persistently existing bright areas as ice covers in several pictures taken over period of say one week or so. Figure 9 is an ice chart interpreted from TIROS-VII picture taken on February 23, 26 and 27, 1964, where the shaded area shows the ice cover possibly larger than 5/10 in concentration. Such ice data by satellites are incalculably valuable for ice study of course, which are increasingly available since the ESSA-II started this March to send APT pictures every day. In spite of the above there is still a scarcity of ice data at present, especially a marked scarcity is seen in the early ice season before February, most frequently because of bad weather which hinder cruising ships and block

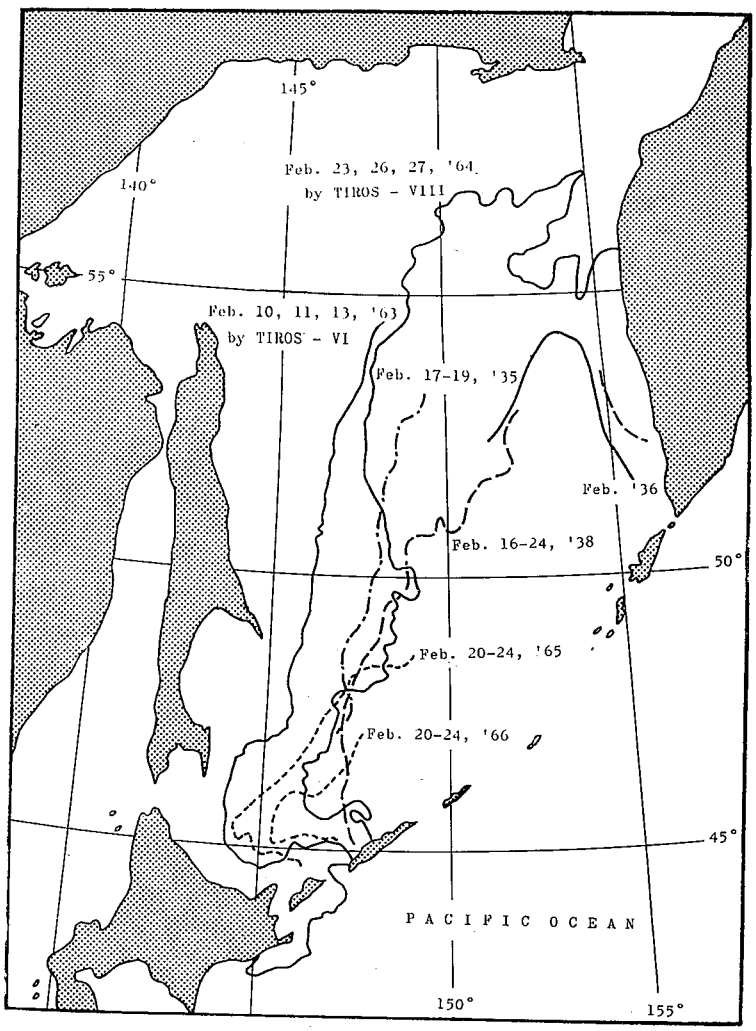


Fig. 10. Available data of ice limits for February

satellite views from space. Under such circumstances the estimated limits of ice-forming areas mentioned before are used for making mean limits of ice area in the early ice season in place of actually observed ice covers, and in the season from February actual ice data by ships and satellites are used. In Fig. 10 are presented all available data of ice limits for February with the exception of a large volume of aerial ice data closely confined to the Hokkaido area, where two ice limits were interpreted from photographs by TIROS-VI and -VII and the other three were observed by ships.

Figure 11 is a chart of mean ice limits in separate periods for the early ice season, where broken lines were made from estimated ice-limits in 6 seasons of 1960-61 through to 1965-66. The solid lines are from actual ice data. In the mean state represented in the figure, we can see that the first ice formation usually occurs at the northwestern

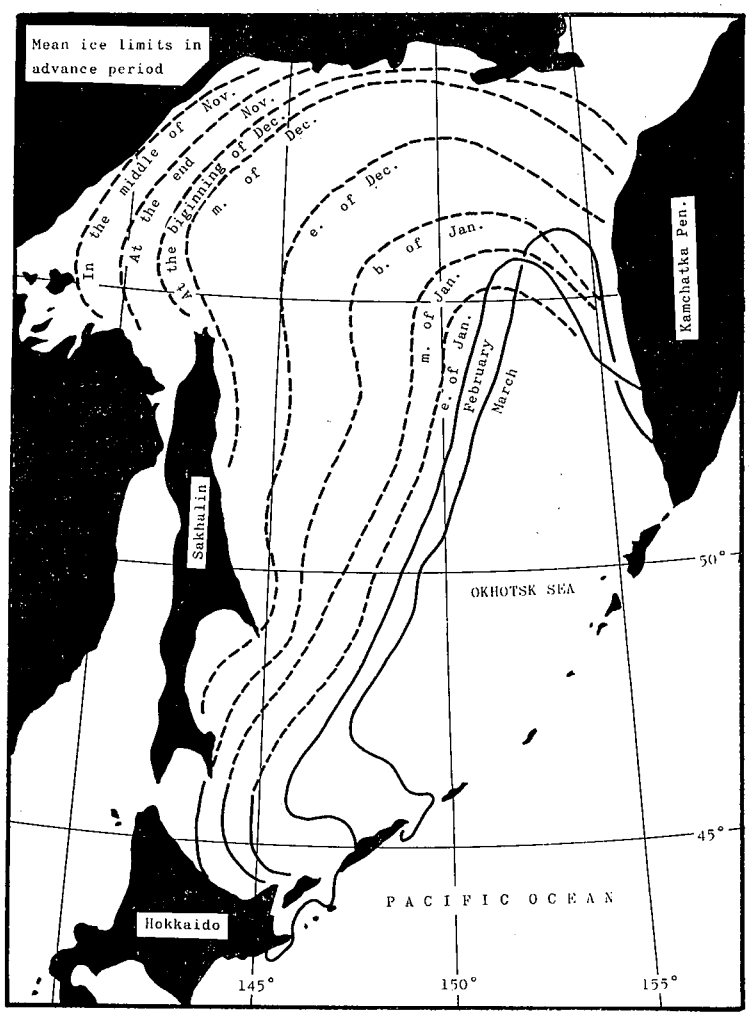


Fig. 11. Mean ice limits in the ice-advance period, where broken lines are made from estimated ice forming areas in the ice seasons from the 1960-61 through the 1965-66 and solid lines from almost all available ice data in February and March

corner of the Okhotsk Sea at about middle of November, and the ice-forming area which is nearly the same as the ice cover possibly with not too large a discrepancy extends towards the central region of the sea as the season advances, reaching the northern tip of Sakhalin at about the beginning of December, and one of the southern most tips of the island at the beginning of January. Then, the first drift ice comes to the northeast coast of Hokkaido usually in the middle of January. This early drift ice there consists of ice-cakes and small icefloes mostly of 30~50 cm in thickness together with newly formed young ices. It is very striking that there is a broad open area in the northern part of the sea up to approximately 57°N parallel west off Kamchatka Peninsula when the northeast coast of Hokkaido at the 44°N parallel has already been blocked by drift ice early in the middle of January. The reason is easily understood from the flow pattern seen in Fig. 1 and the climatic situations in Fig. 4. Namely, the sea ice born in the low saline surface water and which continues to develop is carried southward along the east coast of Sakhalin by the southward directed East Sakhalin Current. In addition the ice drift is accelerated by the northerly winds which persist during the winter. Although the direct measurements of speed of the southward ice-drift are scarce, two estimations have been made on the speed as will be briefly explained in the next section.

IV. Southward Ice-Drift along the East Coast of Sakhalin

In Fig. 12 are presented three charts of ice drift estimated with Fukutomi's theory on wind-induced drift using mean winds at several coastal weather stations, which agree with actual ice situations fairly well at least in pattern, though some of the vectors there are thought to be too large for the wind-induced drift alone (Fukutomi, 1952).

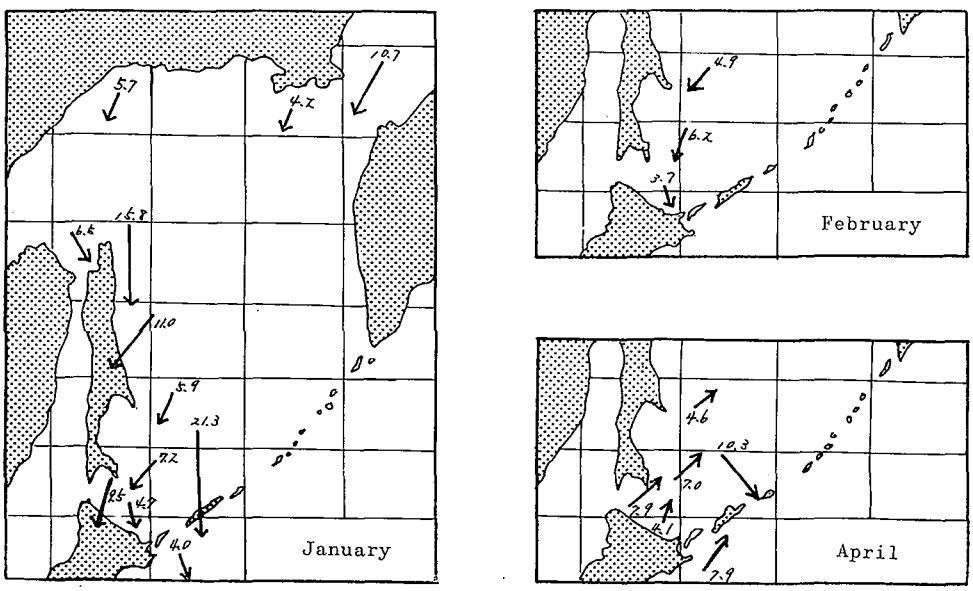


Fig. 12. Wind-induced drifts of ice in a nautical mile per day theoretically estimated by Fukutomi (1952)

The other estimation was tried by utilizing ice-floe thickness actually measured in Hokkaido area in January, 1961 (Watanabe, 1963 a). There the first appearing drift-ices of the north origin are usually of 30 to 50 cm in thickness, not so thin as, for instance, 20 cm or less. This fact suggests that the drift-ices had already developed to the measured thickness under a considerably large integral coldness, *i.e.* degree days of frost, during their southward drift.

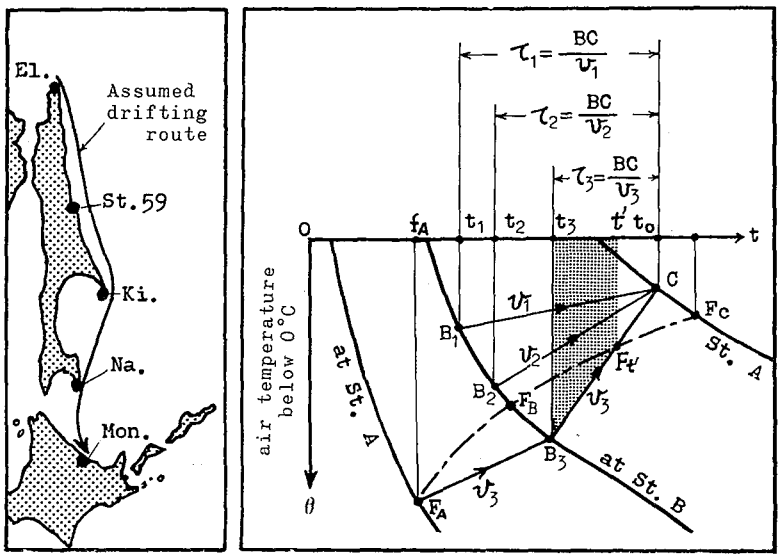


Fig. 13. (Left) Reasonably assumed path of drift ice, where El. means the Cape of Elizabeti, St. 59 the code number of the weather station there, Ki. Cape Kitashiretoko (or Terpeniya), Na. Cape Nakashiretoko (or Aniva), and Mon. Mombetsu. (Right) Schematical representation of the time-temperature diagram for graphically computing the amount of degree days of frost acting on an ice drifting southward

The amount of degree days of frost acting on an ice-floe can be estimated by a graphical procedure as illustrated in Fig. 13, if its drifting path is known or can be reasonably assumed like the one shown in the inserted chart. In the figure, the abscissa is for the time and the downward ordinate for the air temperature. Three thick curves are the scheme of the air temperatures descending with time at three locations of St. A, B and C. The temperature curve on the left is for the northern location, St. A, the right one for the southern location, St. C, and the central one for St. B between St. A and St. C. The three points, F_A, F_B and F_C on these three curves represent the conditions at which the first ice formation begins at each location, respectively. Therefore, the dashed curve of $F_AF_BF_C$ gives the condition for the occurrance of the first ice-formation in this time(t)-temperature(θ) diagram. In other words, the water cannot freeze in the condition shown by the domain upward from the curve $F_AF_BF_C$, whereas in the one downward from it the sea ice is being formed. When we assume an ice-floe that arrives at St. C on a date of t_0 after its drift from the north, we connot expect it to have flowed with some slow speed like V_1 or V_2 because its drift with V_1 or V_2 lies in the upward domain in the $t-\theta$ diagram as easily understood in Fig. 13. Whereas

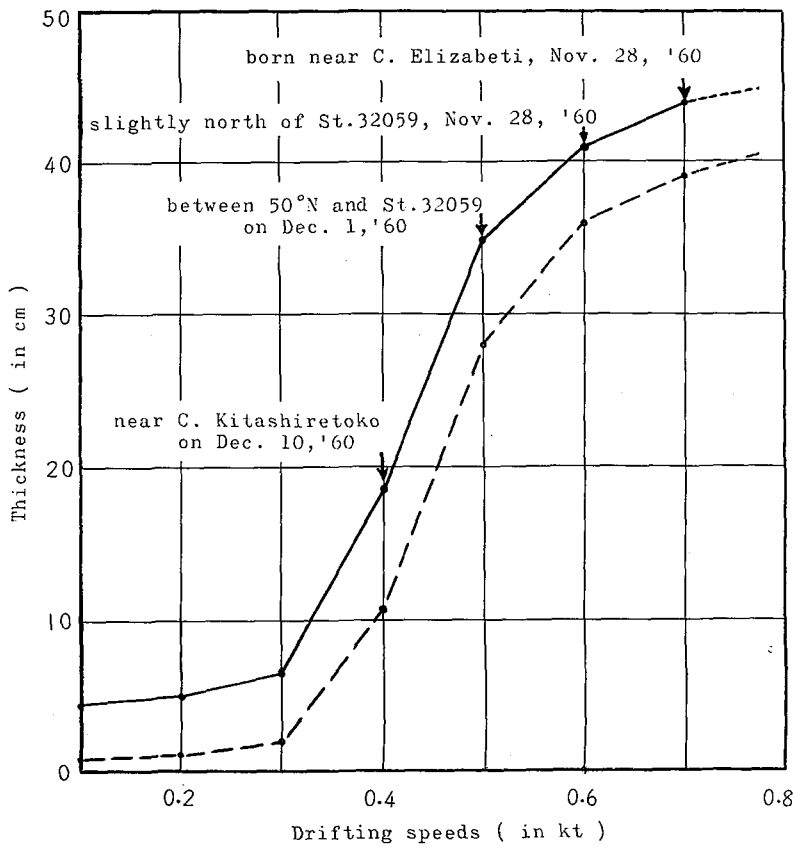


Fig. 14. Ice thickness (cm) expected to ices drifting southward along the assumed path with given drift speeds (kt)

some faster speed of V_3 can be expected, as the ice-drift with V_3 lies partially in the downward domain, which is the ice-forming condition. The amount of the degree days of frost acting on the ice during its drift from St. A to the time-temperature condition of F_t' is measured from the area of $f_A F_A B_3 F_t' t' f_A$. Then, it is converted to an ice thickness with Zubov's formula (Zubov, 1945, Chapter IV. Growth of ice) or with the one by Fukutomi and his corraborators (1950). Figure 14 shows two curves for thus estimated ice thickness (cm) varying with a given speed (kt) for the drift-ice actually arriving at Mombetsu on January 4, 1961, using the air temperatures at several weather stations shown by dots in the left chart of Fig. 13. The solid curve in Fig. 14 is for the ice thickness converted from the formula by Fukutomi and the broken one is from Zubov's formula. If a drift speed is given as 0.4 kt for the ice drift, the ice would be formed near Cape Kitashiretoko (or Terpeniya) on December 10, 1960 and would show an amount of 10~20 cm in thickness when it reaches the vicinity of Mombetsu. But that can not be expected because the actually measured thickness is 30~50 cm. Hence, it is reasonably assumed from Fig. 14 that the ice measured at 30 cm in thickness must have been born in the area near the 50°N parallel about December 1, 1960 and must have drifted southward towards Mombetsu with a mean speed of about 0.5 kt, and that the 50 cm thick

ice among the measured drift ices must have formed in the northern region north of Cape Elizabeti before November 28, 1960, then must have drifted southward with a mean speed of over 0.8 kt. Though this amount seems fairly large, it is likely for the southward drift of early drift ice due to the combined action of the East Sakhalin Current and the fairly strong northerly wind. The velocity of the East Sakhalin Current has never been measured in winter, but it has been surveyed in late autumn by the observation vessel of the Hakodate Marine Observatory successively these 4 years, revealing that the southward speed in its stream axis is about 0.6 kt or so in late autumn when the current has not yet been intensified to its maximum state. After reaching its maximum, possibly in December, the speed of southward flow may be reasonably assumed to be slightly faster than the autumn speed. Thus, the mean speed of southward ice-drift from the northwestern region to Hokkaido area estimated at over 0.8 kt is thought to be mainly due to the East Sakhalin Current and partially to the northerly wind, possibly 0.2 kt or more in early ice season.

By the strong ice pressure caused by such a southward drift, there occurs a heavy ice state in the southern most region of the Okhotsk Sea, the area in the near vicinity of the northeast coast of Hokkaido in mid-winter. As drift ices there are strongly packed shoreward from the north, a severe ice situation as seen in the polar regions, though superficially, takes place with heavy pressure ridges several meters high above sea level everywhere.

V. Retreating of the Ice Limit in Spring

A report on mean ice limits in the Okhotsk Sea were once presented on its retreating period together with its advancing period made from a rather incomplete accumulation of available data by substituting limits of ice occurrance of 50% in possibility as mean ice limits (Watanabe, 1964). With additional ice data mostly due to modern satellites, the author made new charts of mean ice limits by a method of spacial average referred to before. Figure 15 is an example of ice charts interpreted from rectified TIROS-IV pictures.

Using the ice data listed in the following Table 1, a chart of mean ice limits in Fig. 16 in the ice retreating period has been made for five separate periods of March, the beginning of April, the middle of April, May and June. Though the pattern seems to have made a fair approach to the likely mean extents of ice cover in comparison with the formerly presented chart, it is still incomplete as the east side limit of each period is arrayed rather irregularly. These limits will become more complete in future with the availability of satellites data.

Now, after reaching the maximum state usually at the period of the end of March or the beginning of April, the edge of ice cover retreats northwestward gradually at first and then rapidly as seen in Fig. 16 with the coming of spring when the northerly wind in mid-winter weakens and reversely turns to a southwesterly direction.

The ice closely off the north shore of the sea seems to break-up much faster than in the offshore area in spring with the warming-up of the land. Such phenomenon is clearly shown on most satellite pictures in the period after the middle of April, and represented

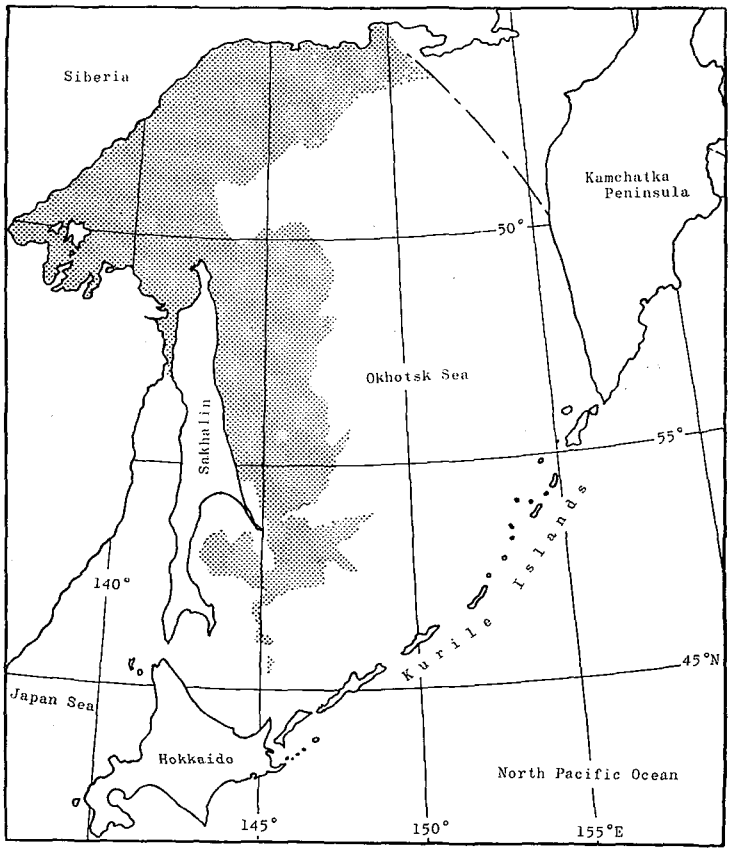


Fig. 15. Ice cover on April 13, 1962, interpreted from rectified pictures by TIROS-IV

Table 1. List of available ice data from March through June

Period	Year	Data source	Period	Year	Data source
March	1936	ship	May	1937	ships
	1939	ship		1939	ship
	1966	ESSA-II		1940	ships
Beginning of April	1955	ships		1942	ship
	1960	TIROS-I		1956	ships
	1962	TIROS-IV	June	1931	ships
	1964	TIROS-VII		1940	ship
Middle of April	1942	ship		1960	ships
	1955	ship		1961	ship
	1956	ship		1964	ship
	1962	TIROS-IV			
	1963	TIROS-VI			

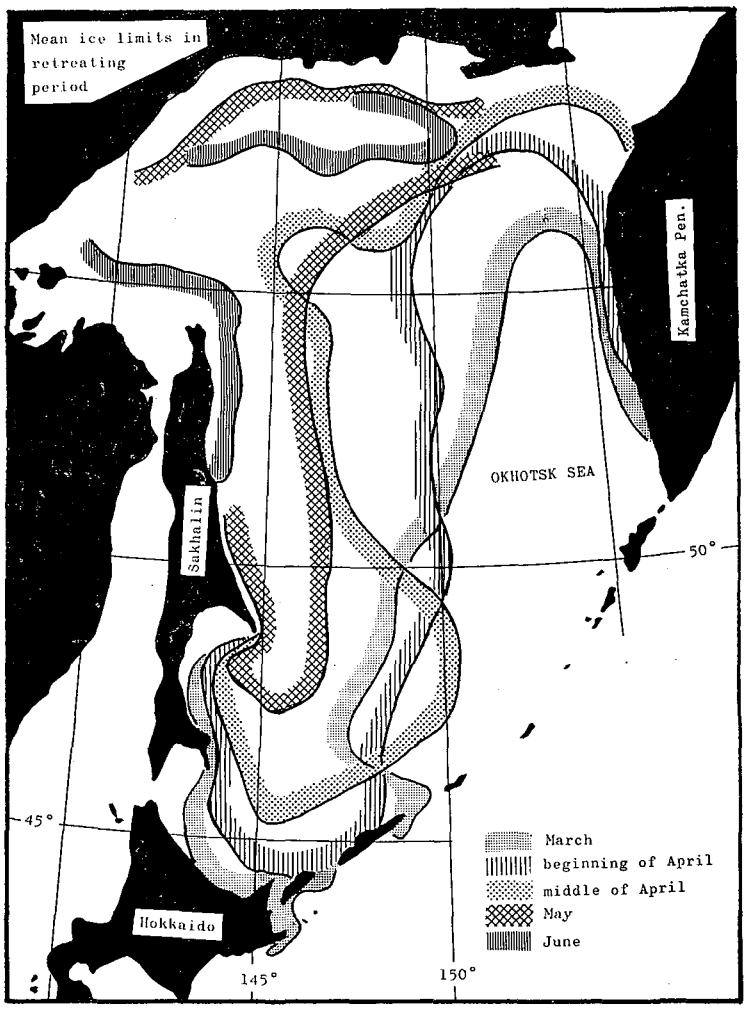


Fig. 16. Mean ice limit in the ice-retreating period for five separate period

by the mean limits of ice for May and July in Fig. 16 where the inshore area 5 to 10 nautical miles off the coast is open. The ice cover keeps on retreating towards the northwestern corner of the sea in late spring, then it seemes to be confined to the westmost corner around Shantar Island at the 55°N parallel at about the beginning of July. In fact, APT pictures by ESSA-II received in Tokyo show the ice cover surrounding the island until the middle of July, 1966.

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