An oceanographic study of the Okhotsk Sea
—Particularly in regard to cold waters *—

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Contents

Ⅰ. Introduction

It is known that in summer the subarctic area is generally characterized by a minimum temperature stratum called "cold bottom water" near the bottom in the shallow regions and "dichothermal (or intercooled) water" at the intermadiate layer in deeper regions (UDA 1935, 1955, DODIMEAD *et al.* 1963, OHTANI 1969).

Precise knowledge of these waters seems to be very significant for the fisheries in the subarctic area, because the extremely cold water has been considered to give significant influence on fisheries resources. That is, it had been pointed out by many workers that the cold water intensity, which means the temperature and horizontal or vertical spread of the cold water, influences not only the formation of the fishing ground associated with the distribution or migration of fishes, but also the abundance of marine resources, as well as, survival and growth rates (SHTUNTOV 1966, POLUTOV and PASKKEEV 1967, MAEDA 1967, 1971, CHERNYAUSKII and KHARITONOVA 1968, KIHARA and UDA 1969). Therefore, it is important to know about actual status in both the cold bottom water and dichothermal water, and to clarify the various processes that influence them.

The Okhotsk Sea has a great amount of the cold water as compared with the other

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part of the subarctic region, and this cold water has a relatively high value of the dissolved oxygen (REID 1965). The subsurface cold water in summer (referred to above as "dichothermal water") has been explained as the water originating from the winter mixed water extending to about 100 m (UDA 1935, KAJIURA 1949, TABATA 1952). Furthermore, it has been reported that water beneath the subsurface cold water originates in the open Pacific Ocean and is formed by vertical diffusion between 150 m and 800 m because the water originating in the open Pacific Ocean probably has a longer residence time in the Okhotsk Sea than in comparable areas of the open Pacific Ocean (REID 1965).

Although, as stated above, there is a bit of information regarding the cold water in the Okhotsk Sea, such infomation, which has been provided in relation to oceanographic conditions, is not adequate to clarify the actual status and the various processes occurring in the cold water.

The author participated in the investigation aboard the R. V. Oyashio Maru in 1969 and 1970 in the northern Okhotsk Sea, where only a few observations had been carried out by that time, and could obtain the available data for the analysis of the formation of the cold water in the Okhotsk Sea. He has, also, examined the characteristics of the cold water and the mechanism of its variation by means of adding other data obtained from the observation in the central and southern Okhotsk Sea and other waters in the North Pacific. Particularly, he has studied in detail the thick cold water which characterizes the oceanic structure of the Okhotsk Sea.

II. Sources of data

Sources of data used for this study are shown in Table 1. Investigations aboard the T. V. Hokusei Maru (the Faculty of Fisheries, Hokkaido University) have been carried out every year since 1957, except in 1961, and especially in 1958, 1962 and 1963 relatively wide areas of the Okhotsk Sea were covered.

Conditions in the northern Okhotsk Sea, where the continental shelf is extensive, were observed in detail from aboard the R. V. Oyashio Maru (the Faculty of Fisheries, Hokkaido University) in 1970.

In 1967, investigations carried out aboard the S. V. Seifu Maru (Japan Meteorological Agency) provided valuable results and observations were made at a number of hydrographic stations.

Oceanographic data are far more abundant in summer than in the other seasons. There are only a few winter data available ; those are provided by the P. S. Soya (Japan Maritime Safety Agency) and the R. V. Argo (Scripps Institution of Oceanography). And these observations were carried out only in a narrow region of the southern Okhotsk Sea because of the presence of sea ice extending from the northern part.

The data used in the present paper have already been published by each organization as the results of the oceanographic observations or the cruise reports.

Table 1. Sources of data dealt for the present paper.

Vessel	Organization	Date	Source
Argo	Scripps Inst. Oceanogr.	Jan. 27-Apr. 1, 1966	PDR-CSK, 36, 1967
Hokusei Maru	Fac. Fish. Hokkaido Univ.	Jul. 10-29, 1957	DROOEF, 2, 1958
		Jul. 7-30, 1958	DROOEF, 3, 1959
		Jul. 7-27, 1959	DROOEF, 4, 1960
		Jun. 18-Aug. 4, 1961	DROOEF, 6, 1962
		Jul. 5-Aug. 28, 1962	DROOEF, 7, 1963
		Jul. 6-Aug. 4, 1963	DROOEF, 8, 1964
		Jul. 3-27, 1964	DROOEF, 9, 1965
		Jun. 26-Jul. 17, 1965	DROOEF, 10, 1966
		Jul. 4-Aug. 3, 1966	DROOEF, 11, 1967
		Jul. 3-18, 1968	DROOEF, 13, 1969
Kofu Maru	Hakodate Mar. Obs.	Nov. 2-28, 1963	RMMOO, 34, 1965
		May 14-Jun. 5, 1964	RMMOO, 35, 1966
		Aug. 6-Sep. 17, 1964	RMMOO, 36, 1697
		Oct. 19-Nov. 23, 1964	RMMOO, 36, 1967
		Jul. 2-Aug. 22, 1969	RMMOO, 46, 1971
Komahashi	Imp. Japanese Navy	Apr. 7-Jul. 16, 1937	HB, spec, 6, 1951
Oyashio Maru	Fac. Fish. Hokkaido Univ.	Aug. 1-Sep. 1, 1969	OKGH, 1969
		Jul. 5-Aug. 2, 1970	OKGH, 1970
		Aug. 6-Sep. 21, 1970	OKGH, 1970
Ryofu Maru	Imp. Japanese Navy	Jul. 1-Aug. 21, 1942	HB, 74, 1963
Seifu Maru	Maizuru Mar. Obs.	Jun. 12-Jul. 5, 1967	RMMOO, 41, 1970
Soya	Maritime Safety Agency	Feb. 18-23, 1964	DRHO, 4, 1967
		Feb. 13-25, 1966	DRHO, 7, 1968
		Feb. 11-17, 1967	DRHO, 8, 1970

DRHO : Data Report of Hydrographic Observations, Maritime Safety Agency, Tokyo.

DROOEF : Data Records of Oceanographic Observations and Exploratory Fishing, Fac. Fish., Hokkaido Univ., Hakodate.

HB : Hydrographic Bulletin, Maritime Safety Agency, Tokyo.

OKGH : Oyashio Maru Kaiyo Chosa Gyogyo Shiken Hokoku, Fac. Fish., Hokkaido Univ., Hakkodate.

PDR-CSK : Preliminary Data Report of CSK, Kuroshio Data Center, Maritime Safety Agency, Tokyo.

RMMOO : The Results of Marine Meteorological and Oceanographical Observations, Japan Meteorological Agency, Tokyo.

III. Analysis of data and discussion

1 Oceanic structure of the Okhotsk Sea

The bottom topography of the Okhotsk Sea is shown in Fig. 1. The Okhotsk Sea is separated from the North Pacific Ocean by the Kuril Islands but the considerable amount of water exchange exists through the numerous straits between them. Among them Mushiru Straits and Uruppu Straits, having the sill depth around 2000 m, contribute particularly to the water exchange between the Okhotsk Sea and the North Pacific Ocean (KURASHINA *et al.* 1967, YASUOKA 1968). The bottom topography of the Okhotsk Sea is characterized by a shallow bottom in the northern part and a deep basin in the southern part.

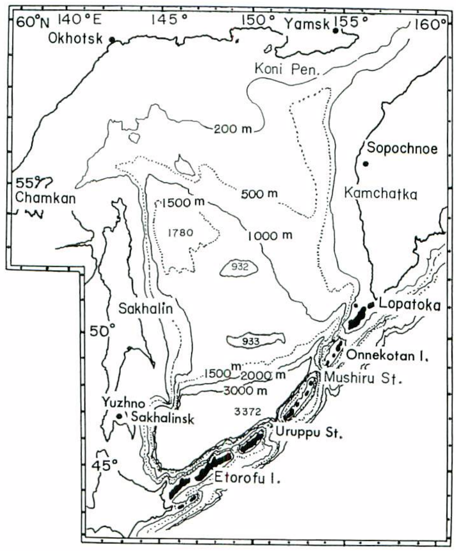

Fig. 1. Sea-bed relief of the Okhotsk Sea (Bezrukov, from Zenkevitch, 1963)

Fig. 2 shows the vertical temperature distribution on a meridian section approximately along the central axis of the Okhotsk Sea. The warm summer surface water forms a thin stratum above the thermocline (20 m—50 m). A stratum of minimum temperature, which is frequently called as a dichotherml water, appears just beneath the summer surface water. In general, the water temperature increases gradually downward from the stratum of minimum temperature and has a maximum value of 2.0°C or more at the depth of about 1000 m. The author calls the warm water core at the layer of about 1000 m as "deep warm water". Furthermore he calls the water between the subsurface cold water and the deep warm water as "transitional water".

Fig. 3 shows the T-S relations and the O_2-S relations of sea water from surface to near the bottom in the southern Okhotsk Sea. In summer, the salinity of the surface water is generally very low, less than 32.8‰, because of the melting of sea ice and/or the inflow

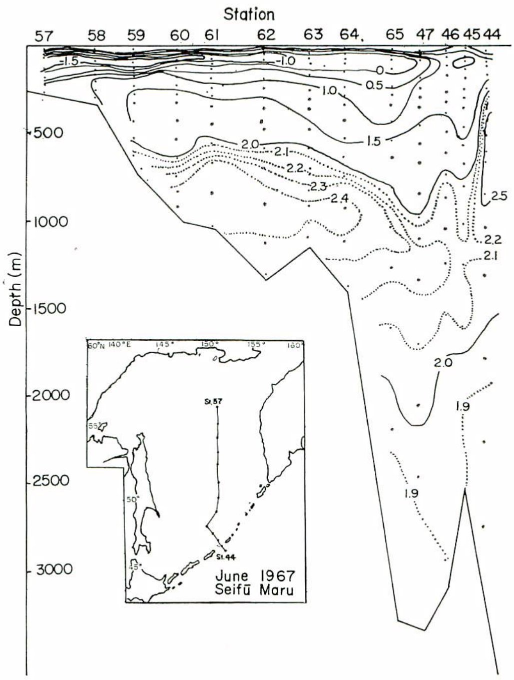

Fig. 2. Temperature (°C) on the vertical section along approximately meridian in the Okhotsk Sea.

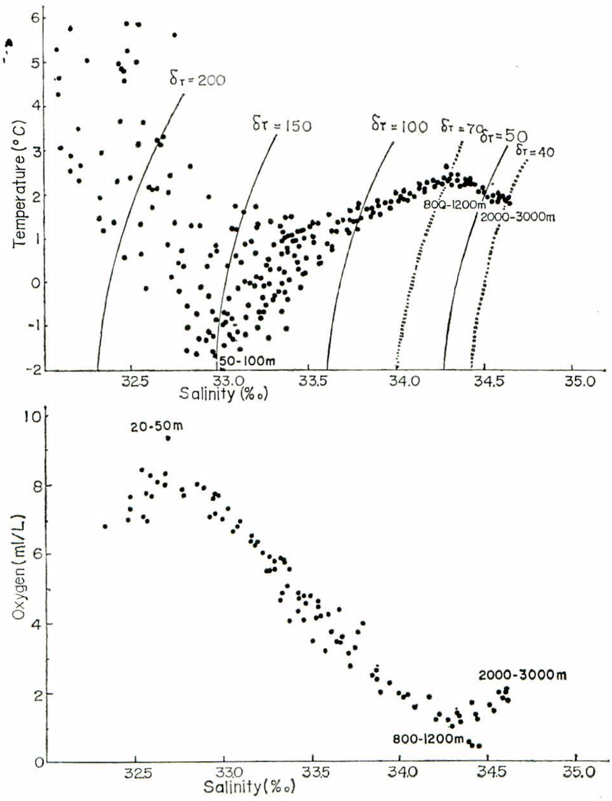

Fig. 3. T-S relations (upper panel) and O_2-S relations (lower panel) from surface to 3000 m in summer in the southern Okhotsk Sea.

of river water. However, the salinity increases gradually with depth and shows the highest value, more than 34.5‰ in a layer between 2000 m and 3000 m. The remarkably low temperature water with approximately 33.0‰ in salinity and the thermosteric anomaly $\delta_T=150$ cl/ton is found as shown in Fig. 3. The remakable thermocline, halocline and pycnocline are formed between the surface and the minimum temperature water, and the maximum value of the dissolved oxygen appears at this discontinuous layer, even a super-saturation occasionally. Below this layer the oxyty decreases with depth and shows the minimum value of about 1 ml/l, for the water having the thermosteric anomaly $\delta_T=70$ cl/ton, which corresponds to the deep warm layer. Below the deep warm layer the temperature decreases slightly and the dissolved oxygen increases gradually with depth. The author calls this water below the deep warm water as "deep water".

As we have seen, the sea water in the Okhotsk Sea in summer is generally divided vertically into five strata, *i.e.* the summer surface water, the subsurface cold water, the transitional water, the deep warm water, and the deep water.

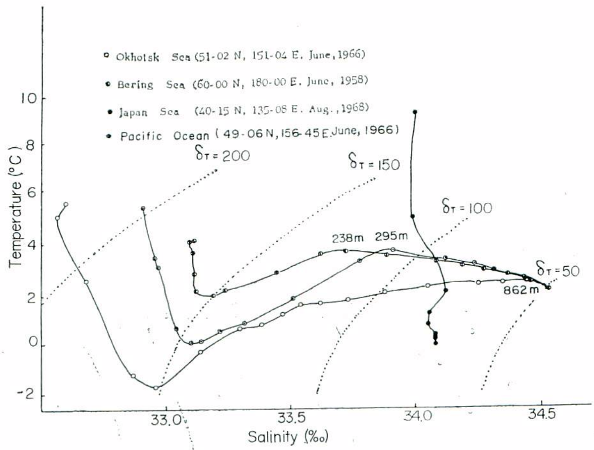

Fig. 4. Typical T-S curves in the Okhotsk Sea and other waters in the North Pacific.

Fig. 4 shows the example of typical T-S curves in the Okhotsk Sea and adjacent waters. These T-S curves, except that in the Japan Sea, have the similar characteristics, *i.e.* the minimum temperature water and the maximum temperature water are recognized on the T-S curve. But the depth of maximum temperature in the Bering Sea and in the subarctic western North Pacific Ocean off Kamchatka Peninsula are shallower than that in the Okhotsk Sea, and those waters are very different in temperature, salinity and density from that in the Okhotsk Sea. Therefore, these maximum temperature waters which are called "mesothermal water", should be considered different from the maximum temperature water in the Okhotsk Sea, namely the deep warm water. The properties of the deep warm water in the Okhotsk Sea are the similar to those of the water between the mesothermal and deep waters in the Bering Sea and in the subarctic western North Pacific

Ocean. The characteristic feature of the oceanic stratification in the Okhotsk Sea is that the transitional water of comparatively low temperature exists at depth, from 200 m to 400 m, the depth at which the mesothermal water is found in the Bering Sea and in the subarctic western North Pacific Ocean.

The *T-S* curves of southwestern Okhotsk Sea water in different seasons are shown in Fig. 5. In winter, the homogeneous cold water formed by thermal convection is found in a stratum from the surface to about 70 m layer, and in the heating period the properties of this water changes gradually from low temperature and high salinity into high temperature and low salinity owing to the heating and the dilution from the sea surface. Consequently the upper water* has a complex structure during the heating period because

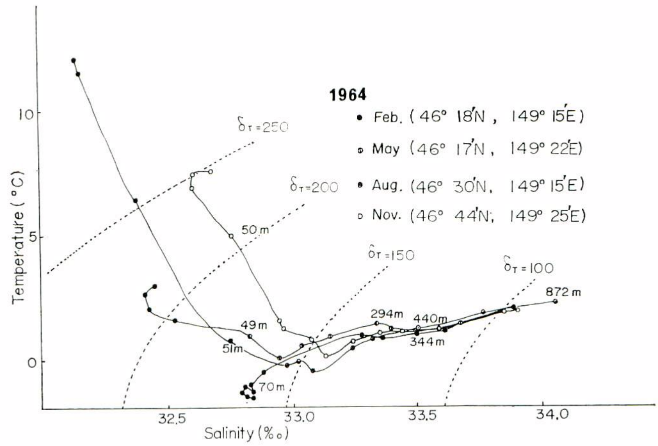

Fig. 5. Seasonal variation of *T-S* curves at the southern Okhotsk Sea.

of the stratification and can be divided into two strata ; the summer surface water and the subsurface cold water. The seasonal variations of temperature and salinity are more remarkable in the shallower layer and seem to penetrate as deep as about 500 m, the mid depth of the transitional water. Examining these *T-S* curves in details, we can recognize slight maximum and minimum of temperature in the upper half of the transtional water.

Fig. 6 illustrates schematically the seasonal variations of surface water in the *T-S* diagram. The surface water at a station changes annually from high temperature-low salinity in summer to low temperature-high salinity in winter. Generally, it is obvious from this figure that the seasonal variation of the surface water is more noteworthy in the coastal area than in other areas. In the area along the Kuril Islands, the surface temperature and salinity varies very slightly and the salinity values are higher than in other areas throughout a year.

In winter, the cold-saline surface water is formed by convective mixing on account of the cooling and the evaporation from autumn to winter. The salinity of this water is in the range of from 32.7‰ to 33.2‰ according to the data so far obtained. On the

* In this paper, the upper water means the water to which winter overtune extends.

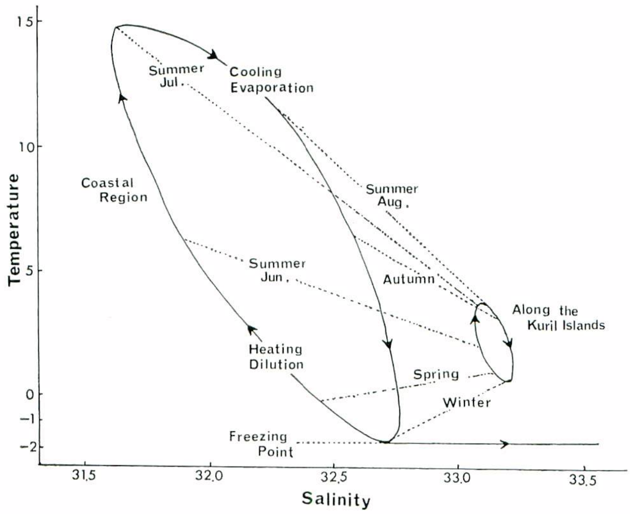

Fig. 6. Schematic representation of the seasonal variation of T-S relations of surface water over the Okhotsk Sea.

other hand, it is reasonable to consider that the convective mixing extends as deep as 100 m from the surface without a surface freezing as shown in Fig. 5. Therefore the salinity of surface water in winter can be estimated from the vertical distribution of salinity in summer assuming that the thickness of mixing layer is 100 m and the advective effect is negligible. The mean salinity of upper 100 m in summer is lower than 33.1‰. If the net evaporation from summer to winter is 30 cm, which seems somewhat a large value, the water column from surface to 100 m depth should increase about 0.1‰ in salinity. Consequently, it is reasonable to consider that the mixed surface water formed by thermohaline circulation before the freezing does not exceed 33.2‰ in salinity.

2 Minimum temperature water

The distribution of minimum temperature in summer is shown in Fig. 7. Generally in this distribution the high temperature appears at the north of North Kuril Islands, and the low temperature appears in the northern Okhotsk Sea and east of Sakhalin Island, where the isotherms run approximately from northeast to southwest and have a range of −1.7°C to 2.0°C. The minimum temperature is relatively high in the northeast of the Sakhalin Island and in the south of the Koni Peninsula. While, on the continental shelf in the northern part of the Okhotsk Sea, it is lower than −1.7°C. In summer, the horizontal distribution of minimum temperature is different from that of the surface temperature ; the area where the minimum temperature is high corresponds to the area where the surface temperature is low, and *vice versa*. Therefore, the vertical temperature gradient from the surface to the minimum temperature stratum is very small in the region where the minimum temperature is high. Also, in this region the vertical gradient of salinity is very small from the surface to the minimum temperature stratum.

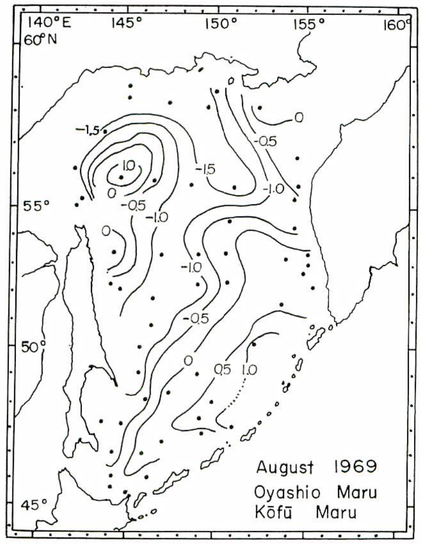

Fig. 7. Horizontal distribution of the minimum temperature (°C) in summer.

The vertical stability, E, between the surface and the minimum temperature stratum is obtained approximately by

$$E=\frac{\sigma_t'-\sigma_t}{\Delta z}\times 10^{-3}\ (g/cm^3/m)$$

where σ_t and σ_t' stand for the *sigma-t* of the surface water and the minimum temperature water, respectively, and Δz is the depth from the surface to the minimum temperature stratum.

Fig. 8 shows relationships between the minimum temperature and the vertical stability ($E\times 10^6$). Points plotted in the figure indicate the T-S relationships only in the southern and central parts of the Okhotsk Sea. In this figure, we can recognize that the

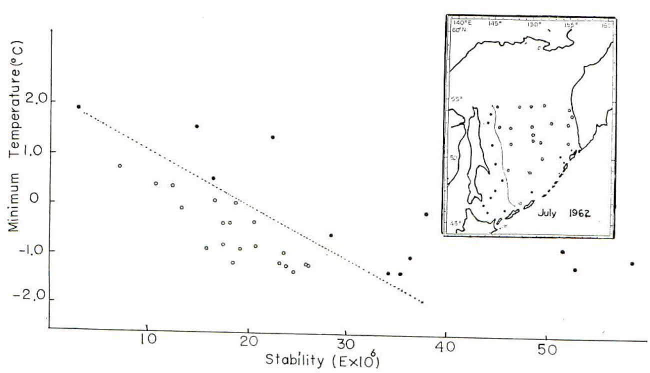

Fig. 8. Relations between the minimum temperature and the vertical stability from the sea surface to the minimum temperature stratum.

vertical stability as against the minimum temperature is generally higher in the western part than in the eastern part. This seems to be caused because of the lower surface salinity in the western part than that in the eastern part, owing to the inflow of river water and/or the melt of sea ice. Furthermore, in the respective areas we can recognize a tendency that the vertical stability increases with the decrease of the minimum temperature. KOTO and MAEDA (1965) explained by actual examination in the Bering Sea that the thermal eddy conductivity is low at the station where the vertical stability is high and this relation might also be applicable to the Okhotsk Sea. The surface temperature at the station where the vertical stability is high is higher than at the station where the stability is low because the heat quantity incident on the sea surface is absorbed in the shallow layer of the surface without being hardly conducted to the lower layer. Thus at such a station, the water in the lower layer would not be heated and its temperature would be preserved. Therefore, the minimum temperature is low at the station where the vertical stability is high.

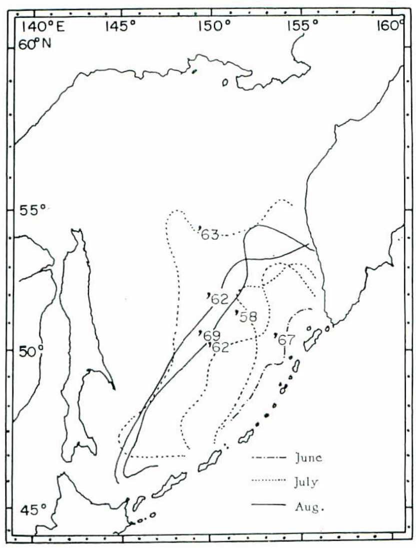

Fig. 9. Location of the 0°C isotherm in the minimum temperature during summer (in 1958, 1962, 1963, 1967 and 1969).

Fig. 9 shows the positions of 0°C isotherms of the minimum temperature in summer months of 1958, 1962, 1963, 1967 and 1969, when sufficent stations were occupied covering a wide area in the Okhotsk Sea. The minimum temperature below 0°C are always observed in the northwest of 0°C isotherms, except in the northeast of the Sakhalin and in the south of the Koni Peninsula. These distributions suggest that the 0°C isotherm moves gradually northward during summer, but the year of 1963 seems abnormal with the very north isotherm in July than usual. It has been already reported that the temperature minimum water occupying the wide area of the Okhotsk Sea in summer is the remainder of cold surface water in winter (UDA 1935, KAJIURA 1949, TABATA 1952).

In 1963, the weather was abnormal all over the world (SHINJI 1964), and the monthly mean air temperature in January in the Okhotsk Sea was very high, 3 to 6°C higher than in the normal year (HIRASAWA 1964). The 0°C isotherm of minimum temperature water in 1963 was, therefore, located farther north than in other years due to the abnormally warm air temperature in the preceding winter.

Fig. 10 shows the seasonal variation of the water temperature north of Uruppu Island. In winter (February), the homogeneous water colder than 0°C is formed from the surface to the depth of about 80 m due to the active convective mixing. From spring to summer, the surface temperature increases remarkably, while the temperature in the layer below 100 m decreases slightly during this period ; the minimum temperature water does not remain at the fixed depth but is found at deeper depths with time. The variation of vertical distributions of minimum temperature in this figure suggests seemingly that cold surface water in winter persists as the minimum temperature water until the next autumn through that in spring and summer, although its temperature increases slightly.

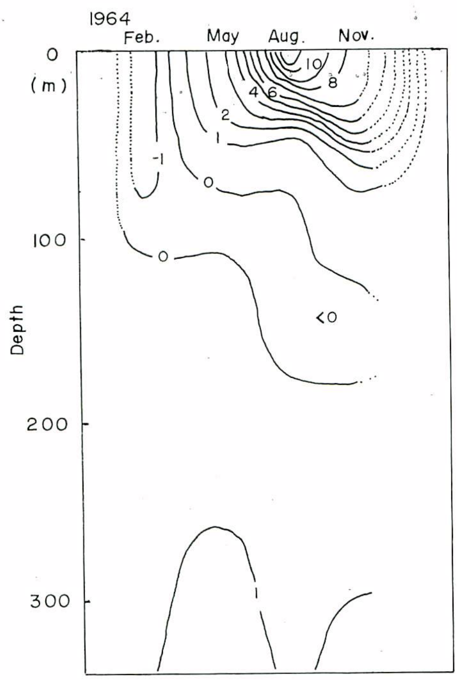

Fig. 10. Isopleth of vertical temperature at the southern Okhotsk Sea in 1964.

Fig. 11 shows the T-S relationships of minimum temperature water in various seasons in the southern Okhotsk Sea. As the minimum temperature water in winter is formed by strong cooling at the surface, the specific volume is comparatively low in winter (Fig. 11-A). On the other hand, the specific volume of the minimum temperature water generally becomes high in summer and autumn with the increase of salinity, in spite

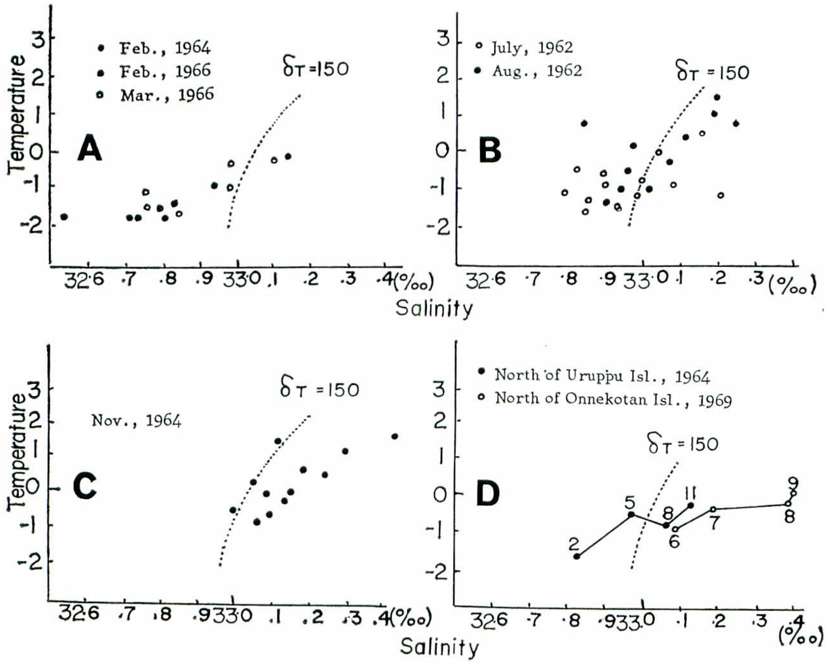

Fig. 11. Seasonal variation of the T-S relation of the minimum temperature water in the southern Okhotsk Sea. Panel A, B and C show those in winter, summer and autumn, respectively. Panel D shows those at two stations, the numeral in this panel indicates the months of year.

of the rising of temperature (Fig. 11-B, C). Furthermore, the seasonal variation of T-S relationships of the minimum temperature water at two stations, one at the north of Uruppu Island and the other at the north of Onnekotan Island, are shown in Fig. 11-D. As being shown in this figure, both the temperature and salinity of minimum temperature water generally increase from winter to autumn, and the specific volume decreases gradually with time. This suggests, at least in the southern Okhotsk Sea, that the temperature, salinity, specific volume and depth of the minimum temperature water vary with time, thus the minimum temperature water in summer and autumn is very different from that in winter. If the minimum temperature water is the remainder of the cold water which is formed by winter overturn, its temperature, salinity, specific volume and depth would not change as remarkably as shown in Fig. 10 and 11.

The minimum temperature water in the Okhotsk Sea can be classified into four typical types from the distribution patterns of the vertical temperature and salinity as shown in Fig. 12.

Type A : This type has a clear minimum temperature stratum of tens of metres thickness in which the temperature and salinity is vertically uniform.

Type B : This type also has fairly an obvious minimum temperature stratum, but

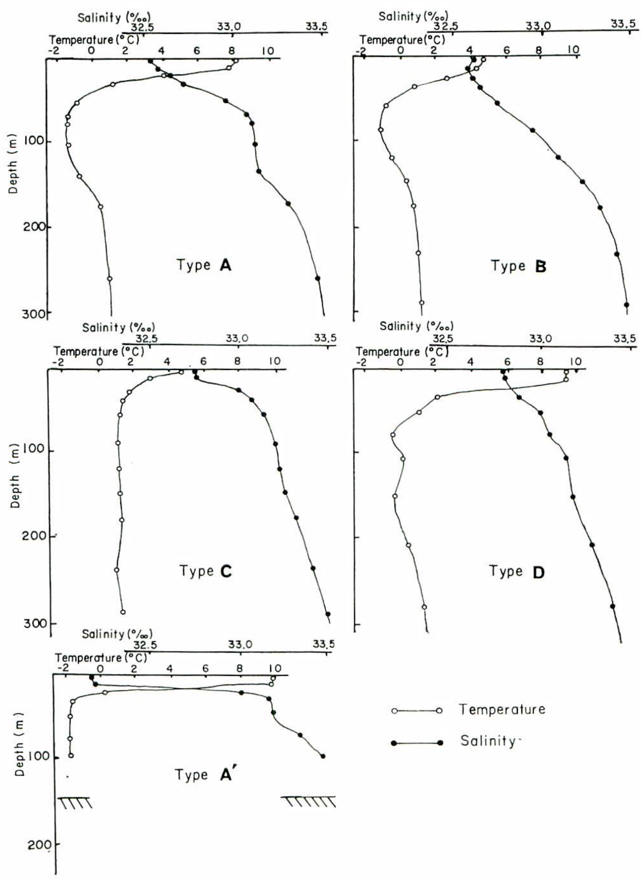

Fig. 12. Typical profile of the vertical temperature and salinity in summer in the Okhotsk Sea.

the temperature and salinity in this stratum is not so uniform as in the case of type A.

Type C : In this type the vertical gradient of the temperature near its minimum is very small, so that the minimum temperature stratum is somewhat obscure.

Type D : This type has complicated vertical temperature and salinity profiles, having two minimum temperature strata. In the present paper, the upper one is called the "first minimum temperature stratum" and the lower one is called the "second minimum temperature stratum". In addition to the four types as classified above, another type occurs on the continental shelf in the northern Okhotsk Sea. This type has homogeneous water in the minimum temperature stratum, so that this type belongs to type A according to the aforesaid classification. However, the minimum temperature stratum of this type includes the bottom water which increases in salinity toward the bottom beneath the homogeneous minimum temperature water as shown in Fig. 12. Therefore, this type could be differentiated from type A, particularly because of the saline, cold and low specific volume water. Now, this type is defined as type A′ and the author defines the saline and low specific volume water near the bottom in the minimum temperature stratum as the "cold saline bottom water".

Fig. 13 shows the distribution of typical types of the minimum temperature water, in this figure, however, no distinction is made between type A and A′. Type A appears mainly in the northern Okhotsk Sea except the regions northeast of the Sakhalin and south of Koni Peninsula, where some types are distributed complicatedly. Type C occupies narrow regions along the Kuril Islands, northeast of Sakhalin and south of the Koni Peninsula. As to type B, it should be noted that its regions are always found between two regions of type A and Type C. The region of type B extends southwestward from the eastern Okhotsk Sea off the Kamchatka Peninsula, and the other regions of this type occupies around the region of type C northeast of Sakhalin and south of the Koni Peninsula. Type D is distributed in the Soya Warm Current region, which stretches northeastward from the coast of Hokkaido, and it appears also in the central region of the Okhotsk Sea scattering in the region of type B. Since the vertical temperature variation is very small in the layer between the first minimum temperature water and the second minimum temperature water, type D is hardly observable by a serial observation. Therefore, it is considered that the minimum temperature stratum belonging to type D might exist in a broader region than as is shown in Fig. 13.

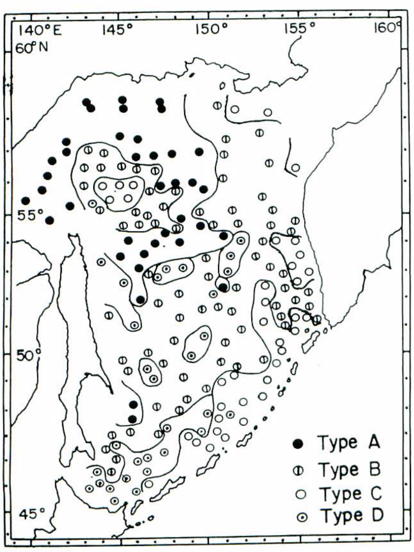

Fig. 13. Occurrence location of each type of the minimum temperature water in summer. Type A, B, C and D are classified according to the vertical profile of the temperature and salinity as shown in Fig. 12. Type A′ is included in type A.

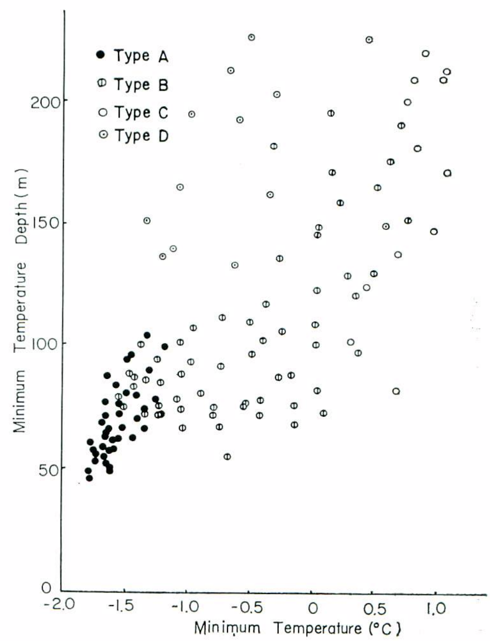

Fig. 14. Relations between the minimum temperature and its depth.

Fig. 14 shows the relationship between the minimum temperature and its depth. In this figure, the relationship of type D indicates particularly that of the second minimum temperature water. With regard to the minimum temperature water having thickness such as type A, type A′ and a certain type B, the depth of the top of the minimum water is considered as the minimum temperature depth in the present paper. The region where the minimum temperature is observed at the layer deeper than 100 m is confined in a narrow region in the southern Okhotsk Sea. The minimum temperature depth of type A occurs in a comparably shallow depth from 40 m to 100 m. Further, the minimum temperature of this type is remarkably low, colder than −1.5°C. For the type B the minimum temperature colder than −1.0°C generally occurs only above the 100 m layer, while the warm minimum temperature is sometimes found below 100 m. The minimum temperature of type C is generally high and distributed in a much wider range than that for the other types. The second minimum temperature always occurs in the layer deeper than 100 m and is generally lower than the other minimum temperature at the same depth, as shown by type D in Fig. 14.

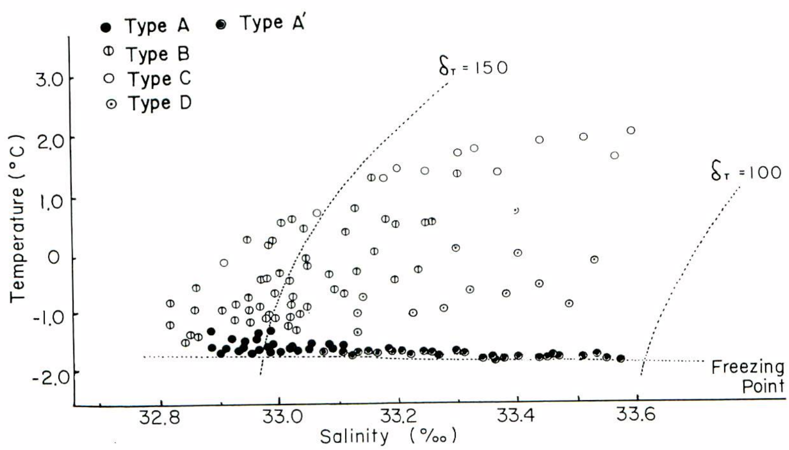

Fig. 15. *T*-*S* relations of the minimum temperature water all over the Okhotsk Sea in summer.

The temperature-salinity relationships of minimum temperature water are illustrated in the *T*-*S* diagram in Fig. 15. In constructing this figure, for type D the *T*-*S* relation of the second minimum temperature water is adopted. As it is shown in Fig. 12, for type A′ the minimum temperature water appears as an isothermal stratum above the bottom with a thickness of several tens of metres, and the salinity increases considerably with the increasing depth. All *T*-*S* relations obtained by a Nansen cast at a station beloging to type A′ are plotted in the figure, but not by a single point as in the case of other types. It should be noted that each type occupies a confined domain in the *T*-*S* diagram of the minimum temperature water. Types A and A′ lie a little above the line corresponding to the freezing point of sea water, within the salinity range of 32.8 to 33.6‰ or δ_T, 160 to 100 cl/ton, and the salinity of 33.1‰, or $\delta_T=140$ cl/ton, is the boundary of these two types. The minimum temperature of other types are warmer than those of types A and A′, but still $\delta_T=140$ cl/ton is the line of demarcation between types B and D. The minimum temperature of type C is the highest among the five types, for the same salinity. As it has been clarified that the minimum temperature water with high salinity and small thermosteric anomaly exist in the Okhotsk Sea, the homogeneous cold water formed by winter overturn before freezing never attains the salinity higher than 33.2‰ and the thermosteric anomaly less than 132 cl/ton, corresponding to that at the freezing points of salinity 33.2‰ water. This suggests that the minimum temperature waters of salinities higher than 33.2‰, *e. g.*, the cold saline bottom water of type A′, the second minimum temperature water of type D, and some minimum temperature water of type C, are formed by a mechanism different from the other minimum temperature waters which are formed by the winter overturn without freezing. The minimum temperature waters of type A′, type D and type C are roughly arranged in order toward increasing minimum temperature on the isosteric surface in small thermosteric anomaly. That is, the minimum temperature waters of different types, which are cold saline bottom water of type A′, second minimum temperature water of type D and the minimum temperature water of some type C, exist on a similar isosteric surface.

Assuming that the minimum temperature water observed in summer is the remains of the convective mixing water in winter, retaining its properties without any noticeable change, and moreover neglecting an advectional effect during heating period, we can estimate the heat quantity Q_1 (cal/cm²) received by a water column during heating period as

$$Q_1 = s\int_0^z \rho_1 c\,\{\Theta s\,(z) - \Theta \min\}\,dz \quad\cdots\cdots(1)$$

where ρ_1 is the density of sea water, c is the specific heat of sea water, s is the surface area of water column, $\Theta s\,(z)$ is the temperature in summer at the depth z, and $\Theta\min$ is the minimum temperature. Here, $\rho_1 c$ is approximately constant, 1 (cal/cm³).

Since the sea ice is present over a wide region of the Okhotsk Sea at the beginning of melting period, it is considered that the incoming heat through the sea surface is consumed in melting the sea ice in early melting period. The heat quantity of melting, Q_2 (cal/cm²), is given by

$$Q_2 = L \cdot \rho_2 \cdot \varDelta I \quad\cdots\cdots(2)$$

where L is the latent heat of fusion per unit mass of sea ice(cal/g), ρ_2 is the density of the molten water of sea ice, $\varDelta I$ is the thickness of the molten water of sea ice. Here, $L \cdot \rho_2$ is approximately 70 (cal/cm³).

In Fig. 16, the vertical salinity distributions immediately after the melting of sea ice and that in summer, Sw (z) and Ss (z) respectively, are shown schematically. In this figure, Zm is the depth to which the convective mixing reaches in winter and Z_1 is the depth to which the surface mixing of dilute surface water reaches in summer, and Z_1 is smaller than Zm because of the assumption that the minimum temperature water in summer is the remains of the convective mixing water in winter. Assuming further that the evaporation is equal to the precipitation from winter to summer, the total salt contents of the unit water column remains unchanged from winter to summer. Therefore,

$$s\int_0^Z \rho \cdot Sw(z)\,dz - s\int_0^Z \rho_1 \cdot Ss(z)\,dz = 0 \qquad (3)$$

where ρ and ρ_1 are the density of sea water in winter and in summer, respectively. Thus, the equation (3) is written as

$$s\int_0^{\Delta I} \rho_2 \cdot Sw(z)\,dz + s\int_{\Delta I}^{Z_1} \rho \cdot Sw(z)\,dz - s\int_0^{Z_1} \rho_1 \cdot Ss(z)\,dz = 0 \qquad (4)$$

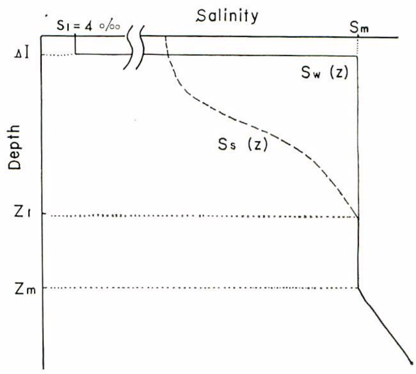

Fig. 16. Schematic diagram of salinity profiles in summer and winter. Ss (z) shows the one in summer, Sw (z) shows the other one in winter.

Sm stands for the salinity of the homogeneous water formed by the convective mixing, then, between the depth from ΔI to Z_1, Sw (Z) is equal to Sm. For a rough estimation, the density of sea water can be considered constant, and $Sw = S_I =$ const. for $0 < z < \Delta I$, $Sw = Sm =$ const. for $\Delta I < z < Zm$, then ΔI is given by

$$\Delta I = \frac{1}{Sm - S_I}\int_0^{Z_1} \{Sm - Ss(z)\}\,dz \qquad (5)$$

and S_I, the salinity of molten water of sea ice, is approximately 4 ‰ (FUKUTOMI *et al.* 1951).

The total heat quantity Q_T (cal/cm²) incident to the sea surface during the period from the melting to summer is used partly for melting the sea ice and partly to warm the water column, then,

$$Q_T = Q_1 + Q_2 \qquad (6)$$

From the equation (2) and (3), the equation (6) becomes

$$Q_T = s\int_0^{Z_1} \rho_1 c\,\{\Theta s(z) - \Theta min\}\,dz + \frac{L \cdot \rho_2}{Sm - S_I}\int_0^{Z_1} \{Sm - Ss(z)\}\,dz \qquad (7)$$

Therefore, the total heat quantity Q_T can be estimated by the temperature and the salinity profile in summer.

Fig. 17 shows the total heat quantity, Q_T, in the relationship between Q_1 and ΔI, which are calculated for every type of the minimum temperature water basing on the data observed by R. V. Seifu Maru in early summer of 1967. Although the total heat quantity, Q_T, varies between 4 to 43 kg-cal/cm² · z, only that of type A indicate comparatively confined values, 17 to 24 kg-cal/cm² · z. As the melting of the sea ice seems to begin manly in April (FUKUTOMI 1947), it is from two to three months in advance of the observation. TULLY and DODIMEAD (1957) have estimated the incident energy into the sea water from the atmosphere through a year at the northern North Pacific Ocean from the

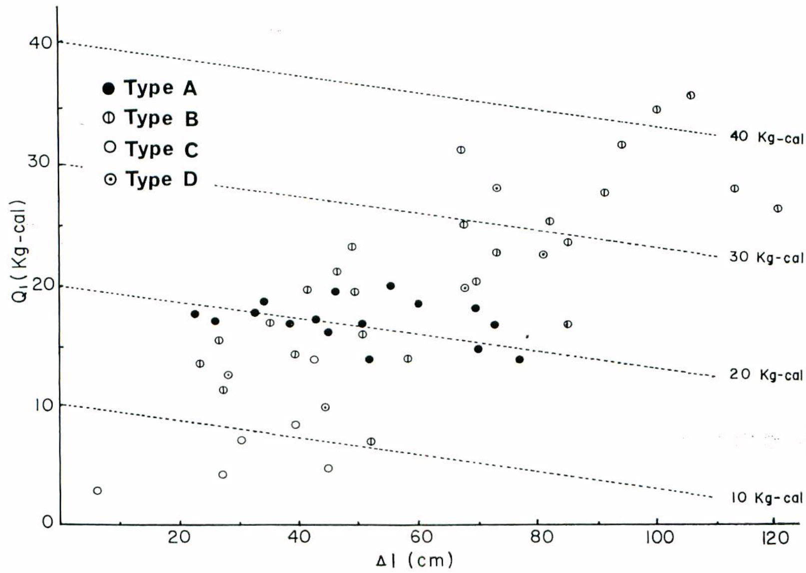

Fig. 17. Relation between heat quantity (Q_1) and dilution quantity (ΔI). Dotted lines show the isopleth of total heat quantity (Q_T).

latitudes 35°N to 60°N, disregarding the cloud cover. The author has reestimated the incident energy using the average monthly cloud covers of April, May and June at weather stations in the coast of the Okhotsk Sea, and obtained 29 kg-cal/cm^2 at the latitude 55°N in the Okhotsk Sea. In this estimation, the back radiation, the evaporation and the conduction of heat from the sea surface are not considered. Therefore, it is reasonable that the incident energy is greater than the total heat quantity, Q_T, which is regarded as a residual heat quantity in the result of the heat budget. As the total heat quantity of type A is somewhat smaller than the incident energy, we could say that the assumption in this computation is satisfied for type A at least. As to the other types, the total heat quantity indicates various value. It is considered that the other types do not satisfy the assumptions, particularly, that the minimum temperature water in summer is remains of the convective mixing in winter.

3 . Cold saline bottom water

Fig. 18 shows the temperature and salinity distribution at 100 m in the northern Okhotsk Sea. The singular region centering at around 55°-30′N, 145°-00′E, where a homogeneous water occupies from the surface to the bottom, complicates the oceanic structure of the northern Okhotsk Sea. The cold water with temperature lower than −1.5°C, the salinity higher than that in the other regions is distributed widely on the continental shelf in the northern Okhotsk Sea and the salinity is remarkably high in the coastal region of the northwestern Okhotsk Sea.

The temperature and salinity profiles below the halo-thermocline at stations in the continental shelf region of the northern Okhotsk Sea are shown in Fig. 19. The water

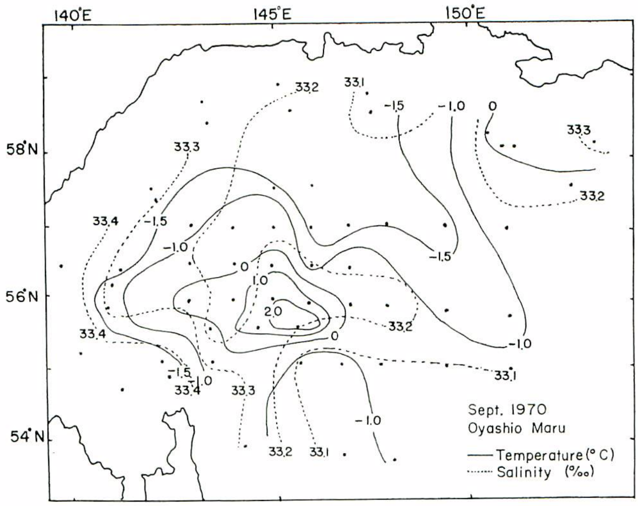

Fig. 18. Temperature and salinity on 100 m layer in the northern Okhotsk Sea. Solid lines are isotherms and Dotted lines are isohalines (After KITANI and SHIMAZAKI 1971).

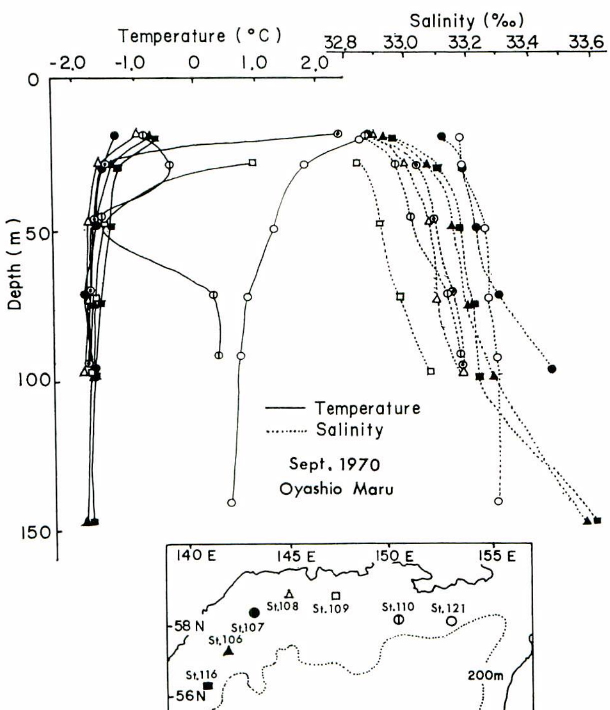

Fig. 19. Vertical profiles of temperature and salinity of the shelf region in the northern Okhotsk Sea. Solid lines show temperature and Dotted lines show salinity.

above the halo-thermocline, of which the depth is generally shallower than 30 m in this region, is the summer surface water with a high temperature and a low salinity. The cold water below the thermocline generally shows little vertical variation in temperature. However, the region south of Koni Peninsula, as shown in St. 110, St. 121, seems to be considerably different in the water mass stratification from other regions in the northern Okhotsk Sea. In the northern Okhotsk Sea, except in the region south of Koni Peninsula, under the halo-thermocline the temperature and salinity is almost uniform vertically. And these homogeneous waters have a noticeable local differences in salinities, although they are almost similar in the temperature, which is near the freezing point. The cold homogeneous water of the western stations on the continental shelf, such as St. 104, St. 116, are high in salinity while in the other stations, such as St. 108, St. 109, are low in salinity. Furthermore, special attention should be paid to the salinity profile on the continental shelf, where the salinity under the homogeneous water increases with depth in spite of a uniform temperature. This suggests that the cold water below the halo-thermocline can be divided into two strata ; the upper one is cold homogeneous water just under the thermocline and the lower one cold water with increasing salinity toward the bottom. The latter is especially named as a "cold saline bottom water" in the present paper.

The cold saline bottom water observed near the bottom (149 m) at 57°-22′N, 142°-07′E in August 22, 1970, on board the R. V. Oyashio Maru, has the smallest specific volume, with the thermostric anomaly $\delta_T=$ 102 cl/ton, the temperature -1.76°C, salinity 33.59‰, and the dissolved oxygen 6.1 ml/1. But these values do not indicate that of the water at bottom as this observation is not carried out to the bottom. By means of the extrapolation, the specific volume at the bottom is estimated to be $\delta_T=100$ cl/ton.

Although more or less different from year to year, the sea ice formation in the Okhotsk Sea as observed by the weather satellite "ESSA 8" begins in November from the northwestern coastal region and gradually extends eastward. And, in severe cooling periods, most of the Okhotsk Sea is covered with the sea ice except the narrow region along the northern Kuril Islands. Fig. 20 shows the distribution of sea ice in March, the last month for the sea ice formation. In this month it is noticeable that the open sea is found along the northern coast, although this area is covered by sea ice in the severe cooling period of January and February. The

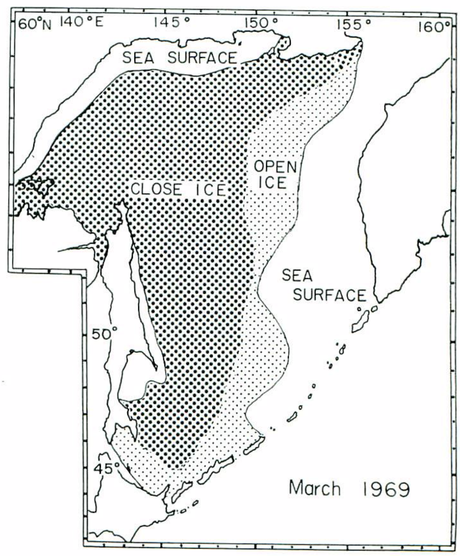

Fig. 20. Sea ice distribution in March over the Okhotsk Sea (by weather satellite "ESSA 8").

Table 2. Monthly mean of the atmospheric pressure around the Okhotsk Sea. At stations except Lopatoka, anomaly of the atmospheric pressure is shown as the deviation from one at Lopatoka. The station name is shown in the chart of Fig. 1.

Lopatoka	Jun.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.
	1004.0	1003.5	1007.0	1007.8	1011.0	1012.3	1011.0	1011.8	1012.6	1011.0	1007.8	1003.8
Sopochnoe	4.5	4.5	3.5	3.2	0	−1.3	−0.8	−0.8	−1.1	−0.2	1.0	2.7
Yamsk	8.0	9.5	7.0	4.2	1.0	−2.5	−1.8	−1.3	−0.6	1.0	4.2	7.2
Okhotsk	15.5	16.0	9.3	4.1	−0.8	−4.5	−2.2	−1.3	−0.3	3.2	8.0	12.7
Chamkan	18.0	16.5	9.8	2.2	−2.2	−5.8	−4.0	−3.9	−0.8	4.5	9.8	16.2
Yuzno Sakhalinsk	9.7	10.5	5.8	3.2	−0.7	−3.3	−3.3	−1.8	0.4	3.0	5.2	7.2
Etorofu	6.0	6.5	3.0	3.2	0.2	−1.3	−0.2	−0.5	1.5	3.0	4.2	4.0

monthly mean atmospheric pressures at some stations around the Okhotsk Sea are shown in Table 2. In winter, the pressure is high at Okhotsk and Chamkan, in the northwest coast of the Okhotsk Sea, while it is low at the Cape of Lopatoka in the southeast of the Okhotsk Sea. The northwesterly wind prevails in winter in the Okhotsk Sea, particulary strong in January and February as it can be inferred from the atmospheric pressure gradient. It has been already reported that the sea ice drifts as a result of the wind stress (AKAGAWA 1958, FUKUTOMI 1951, 1953). Thus, it is considered that the sea ice formed in the northern Okhotsk Sea drifts southward due to the northwesterly wind and open sea occurs in the coastal region in the northern Okhotsk Sea. However, in Jaunary and February the open sea in the coatsal region of the northern Okhotsk Sea is scarcely evident in observations of the weather satellite "ESSA 8". This fact suggests that a new sea ice is formed continuously in the northern coastal region during severe winter time. Therefore, it is considered that the sea water below the sea ice in this region becomes remakably salty as a result of the formation of sea ice.

The increase of salinity ΔS by freezing in the water of homogeneous salinity due to the convectiction below the sea ice is given by

$$\Delta S = \frac{\Delta I\,(Sm - S_I)}{Dm - \Delta I} \qquad (8)$$

where Dm is the depth of convection layer, ΔI is the thickness of water corresponding to the thickness of sea ice, Sm is the salinity of the homogeneous water before the sea ice formation, and S_I is the salinity of the sea ice, being assumed as 4‰ here (FUKUTOMI *et al.* 1951). As the salinity Sm is approximately in the very small range of 32.8‰ to 33.2‰ as mentioned previously, the variation of Sm in this range has little influence of ΔS in the equation (8). The value of ΔS is calculated for different values of Dm and ΔI taking Sm as 33.0‰ as shown in Table 3. In the northern coastal region, the depth of convection layer Dm seems to be the same as that to the bottom because the water of convective mixing in this region almost reaches the bottom. The loss of heat from the sea surface seems to be uniform in the whole northern coastal region in spite of the

Table 3. Increasing salinity from 33.00‰ in connection with the freezing thickness and convective mixing depth.

(Sm=33.00‰)

△I (Freezing Thickness) / Dm (Mixing Depth)	50 cm	100 cm	150 cm	200 cm
50 m	0.29‰	0.59‰	0.90‰	1.21‰
100 m	0.15‰	0.29‰	0.44‰	0.59‰
150 m	0.10‰	0.19‰	0.29‰	0.39‰
200 m	0.07‰	0.15‰	0.22‰	0.29‰

difference of depth to the bottom. Therefore, the formation of sea ice starts much earlier in a shallow region than in a deep region, because of more rapid cooling of a water column. For the same thickness of sea ice, the increase of salinity, ΔS, is greater in a shallow region than in a deep region, as shown in Table 3. Considering further the influence of cold wind from the continent in winter, it is reasonable to consider that the increase of salinity is remarkably large in the narrow region along the northern coast of Okhotsk.

Fig. 21 shows the temperature and salinity distribution along the NW-SE section in the northern Okhotsk Sea. Across the singular region at the northeast of Sakhaline,

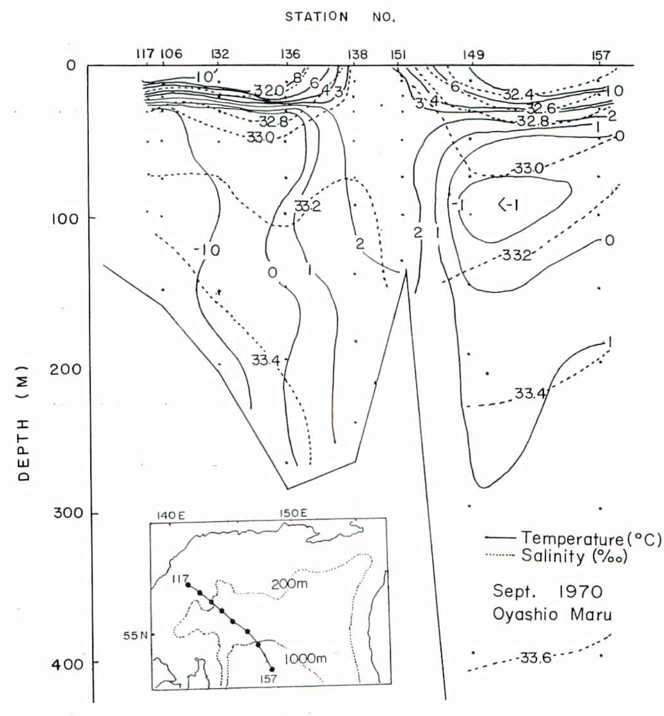

Fig. 21. Temperature and salinity of the vertical section in the northern Okhotsk Sea. Solid lines are in isotherms and Dotted lines are isohalines (After KITANI and SHIMAZAKI, 1971).

this section shows the complicated distribution of the temperature and salinity. In these distributions we should note that the cold saline (below $-1.7°C$ and above 33.4‰) bottom water exists on the continental shelf, such as St. 117, St. 106, and seems to spread downward on the continental slope. As a matter of fact, this cold saline bottom water has a high dissolved oxygen content, more than 6 ml/l. The reason of this phenomenon might be that a large quantity of the cold saline mixing water is formed in winter in the northern coastal region, and it flows downward along the continental shelf as a cold saline bottom water, because it has a remarkably high density compared to water normally found at these depths. Therefore, the cold saline water near the bottom at St. 104, St, 116 in Fig. 19 is interpreted as an advective water, which originates in the convective mixing water at the shallow region with the increase of salinity due to freezing in winter and moves downward to the deeper region.

4 . The movement of the transitional water

Typical T-S curves in the Okhotsk Sea and the western North Pacific Ocean are shown in Fig. 22. The mesothermal water has the thermostric anomaly of $\delta_T=105$ cl/ton at the south of Kamchatka Peninsula. The specific volume of the most heavy water among the cold saline bottom waters is approximately the same as that of the mesothermal water. These two waters are, however, quite different in properties ; one, the mesothermal water, with the high temperature warmer than 3°C, the dissolved oxygen content less than 1 ml/l, and the other, the cold saline bottom water, with the low temperature lower than $-1.5°C$, high dissolved oxygen content more than 6 ml/l. In the central and southern regions, the water of $\delta_T=105$ cl/ton is found just in the mid layer of the transitional stratum with the intermediate properties between the mesothermal water and the cold saline bottom water. The second minimum temperature water is recognized in the central region, although it is not so clear, this water generally exists on the layer above the $\delta_T=100$ cl/ton surface.

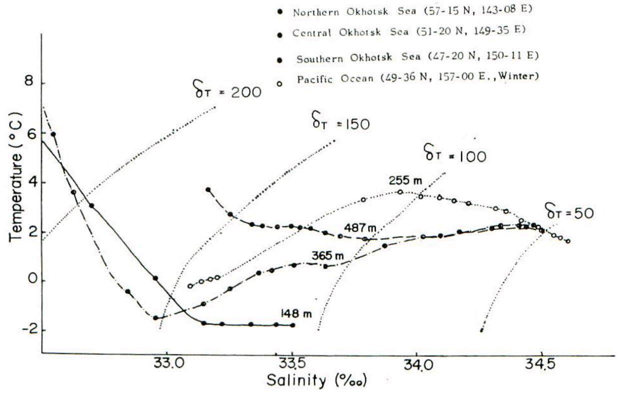

Fig. 22. Typical T-S curves in the Okhotsk Sea and northwestern Pacific.

The distributions of temperature and dissolved oxygen on the isosteric surface of $\delta_T = 105$ cl/ton, as well as its depth, are shown in Figs. 23-a, b and c. Comparing Fig. 23-c with Fig. 1, it is noticeable that the cold saline bottom water of $\delta_T = 105$ cl/ton exists only on the continental shelf in the northwestern Okhotsk Sea. The temperatures on

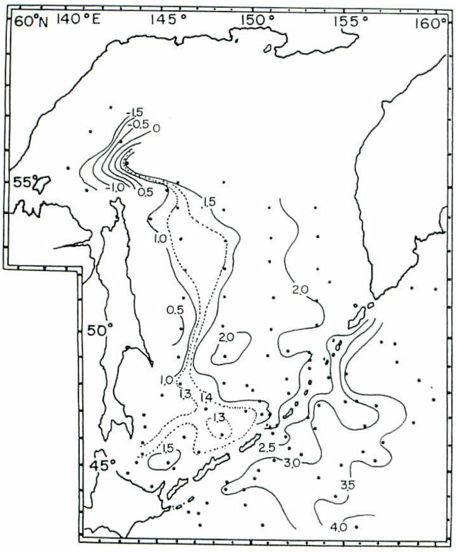

Fig. 23. a Temperature (°C) on the surface where $\delta_T = 105$ cl/ton. No water of $\delta_T = 105$ cl/ton has been observed in the blank area in the northern Okhotsk Sea.

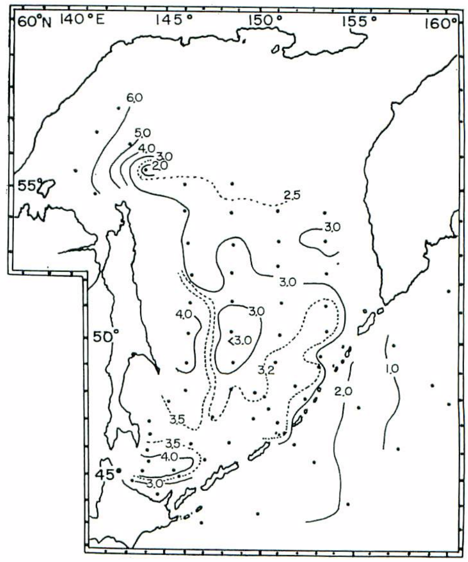

Fig. 23. b Oxygen concentration (ml/l) on the surface where $\delta_T = 105$ cl/ton.

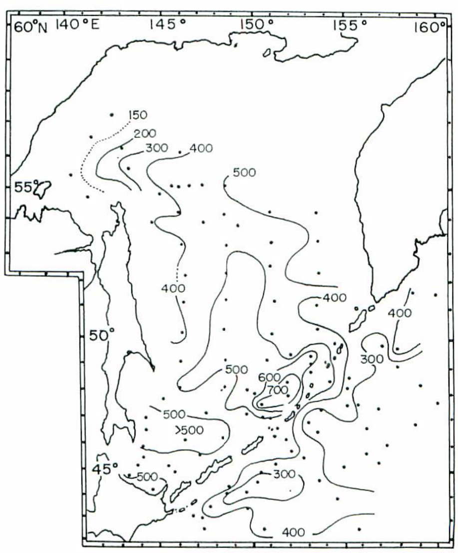

Fig. 23. c Depth (m) of the suface where $\delta_T = 105$ cl/ton.

this isosteric surface indicate the lowest value in the northwestern region of the Okhotsk Sea and the highest value in the region south of the Kamchatka Peninsula. The temperature in the area between these two regions decreases toward the west (Fig. 23-a). The dissolved oxygen on this isosteric surface is highest in the northwestern Okhotsk Sea, while it is lowest in the region south of the Kamchatka Peninsula (Fig. 23-b). It should also be noted that this isosteric surface is remarkably deep, more than 700 m, in the region north of the central Kuril Islands (Fig. 23-c). This distributions of temperature, dissolved oxygen and depth suggest that the cold water originating from the cold salıne bottom water in the northwestern Okhotsk Sea flows southward in the western part of the Okhotsk Sea and the warm water originating from the mesothermal water in the western North Pacific Ocean intrude northward in the eastern part. The horizontal mixing of both the waters occurs in the layer up to ca. $\delta_T=100$ cl/ton. Since the second minimum temperature water has generally the thermosteric anomaly of $\delta_T=100$ cl/ton or a little more, it might be formed by the horizontal mixing of the cold water with the warm water. In the southwestern Okhotsk Sea, Soya Warm Water, which is warm, saline and high oxyty water, is sligtly recognized on the isosteric surface of $\delta_T=105$ cl/ton (Fig. 23-b). The volume transport of Soya Warm Water from the Japan Sea into the Okhotsk Sea is very small, 17,520 km^3/year (KURASHINA *et al.* 1967), in comprison with the water volume of the Okhotsk Sea, 1,365,000km^3. However, the influence of Soya Warm Water upon the water mass in the Okhotsk Sea, at least in the southwestern Okhotsk Sea, might not be ignored as shown in Fig. 13 and Fig, 23.

The dynamic topography of 400 surface over 1500 decibar in the region along the Kuril Islands is shown in Fig. 24. A remarkable anticyclonic gyre is found to the north of the central Kuril Islands, and, to the south of it, cyclonic and anticyclonic gyres are found side by side along the Kuril Islands, therefore the region along the Kuril Islands is rather complicated in structure, where some gyres develop and a strong vertical water mixing

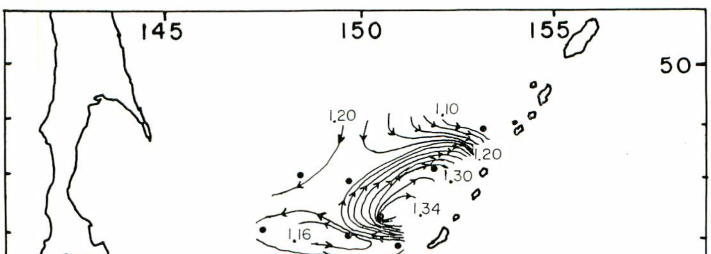

Fig. 24. Dynamic topography of the 400-decibar layer with relative to 1500-decibar surface.

occurs.

Fig. 25 shows the profile of geostrophic velocity along the Kuril Islands referred at 2500 decibar level except in the southwestern margin, as shown in the figure with broken lines. A positive number in the figure indicates northwestward flow and a negative one southeastward flow. Since this section along the Kuril Islands crosses several cyclonic and anticyclonic gyres, the flows of different direction appear alternatively in this profile. The greatest velocity is found at the north of Uruppu Island, between the stations No. 66 and No. 47. Although St. 66 was occupied a week later from time of observation at St. 44, considering the scale of phenomena and the general features of temperature and salinity profiles of the section, the strong northwestward current at the north of Uruppu Straits is considered not to be fictitious, although the numerical values might be doubtflul.

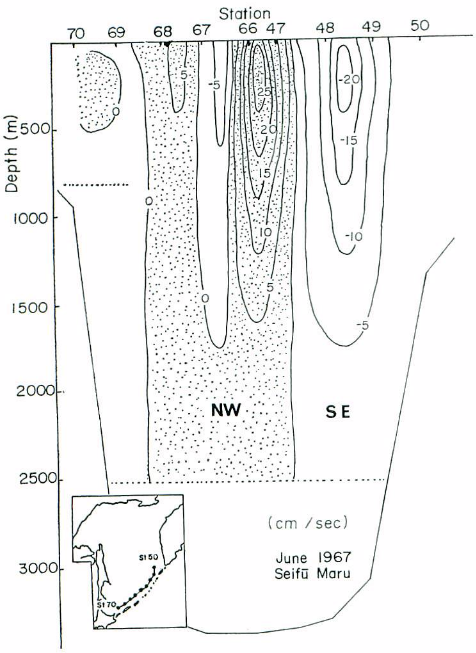

Fig. 25. Velocity (cm/s) profile across the vertical section along the Kuril Islands with relative to the 2500-decibar surface (in southwestern part of this section, with relative to the 800-decibar surface).

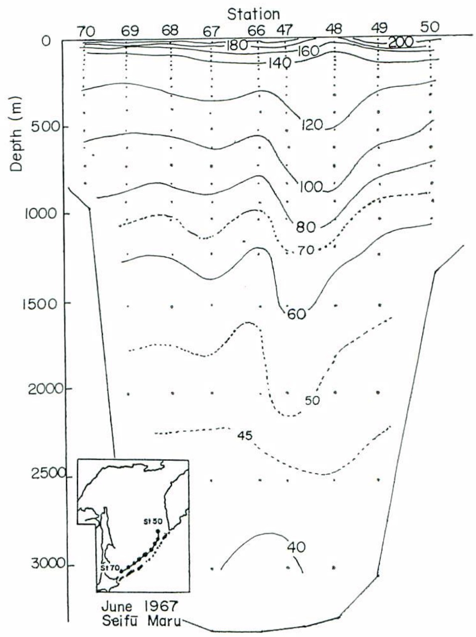

Fig. 26. Thermosteric anomaly (cl/ton) on the vertical section along the Kuril Islands.

The profile of the thermosteric anomaly along the Kuril Islands is shown in Fig. 26. The figure shows that in the region of the remarkable anticyclonic gyre near St. 48 in Fig. 24 the vertical mixing occurs centering around about 300 m layer, and around this station the sinking of large scale takes place from $\delta_T = 120$ cl/ton to $\delta_T = 50$ cl/ton. Furthermore, the distributions of the phosphate-phosphorus and the dissolved oxygen indicate the remarkable sinking with vertical mixing in the layer from 500 m to 1500 m.

Among the transitional water in various types of vertical structures, those of types C and D have particular characters, disclosing the mechanism of its formation. The type C water, which occupies not only the area along the Kuril Islands but also the northeast of Sakhalin and the south of Koni Peninsula, is characterized by the intensive vertical mixing. While the type D water, which exists in the boundary of the cold water and the warm water scattering in the central part of the Okhotsk Sea, represents the horizontal mixing in the layer shallower than ca. $\delta_T = 100$ cl/ton surface. Therefore, the transitional water is formed through two processes, one is the vertical mixing below the surface layer, and the other horizontal mixing of the warm water originating from the mesothermal water and the cold saline bottom water. The transitional waters of types A and B are formed through a process in between the above extremeties.

Ⅳ. Conclusions

The water mass stratifications and the movement of water in the transitional stratum are shown schematically in Fig. 27. In winter, it is considered that, in general, due to the convective mixing, the waters on the continental shelf of the northern Okhotsk Sea become homogeneous vertically in the temperature and the salinity from the surface to near the bottom, but temperatures and salinities are different horizontally by regions, although, there is a movment of water to keep the dynamical equilibrium. And generally a heavy water with a high salinity is formed in the shallow region on the continental shelf because the quantity of the sea ice per a unit area of sea surface is greater in a shallower region than in a deeper region. The cold saline water formed in winter moves toward the deeper regions along the bottom of the continental shelf, reaching the continental slope. Then,

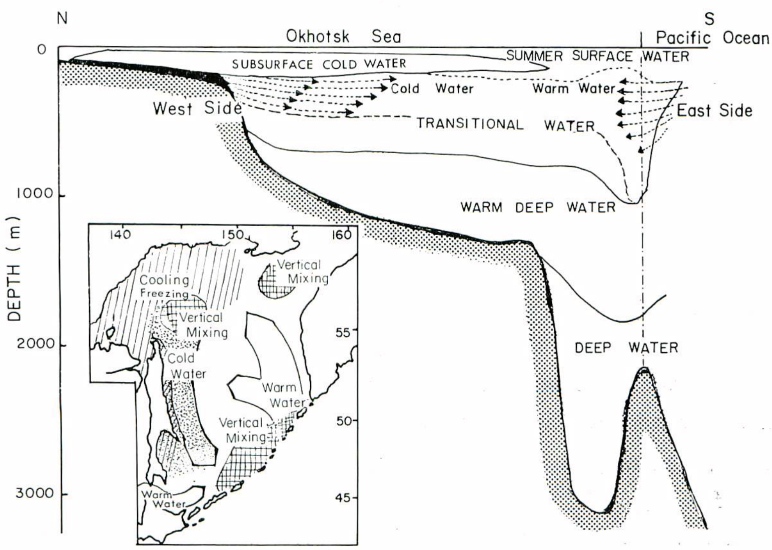

Fig 27. Schematic representation of the oceanic structure and the water movement in the transitional layer in the Okhotsk Sea.

it spreads horizontally on an isosteric surface, corresponding to its own density, on leaving the sea bottom. The smallest thermosteric anomaly of the cold saline bottom water is $\delta_T=102$ cl/ton on the northern continental shelf, and this is approximately equivalent with that of the mid-layer of thick transitional water in the deeper region. The cold water with a high density flows down over the continental shelf, then it spreads southward very slowly along the western margin, diffusing into the upper stratum of the transitional layer. The densities of the mesothermal water in the western North Pacific Ocean and the cold saline bottom water in the northern Okhotsk Sea are almost the same. A portion of the mesothermal water enters the Okhotsk Sea through the straits of the northern Kuril Islands. Due to the vertical mixing in the narrow region near the northern Kuril Islands, the mesothermal water looses its characteristic properties, and the surface water in this region becomes colder than in other regions. While, the subsurface water below the summer surface stratum in this region is warmer than those in the other regions of the Okhotsk Sea, although it is colder than in the western North Pacific water. The most of this subsurface water spreads northwards in the eastern Okhotsk Sea and partially reaches the northern Okhotsk Sea with a remarkable decrease of temperature and salinity and the increase of dissolved oxygen. The remarkable movements of two waters with different properties coexist in the transitional stratum. It is considered that the horizontal mixing of the two waters occurs along a layer above ca. $\delta_T=100$ cl/ton in the area where two movements neighbour each other horizontally.

The second minimum temperature water that appears mainly in central part of the Okhotsk Sea seems to be formed by the intrusion of the cold water originating in the northern Okhotsk Sea. We can consider further that the maximum temperature above the second minimum temperature is formed by the intrusion of the warm water originating in the western North Pacific. It is considered that this intrusion takes place in the layer above ca. $\delta_T=100$ cl/ton surface because the cold water originating in the northern Okhotsk Sea seems to have the thermosteric anomaly δ_T of more than 100 cl/ton. It is considered that the transitional water with δ_T of less than 100 cl/ton is formed mainly in the northern region along the Kuril Islands by the vertical mixing of two waters ; the upper transitional water in the Okhotsk Sea and the Pacific water below the mesothermal water.

The minimum temperature water of type A, which is homogeneous for the temperature and salinity in the minimum temperature layer, is interpreted as the remaining water of the convective water in winter. Therefore, we are able to infer the oceanic condition in winter from this water in summer. This homogeneous water, except in the northern region, generally indicates a salinity as low as that of the convective mixing water without freezing. This fact suggests that the freezing hardly takes place except in the northern Okhotsk Sea and the majority of the sea ice observed over the southern and central region has drifted from the northern Okhotsk Sea by the northwesterly wind in winter. The homogeneous cold water formed in winter disappears from the surface due to the heating after winter. Particularly, in the region where the vertical stability between the surface and the minimum temperature layer is low, the homogeneous cold water disappears rapidly, because the eddy conductivity of the heat from the sea surface is remarkably large in such region. Concerning the water mass structure, the transitional water with comparatively low temperature exists below the homogeneous cold water. Therefore, this transitional layer forms the minimum temperature layer after the homogeneous cold water disappears completely. And then, some minimum temperature waters of type B and C which were described previously constitute the transitional water. Furthermore, the second minimum temperature water of type D also, consists of the transitioanal water. That is, in the Okhotsk Sea two cold waters formed by the different mechanism are possible to occur as the minimum temperature water. It may be possible to discriminate the minimum temperature water into two types, by the depth, the specific volume, and the character of the minimum temperature water, *i. e.* the remains of the convective mixing water in winter and the transitional water respectively. The region where the minimum temperature in the vertical profile exists in the transitional water extends seasonally northward from the southern Okhotsk Sea in consequence of the disappearance of the homogeneous cold water in the subsurface layer.

V. Summary

One of the characteristics regarding the oceanographic structure of the Okhotsk Sea is the thick cold water beneath the summer surface water. The cold water can be discriminated into two cold waters ; the one is the subsurface cold water, which is the remain of the winter surface cold water formed by the thermal convection and is found at the depth shallower than about 100m. The other is the lower cold water, called as the transitional water, which is higher in temperature and salinity than those of the subsurface cold water, and is found at the depth from about 150 m to about 600 m. Particularly, the transitional water is a unique one, that is never found out in other subarctic areas such as the Bering Sea and the western North Pacific Ocean, and is formed by a more complicated mechanism than the subsurface cold water. This transitional water is a mixture of the cold saline bottom water in the northern shelf region and the mesothermal water in the western North Pacific Ocean. The cold saline bottom water has a high dissolved oxygen and a low specific volume, having $\delta_T=102$ cl/ton (temperature -1.7°C, salinity 33.59‰) as its minimum value. This cold saline water, which is formed by the freezing of surface water in the northern Okhotsk Sea, decends on the continental shelf and then diffuses toward the south along the western side of the Okhotsk Sea. While, the warm water originating from the mesothermal water in the western North Pacific Ocean diffuses toward the north along the eastern side of the Okhotsk Sea. Therefore, the oceanic circulation in the Okhotsk Sea is roughly counterclockwise with the northward movement of warm water and southward movement of cold water. The horizontal mixing is intensified in the central Okhotsk Sea where the two waters having different properties

contact each other, because these waters are almost equal in the specific volumes. Moreover, the vertical mixing takes place remarkably around the Kuril Islands. Such mixings contribute greatly to the formation of the transitional water in the Okhotsk Sea. The disappearence of the subsurface cold water, extending northward from the region along the Kuril Islands, is gradually strengthened by a heat conduction from the surface during the heating period. After the subsurface cold water completely disappears, the minimum of the vertical temperature appears in the transitional water characterizing the water mass stratification in the Okhotsk Sea.

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オホーツク海の海洋学的研究
——特に寒冷水に関して——

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要　　　旨

オホーツク海の海洋構造上，特に有用生物資源にとって無視できない冷水について，その実態と形成機構について検討を行なった。得られた結果は，次のとおりである。

1　夏季オホーツク海の海洋構造における大きな特徴の一つは，夏季表層水の下に厚い冷水層が存在することである。この冷水層は，次表層冷水（Subsurface Cold Water）と移行層水（Transitional Water）との二層に分けることができる。

2　次表層冷水は，冬季の表層冷却によって形成された対流混合冷水の残存したもので，塩分33.2‰以下，水深100 *m* 以浅に見られる。昇温期には，海表面からの渦動伝導などでこの水は，消滅して行く。

3　移行層水は，次表層冷水の下にあって，次表層水よりは，やや高温であるが，他の亜寒帯海域では，見られないオホーツク海固有の厚い冷水層である。

4　北部オホーツク海の陸棚上では，冬季の結氷が活発で，その結果，海氷下の対流混合水では，著しく塩分が増加する。特に北西海域では，塩分33.6‰，比容アノマリー $\delta_T \doteqdot 100$ cl/ton にも達する冷水が形成される。この水は，オホーツク海に現われる冷水としては，著しく高密度であるため，北部陸棚上を降下し，さらに，オホーツク海西側域の中層を等密度面上に沿って南下拡散する。オホーツク海中央域にみられる第2極小水温は，この過程において形成される。

5　オホーツク海固有の移行層水は，二つの機構，即ち，およそ $\delta_T = 100$ cl/ton 以上の層での異なる二水系（北部陸棚起源の高密度冷水，北西太平洋起源の中暖水）の水平混合と千島列島付近での大規模な鉛直混合とによって形成される。

6　次表層冷水が消滅した後は，移行層水が極小水温水となっている。即ちオホーツク海の極小水温水には，二種類の水系が考えられる。これらは，その塩分，密度，深度，水温塩分の鉛直分布型から識別することができる。