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Variability of the Deep Cold Water in the Japan Sea*
—Particularly on the Abnormal Cooling in 1963—

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Abstract: In order to find out the key for the problem of variability mechanism of the Japan Sea, basing on the average temperature field in the Japan Sea in the years of 1954~1966 as normal, some normal characteristics of the Sea and the abnormal cooling phenomenon in 1963 were studied by using temperature anomaly from the normal. Results are summarized as follows;
1) The variation of water temperature at 50 m depth represents to the variation of volume transport of the Tsushima Current.
2) The zone of maximum fluctuation of water temperature at 200 m depth corresponds nearly to the Polar Frontal Zone in the Japan Sea. The 5°C isotherm appears to represent the boundary between the warm and cold water regions.
3) Abnormal cooling in the Japan Sea started in the winter 1963 and terminated in the next winter (1964) in the upper layer which indicated much greater cooling compared to the deeper layer with the termination in the spring of 1964.
4) The abnormal cooling in the Japan Sea varied greatly in space and time. In the Northeastern sea-region cooling (anomaly) was slight until April-May contrary to the considerable one in the Southwestern sea-region in the same season. After July remarkable cooling was observed around the 50 m depth in both sea-regions. In the deeper layer along the coast of Northeastern sea-region the accumulation of warm water appeared more or less in summer.
5) Abnormal cooling of the Japan Sea in the Southwestern sea-region in winter and spring was caused by the severe northerly monsoon in winter (the abnormal drop in atmospheric temperature accompanied in winter over the same region). However, after spring and summer of 1963 the abnormal cooling in the Southwestern and Northeastern sea-regions was caused mainly by the decrease in water transport or heat transport by the Tsushima Warm Current from winter to summer in the said year.
6) The decrease in the water transport of Tsushima Warm Current reguired conceivably the upward prevalent flow of the deeper cold water in the Southwestern sea-region in that year and the southward cold-water intrusion to the southern part of the Northeastern sea-region.

1. Introduction

Concerning past studies of hydrographic variability in the Japan Sea UDA (1934, 1936, 1938, 1950, 1952, 1959) reported some basic features and patterns of the ever-changing Japan Sea. In the present paper, for the purpose of finding out the mechanism of hydrographic fluctuation of the deep cold water in the Japan Sea, the authors investigated as a first basic step some characteristic features of normal temperature anomaly from the above normal, analysed the abnormally cold sea conditions in the Japan Sea.

2. Materials and methods used

In order to construct the maps of normal (averaged) temperature fields in the Japan Sea at the depths of 0 m, 50 m, 100 m and 200 m for each month respectively, general oceanographical maps in the Japan Sea during 1954~1966 published by the Japan Sea Regional Fisheries Research Laboratory were utilized, except the winter one (Dec., Jan. and Feb.) owing to its scanty of data.

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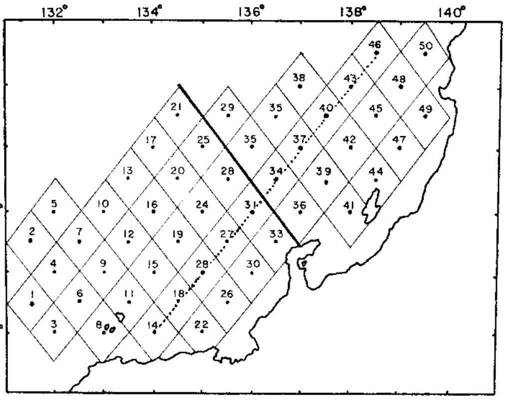

Fig. 1. Divisional areas and associated lattice numbers in the sea regions studied. (Thick line in the middle indicates the boundary of the Northeastern and Southwestern subregions. The oblique dotted line shows the reference sectional line.)

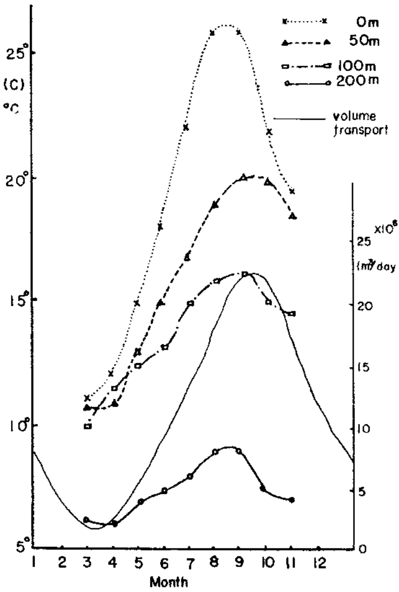

Fig. 2. Seasonal variation of averaged water temperature at each depths (0, 50, 100, 200 m) and the computed water transport of Tsushima-Current (After M. MIYAZAKI, 1952) for reference.

Taking representative points at each center of small grid areas (50 small grid areas as shown in Fig. 1), we have computed the averaged water temperature and the standard deviation at each point. Air temperature anomaly and wind speed anomaly were computed from Geophysical Review (KISHO YORAN) published by the Japan Meteorological Agency. Particularly water temperature anomaly in the period from October of 1962 to June of 1964 was computed to inspect the actual state and variation of the abnormally cooled water in the Japan Sea.

We have divided the sea-region in question into two subdivisions (Southwestern and Northeastern sea-regions) by the thick line from northwest to Noto Peninsula as shown in Fig. 1, and computed anomaly for each sea-region. Finally basing on such features of normal temperature fields, the abnormal cooling of 1963 was studied.

3. Results

1) Characteristic features of average temperature fields

Temperature maximum for each month (March-November) for each depth (0, 50, 100, 200 m depths) is indicated as shown in Fig. 2.

Owing to the scarcity of winter data the period of temperature minimum is not clear. The monthly variation of water temperature at 50 m depth with respect to the phases of maximum and minimum coincides well to those of the water transport* of the Tsushima Warm Current as shown in Fig. 2. (* Refer to MIYAZAKI, 1952)

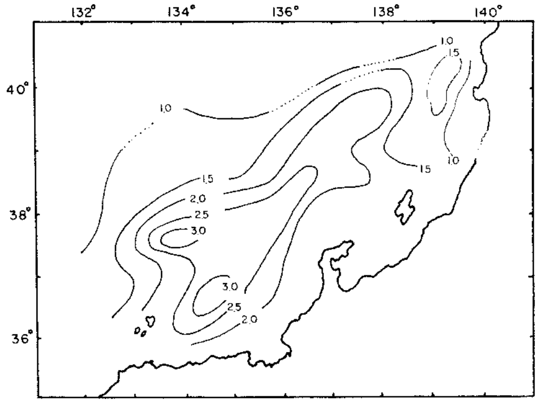

Fig. 3. Example of horizontal distribution of the standard deviation at 200 m layer. (March)

Fig. 3 is the representative map of standard deviation of average water temperature at 200 m depth. Characteristic feature for each month reveals the maximum standard deviation or temperature fluctuation around the Polar Frontal Zone, and also greater amount near around cold water intrusion locally. Those greater variablity

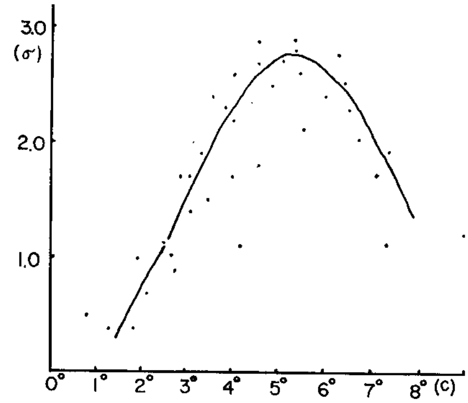

Fig. 4. Rlation between the standard deviation (σ) and its water temprature at 200 m depth. (July for example)

might be mostly due to alternate oceurrence around the cold fronts mentioned. The degree of temperature fluctuation year by year is well denoted by the standard deviation.

Fig. 4 indicates the relationship between the degree of temperature fluctuation and the average water temperature. It shows maximum fluctua-

Table 1. Wind speed anomaly along at the coast of the Japan Sea in Dec., 1962—Mar., 1963.

Month / Weather Station	1962 Dec.	1963 Jan.	Feb.	Mar.
Wakkanai	−0.6	−0.1	−0.4	−0.9
Otaru	−0.5	−0.3	−0.2	−0.6
Hakodate	−0.3	−0.3	−1.0	−0.7
Akita	−0.8	0	−1.2	−1.0
Sakata	−0.5	+0.3	−1.4	−1.1
Aikawa	−1.6	+1.5	−0.9	−0.8
Niigata	−0.8	+0.7	−0.8	−0.5
Takata	0	0	0	−0.2
Wajima	−0.6	+0.2	−0.5	−0.2
Fushiki	−0.3	0	−0.4	−0.2
Tsuruga	0	−0.8	−1.0	−0.3
Maizuru	+0.4	+0.3	−0.3	+0.1
Toyooka	−0.5	0	−1.0	−0.6
Tottori	−0.4	+0.9	−0.6	−0.6
Yonago	−0.1	+0.5	−0.7	−0.3
Saigo	−0.3	+0.4	−1.1	+0.2
Matsue	−0.6	+1.7	−1.0	−0.3
Hamada	+0.2	+2.9	0	0
Shimonoseki	−0.6	+2.2	−0.6	−0.8
Fukuoka	−0.6	+1.7	−0.3	−0.1

Table 2. Air temperature anomaly along at the coast of the Japan Sea in Nov., 1962—Jul., 1963.

Month / Weather Station	1962 Nov.	Dec.	1963 Jan.	Feb.	Mar.	Apr.	May	Jun.	July
Wakkanai	−0.4	+1.4	+2.3	+1.9	+1.9	+1.0	+2.0	+0.2	+0.1
Otaru	−0.2	+0.8	+1.7	+2.5	+2.2	+0.9	+1.3	+0.6	+0.2
Hakodate	−0.6	+1.6	+1.4	+2.1	+1.6	+0.8	+0.6	−0.4	−0.2
Akita	−0.2	+1.6	+0.5	+0.8	+0.6	+1.5	+1.1	−0.2	+0.2
Sakata	0	+1.3	+0.1	+0.6	+0.1	+1.4	+0.9	+0.4	+0.2
Aikawa	−0.4	+1.1	−0.3	+0.4	+0.5	+1.2	+0.7	+0.2	+0.2
Niigata	−0.2	+1.1	−0.5	+0.1	−0.1	+1.3	+1.1	+0.6	+0.5
Takata	−0.3	+1.1	−1.4	0	+0.1	+2.2	+1.4	+1.0	+0.7
Wajima	+0.1	+0.9	−1.0	+0.1	+0.8	+1.9	+1.1	+0.8	+1.1
Fushiki	+0.1	+1.0	−1.9	−0.9	−0.1	+1.7	+1.0	0	+0.9
Tsuruga	−0.4	+1.1	−2.4	−1.6	0	+2.2	+0.9	+1.2	+1.1
Maizuru	−0.8	+0.2	−2.7	−2.2	−0.9	+1.4	+1.3	+1.0	+0.9
Toyooka	−0.3	+0.5	−2.7	−1.6	−0.6	+1.4	+1.4	+0.8	+0.8
Tottori	−0.4	+0.2	−3.5	−2.3	−1.2	+0.8	+0.5	+0.1	+1.0
Yonago	−0.4	+0.8	−3.8	−1.9	−0.5	+1.3	+1.0	−0.2	+1.2
Saigo	−0.3	+0.3	−3.0	−1.6	+0.1	+1.1	+0.6	−0.5	+0.8
Matsue	−0.4	+0.7	−3.3	−2.0	−0.7	+0.9	+0.6	−0.4	+0.8
Hamada	−0.2	+0.8	−2.8	−1.9	−0,3	+1.1	+1.0	+0.1	+0.8
Shimonoseki	−0.5	+0.8	−3.0	−2.2	−0.2	0	+0.3	0	+0.6
Fukuoka	0	+0.8	−2.5	−2.2	0	+0.8	+1.3	+0.3	+0.7

tion around 5°C of average temperature which corresponds to the central isotherm of the Polar Front in the Japan Sea. Or in other words at 200 m depth in the Japan Sea 5°C isotherm locates at the mean position of the boundary between cold water region and warm water region. Accordingly, we can estimate the prevalence of cold and warm water in the Japan Sea at 200 m depth from the location of 5°C-isothermal line approximately.

2) Abnormal cooling in the Japan Sea in 1963 and its Cause

Abnormal weather in 1963 affected on the oceanographic conditions in oriental waters including the Japan Sea greatly. Anomaly of wind speed along the coast of Japan Sea is shown in Table 1, which illustrates stronger wind 2 m/sec than normal along the southwestern coast of Honshu (Japan) around Shimane and Yamaguchi Prefectures in January of 1963 contrary to the weaker wind along the northeastern coast. Anomaly of air temperature is shown in Table 2 which tells us abnormal coldness along the western coast, remarkable in January and February and less in March. Figs. 5 and 6 indicate the distribution of air temperature anomaly in the Japan Sea in the period of particularly abnomal January and February. We can notice easily the regional difference between the northeastern and southwestern sea-regions. Fig. 7 shows the variation of air temperature anomaly averaged in each coastal region, *i.e.* averaged for

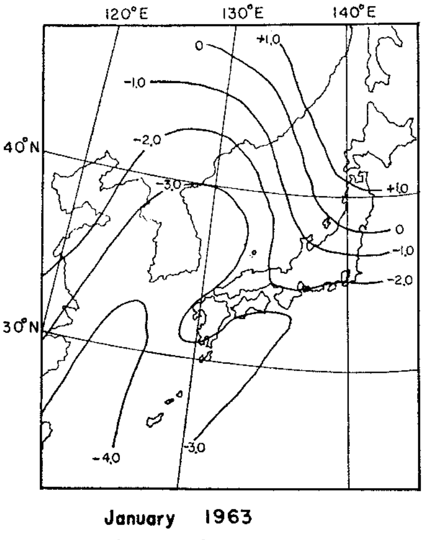

Fig. 5. Distribution of air temperature anomaly in Jan. 1963.

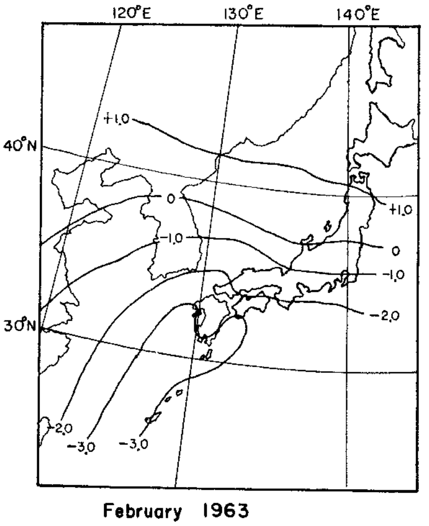

Fig. 6. Distribution of air temperature in Feb. 1963

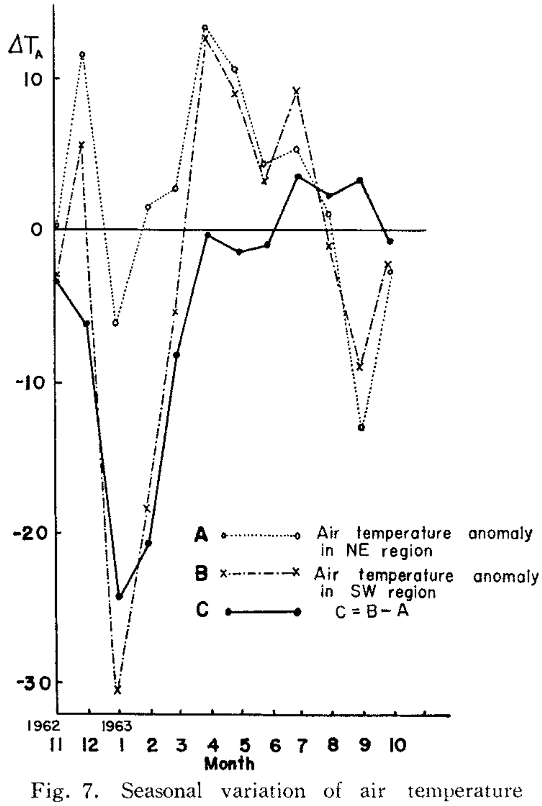

Fig. 7. Seasonal variation of air temperature anomaly and its regional difference.

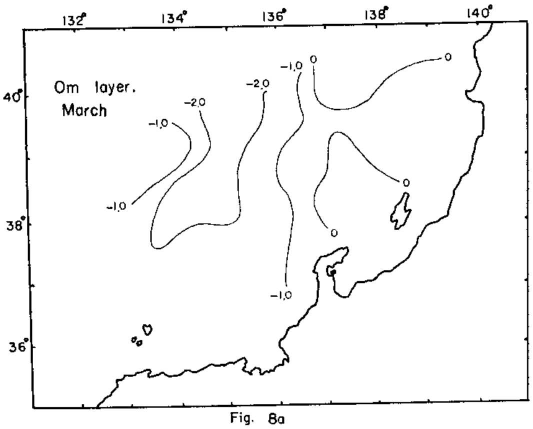

Fig. 8a

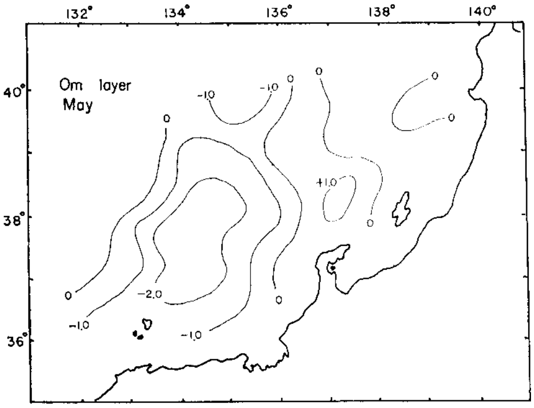

Fig. 8b

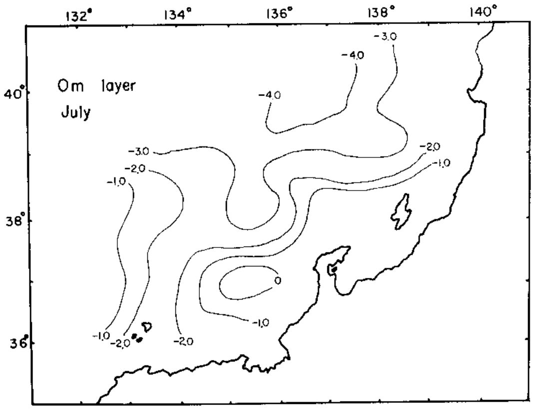

Fig. 8c

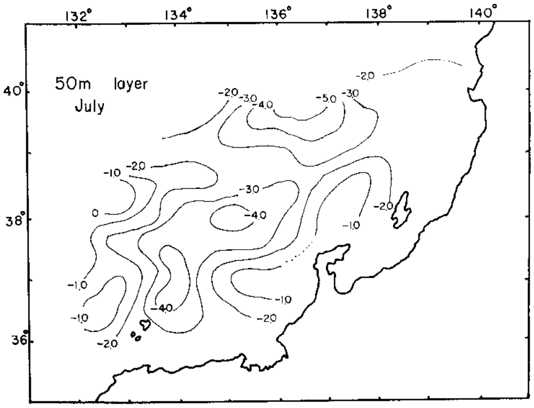

Fig. 8d

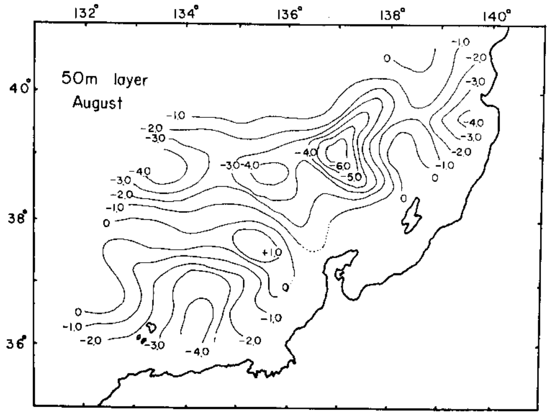

Fig. 8e

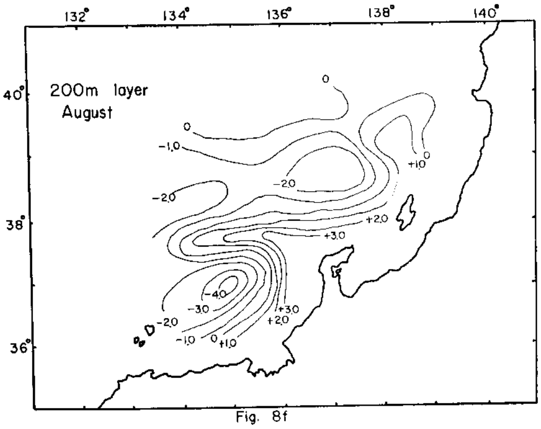

Fig. 8f

Figs. 8a-8f. Some examples of horizontal distribution of temperature anomaly in 1963.

7 stations in the Northeastern coastal region (Akita, Sakata, Aikawa, Niigata, Takata, Wajima, Fushiki) and for 7 stations in the Southwestern coastal region (Tsuruga, Maizuru, Toyooka, Tottori, Yonago, Saigo, Hamada). In January and February great difference between the two regions is observed. In March the difference becomes less and after April no more noticeable. Accordingly, regionally different abnormal coldness (air) occurred in January and February conspicuously.

Inspecting the horizontal distribution of water temperature anomaly, maps indicate different trend between the Northeastern sea-region (normal or a little warmer) and the Southwestern sea-region (colder than normal) in the surface layer till March, April and May of 1963 in less degree compared to the air temperature anomaly distribution (see Figs. 8a, b, c).

Vertical profile of water temperature anomaly at the section stretched to the northeast from St. 14 in Fig. 1 is shown in Figs. 9a and b. Fig. 9a (representative map in the period of the weaker Tsushima Warm Current) denotes the regional difference of cooling in the upper layer shallower than 100 m depth as noticed in the horizontal distribution. In the period of the stronger Warm Current strength after June, different from the weaker period, cooling trend from north in the Northeastern sea-region becomes remarkable, especially around 50 m depth, as shown in Figs, 8d, e, f and Fig. 9b. However, in the deeper layer of the Northeastern sea-region, the anomalous cooling is less and the accumulated warm water mass around Sado Island and Noto Peninsula is noticeable. In the deeper layer of the Southwestern sea-region an enormous cooler anomaly is observed in the northeast of Oki Island presumably due to the more active and persistent upwelling of the deeper cold water than normal, basing on the horizontal and vertical distributions of temperature anomaly. Concludingly, basing on the trend of anomaly distribution, the abnormal oceanographic pattern in 1963 should be considered spatially distinguished into the upper zone and the deeper zone, the Northeastern sea-region and the Southwestern sea-region, and temporally into the weaker period of the Tsushima Warm Current (March, April, May) and the stronger period of the Current (after June).

In order to enhance the abnormal temperature field in 1963 quantitatively averaged anomaly for 50 stations over the whole sea-region is given in Fig. 10. All layer in 1963 is colder than normal except the surface layer in August. Particularly the 50 m depth indicates most remarkable cooling (abnormal) compared to any other depths. Since

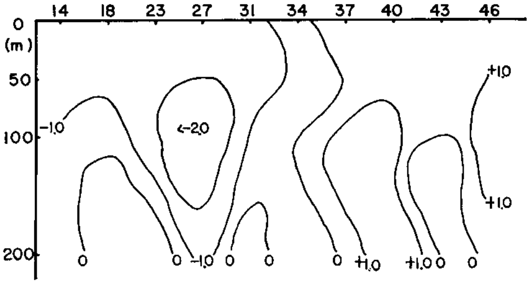

Fig. 9a

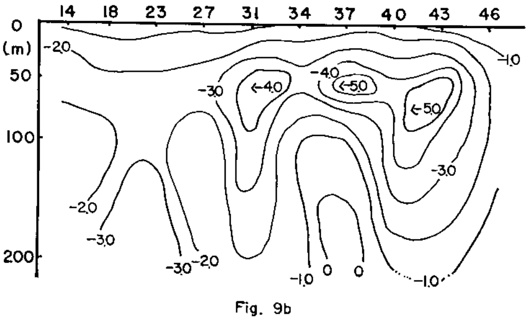

Fig. 9b

Figs. 9a–9b. Profile of water temperature anomaly in March 1963 (Fig. 9a) and August 1963 (Fig. 9b) along the sectional line shown in Fig. 1.

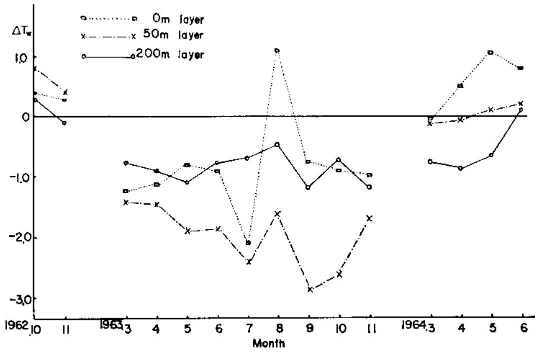

Fig. 10. Abnormal cooling of watermass in the Japan Sea. (Averaged in the areas shown in Fig. 1).

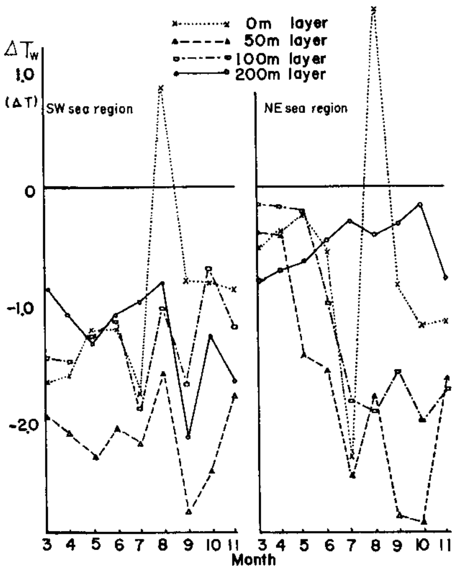

Fig. 11. Degree and trend of abnormal cooling (water temperature anomaly, ΔT_w) in the sea regions shown in Fig. 1.

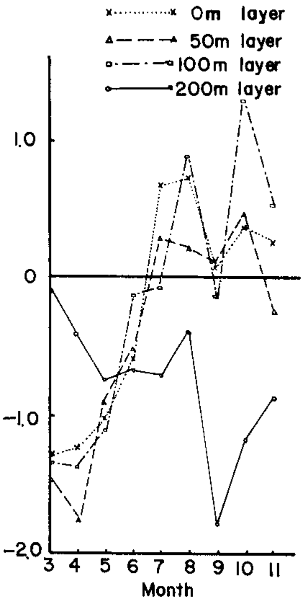

Fig. 12. Seasonal variation of regional difference of water temperature anomaly. (southwestern sea-region minus northeastern sea-region).

we lack the basic maps of the winter periods (Dec., 1962~Feb., 1963 and Dec., 1963~Feb., 1964), the exact beginning period of abnormal cooling and the recovered period to normal are not certain, but the abnormal cooling should be considered to be started in the winter of 1963 (Dec., Jan.). Further, the time of recovery to the normal at 0 m, 50 m and 100 m depths might be estimated as in the winter to spring of 1964. Compared to the above stated layers the recovery at the 200 m depth to normal delayed several months until spring–summer of 1964 conceivably. The degree of abnormal cooling is greater in the upper layer and less in the deeper layer. Fig. 11 shows the degree and trend of abnormal cooling quantitatively denoted by averaged anomaly, for the Northeastern and Southwestern regions, respectively. In the Southwestern sea-region the 50 m depth indicated the most remarkable cooling compared to the other depths, which also indicated conspicuous cooling, throughout the whole year. On the other hand in the Northeastern sea-region different from the Southwestern region, the 0 m, 50 m and 100 m depths were commonly a little cooler than normal until April of that year. However, in May and June in accompany with the growth of Tsushima Warm Current they tended rapidly to the abnormal cooling than normal in which the begining period was earlier at 50 m depth than at sea surface and at 100 m depth. The 200 m depth in the same period was slightly still warmer contrary to the above depths turned to cooling. Fig. 12 shows the difference of the abnormal cooling between both sea-regions. It tells us that in March, April and May (weaker period of the Tsushima Warm Current strength) in the upper layer a greater abnormal cooling occurred in the Southwestern sea-region compared to the Northeastern sea-region. Further, in summer the upper layer in the Northeastern sea-region changed into greater abnormal cooling compared to that in the Southwestern sea-region.

In the deeper layer (200 m depth) against the upper layer, the difference in cooling occurred between two Sea-regions in accompany to the increase of the Warm Current strength. This might be considered as due to the stronger cooling than normal in the Southwestern sea-region owing to the upwelling of deeper cold water contrary to more or less warming in the Northeastern sea-region due to the accumulated warm water.

As already shown in the characteristics of the

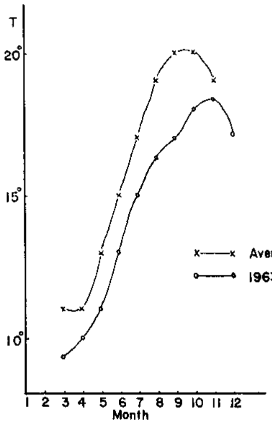

Fig. 13. Seasonal change of the water temperature at 50 m depth in 1963 and in normal year (averaged for 1954~1966).

above average temperature fields, fluctuation of maximum water temperature in the 50 m depth coincides well to the variation of the Tsushima Warm Current transport. Hencefore, if we compare the seasonal variation of water temperature at 50 m depth in 1963 with that in the normal year (1954~1966 mean), Fig. 13 proves us the abnormal coldness carrier in 1963 by the advectional transport from the south. It gives us the water transport in 1963 considerably less than normal, and particularly in September a greater difference than normal, which accords to the greater abnormal cooling found in the upper layer in September (referring to Figs. 10 and 11).

Since the 5°-isotherm represents the boundary line between the cold water and warm water at 200 m depth, comparing the 5°C-line in 1963 and normal year we can get Fig. 14. This illustrates the pattern of remarkable cooling period of September at 200 m depth, and similar tendency in other months. In the Southwestern sea-region warmer water areas than normal almost disappear due to the large-scale upwelling of the deeper cold water. On the other hand, in the Northeastern sea-region location of boundary line between the cold and warm waters is not more different than normal. Similarly if we take 3°C-line, we can see the more southerly shift of the line than normal in the Northeastern sea-region, and nearly normal distribution in the Southwestern sea-region. Accordingly, from the above, the warm water destribution in the Northeastern sea-region at 200 m depth does not differ much from normal in spite of the stronger southerly intrusion of the northern cold water than normal. As a consequence a sharp oceanic front was formed between them. In the Southwestern sea-region it is considered that the southerly intrusion of the northern cold water is weaker and rather broader slow upwelling or rising nearly over the whole area.

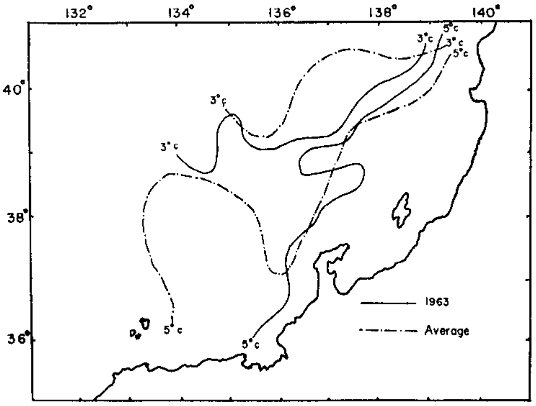

Fig. 14. Isotherms (3 °C and 5 °C) at 200 m layer in 1963 and normal year. (Sep. for example)

4. Considerations

Abnormal cooling phenomenon in 1963 in the Japan Sea is considered heterogeneous in space and time. Concerning air temperature anomaly in the Japan Sea regional abnormality (severe cooling in the Southwestern sea-region and slight warming in the Northeastern sea-region) was conspicuous in the period of January and February of 1963 in response to the severe winter monsoon in the Southwestern sea-region of the Japan Sea and the East Chine Sea, and in March regional difference (of Northeastern and Southwestern Regions) almost disappears. Regional abnormality of water temperature (abnormal cooling in the Southwestern sea-region compared to the normal Northeastern sea-region), although the ambiguity of the beginning period in winter owing to the shortage of the required data, seems to disappear in the period of May and June with the growth of the Tsushima Warm Current Strength. From those evidences we may conclude that the effect of vertical mixing in winter in the Japan Sea is conserved during the weaker period of the

Tsushima Warm Current strength. The contribution from the effect of vertical mixing in winter is much greater until May than that due to the effect of advectional mixing with respect to the abnormal cooling in consideration of the regional abnormality of air temperature, wind speed and water temperature.

It is concluded that abnormal cooling in the weaker period of the Tsushima Warm Current strength in 1963 in the Southwestern sea-region of the Japan Sea might be caused mainly by the abnormally cold air temperature (accompanied with the severe winter monsoon or southerly intruded arctic airmass). Also abnormally poor amount of water transport of the inflowing Tsushima Warm Current than normal in that winter is responsible in addition to the above effect of vertical conventional mixing and intensified it.

Coming in the stronger period of the Tsushima Warm Current, hitherto appeared cooling area in the Southeastern sea-region extends to the Northeastern sea-region and the difference of both regions almost vanishes, This means the change due to the increase of advectional effect in accompany with the increase of the Tsushima Warm Current strength. The persistent abnormal cooling in the layers centered at 50 m depth in both sea-regions may be due to the weaker strength than normal as heat transport of the Tsushima Warm Current.

In contrast to the decrease in the water transport of the Warm Current, the Northern Cold Watermass formed in the Northern sea-region in the Japan Sea in winter is considered more abundant and more cooled abnormally in 1963 by the sweep of severe winter monsoon over the sea surface in December and January in particular.

Accordingly, in response to the decrease of water transport of the Warm Current the increase of cold water mass in the whole Japan Sea might be considered. It is considered that the decrease of water transport of the Tsushima Current occurred in association with the southeasterly shift of the Kuroshio Main Current under the effect of the severe winter monsoon in the East China Sea.

Since the cooling tendency in summer in the upper layer (shallower than 100 m depth) and in the deeper layer (200 m depth), in the Southwestern sea-region and Northeastern sea-region is all different respectively, in the Southwestern region a conspicuous horizontal deep cold water extension and warm water (although cooler than normal) occupation in the upper layer appears compared to the Northeastern region wherein relatively sharp cold northern water intrusion forming the oppressed warm water near the coast by the abnormal southerly shift of the Polar Front in the upper layer is observed.

Such remarkable southerly intrusion of the northern cold water in the Northeastern region results to the oppression of warm current-axis and local accumulation of warm watermasses in the coastal sea-region around Sado Island and Noto Peninsula with the intensified feature corresponding to the bottom topography, and as the consequence more or less warmer deep water accumulated.

In the Southwestern and Northeastern sea-regions divided by the boundary line in Fig. 1, the feature of abnormal cooling and cold water occurrence are greatly different from the normal year, presumably due to the regional difference of abnormal meteorological effects in the winter season of 1963 and to the variation of the route of the Tsushima Warm Current and its decrease of water transport which may be affected by bottom topography. It is also considered that the intruding flow of the abundantly formed Northern Cold Watermass (source of the Deeper Cold Water) than normal in the Japan Sea is affected by the bottom topography greatly in both regions with regions with local peculiarities for each branch.

In future concerning the movement of the Deeper Cold Water in the Japan Sea we need more studies of the formation of the Northern Cold Watermass in winter, variability in strength of the Tsushima Warm Current, and upwelling related to bottom topography.

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日本海下層冷水の変動

ー特に1963年の異常冷却についてー

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要旨　日本海下層冷水の変動機構の問題を解くカギを見つけるため，日本海平年（1964–'66）温度場図を作成し，これに基づいて同海の平年的特性と，1963年（昭和38年）の異常冷却現象を水温偏差によって調べた．その結果を次のようにまとめた．

1）50m層の水温変化は，対馬暖流々量変化に対応し，その指標となる．

2）200m層水温の最大変動水帯は，日本海極前線帯付近に対応し，5°C線がその暖，冷水塊の潮境線を代表するとみてよい．

3）日本海の異常冷却は，1963年の冬に発し上層では翌年の冬に終っている．下層では春まで冷却が続いたが，上層より小さな冷却を示した．

4）異常冷却は時空間的に，大変な差異がある．1963年の3～5月までは，北東海域での異常冷却は，南西海域で相当大きかったのに対してごくわずかであった．7月以降，著しい冷却が，両海区の50m層付近で見られた．北東海域の沿岸下層では，暖水の堆積が多少夏季にみられた．

5）日本海の異常冷却は，冬季強烈な北方からの季節風（異常気温低下）で起る．しかし，1963年の春ー夏以降の，南西海域および北東海域の異常冷却は，主に対馬暖流々量(又は熱輸送量)の減少によって起された．

6）対馬暖流々量の減少は，おそらく日本海南西海域においては下層冷水の上層への卓越と北東海域において，北方冷水の南下を招いたものと思われる．