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North Pacific Intermediate Water in the Northwest Pacific

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Abstract

By laying emphasis on the intermediate layer, water property distribution in the Northwest Pacific is studied using the hydrographic data obtained by Japan Meteorological Agency in the period from 1960 to 1986. The scattering of water type in T-S diagram is relatively small in the Kuroshio Region. Both the envelopes of saline side and of fresh side of the scattered data points shifts gradually from saline side to fresh side as the observation line moves from southwest to northeast. In the Mixed Water Region, the scattering of water type increases rapidly as the observation line moves north; The envelope of fresh cold side moves towards fresh cold side much faster than that of saline side. The thermosteric anomaly value at the salinity minimum decreases as the observation line moves from north to south or southwest. This suggests that the water does not advect along the salinity minimum layer, but that the salinity minimun layer is understood as a boundary of two different waters aligned vertically. We defined the typical water masses for the Oyashio Water and the Kuroshio Water. The water mass below the salinity minimum layer may be created by isopycnal mixing of these two water masses with a fixed mixing rate. While, the water mass above the salinity minimum cannot be created simply by isopycnal mixing. The salinity minimum layer may be eroded from upper side due to active mixing processes in the surface layer, while the water of the salinity minimum layer moves gradually southward. This appears to give an explanation why the thermosteric anomaly value at salinity minimum decreases towards south.

Key Words : North Pacific Intermediater Water, Salinity minimum layer water, Oyashio Water, Kuroshio Water, Isopycnal Mixing, Mixing Rate

1. Introduction

The salinity distributions on the salinity minimum layer suggests that the North Pacific Intermediate Water is generated near the Subpolar Front of the western North Pacific, namely near the Oyashio Region, and that the water circulates clockwise in the intermediate layer of the North Pacific (see, for example, Fig. 202 of Sverdrup et al., 1942). However, the formation mechanism has not been clarified, and the detailed flow pattern especially near the western margin of the circulation area has not been determined.

It was shown that the water characteristics of the typical Oyashio Water found to the east of Hokkaido can be explained as a mixed water between the Subpolar Water supplied from the East Kamchatka Current and the Okhotsk Water (Ishikawa, 1988, and Ohtani 1989). Very cold water is formed in the northwest shelf region in the Okhotsk Sea is considerably modified before it flows out into the North Pacific (Kitani, 1973) but is the source of the coldest (and so freshest) water in the North Pacific on the potential density surfaces from σ_t =26.8 to 27.6. This cold water is believed to play an important role in formation of the North Pacific Intermediate Water, but it needs to receive salinity supply in order to be modified into the Intermediate Water. Ohtani (1989) suggested that isopycnal mixing with the Subtropical Water which has been carried into this region with warm-core rings may play an important role. The upwelling motion prevailing in this region associated with the global abyssal circulation is the other possible salinity source. A dense water which is capable to be a source of the Intermediate Water is found in Funka Bay in winter season. The bay is located near the mouth of the Tsugaru Strait, and the water has high salinity value as influenced by the Tsugaru Current Water. The third possible salinity source may be sought to the saline Tsugaru Current Water.

A broad mixed water area is formed in the sea to the east of Honshu, Japan between the Oyashio Front and the Kuroshio Front. The oceanogeraphic situation of this area is very complicated with many of cold and warm eddies, and is called as the Mixed Water Region or the Perturbed Region (Kawai, 1972). The Tsugaru Current water flows southward along the coastal margin, and loses its identification inside of the Mixed Water Region. The main part of the Oyashio Water to the east of Hokkaido is carried eastward along the Oyashio Front or the Subpolar Front, but some parts appears to be carried southwest along off Hokkaido and flow into the Mixed Water Region (e.g. Talley 1991). As discussed by Fujimura and Nagata (1992), vertical temperature and salinity profiles in the Mixed Water Region exhibit wiggled structure near the salinity minimun indicating strong mixing processes and water mass modification there. They also pointed out that winter convection reaches to salinity minimum layer, at least, in the northern part of the Mixed Water Region near the Oyashio Front. The Oyashio Water appears to be carried southward down to near the Kuroshio Front, though it is modified considerably in the Mixed Water Region. One of the southward paths of the Oyashio Water exists along off Sanriku and Joban Coasts, and called as the First Branch of the Oyashio. Yang et al. (1993) showed that the Oyashio Water often intrudes in the intermediate layer farther south into Sagami Bay along just off Boso coast. Shin et al. (1991) showed that the Oyashio water in the intermediate layer is captured in nearshore area by flow of the Kuroshio, and is carried eastward along the north edge of the Kuroshio or Kuroshio Extension.

The Mixed Water Region would be a key region to understand the formation and modification mechanisms of the North Pacific Intermediate Water. By using the data obtained along the routine observation lines occupied by the research vessels belonging to Japan Meteorological Agency, the water type distribution in T-S plane and its spatial variation are sutdied statistically in the seas adjacent to Japan by laying an emphasis on intermediate layers. The spatial variation of the water mass characteristics in the Mixed Water Region is much larger than in the Kuroshio Region, but a systematic change from north to south is recognized through these two regions. The results would give a useful reference to the study on the intermediate water in and near the Mixed Water Region.

2. Data

The hydrographic data along several routine observation lines occupied by Japan Meteorological Agency are used in our analysis. The positions of these observation lines are shown in Fig. 1. We use the data taken in the period from 1960 to 1985 except KJ line. As to KJ line, the routine observation started in 1973, and the data taken in the period from 1973 to 1986 are used. The lines occupied basically four times a year in these period.

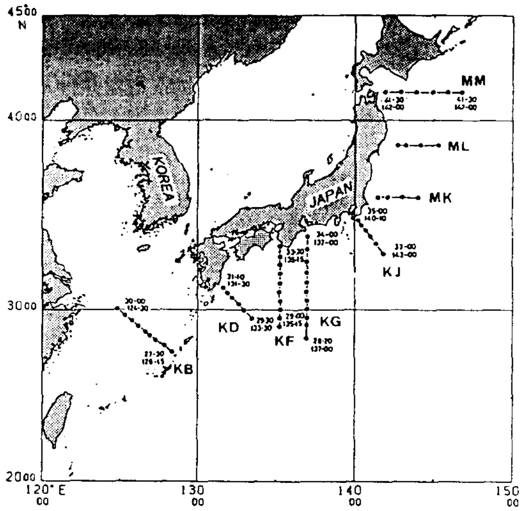

Fig. 1. Routine observation lines in the vicinity of Japan occupied by Japan Meteorological Agency. The line names from KJ to KB correspond to those used in the Kuroshio Exploitation and Utilization Research(KER) and the Japan-China Joint Research Programme on the Kuroshio(JRK) reports. The line names in the Mixed Water Region MK, ML and MM are adopted here for convenience. The block circles attached to each observation line indicate the standard observation points. These lines are occupied basically four times a year in the period analyzed.

As an example, the horizontal salinity distribution on the salinity minimum layer in the Northwest Pacific Japan for the period from July 7 to September 16 1965 and the period from February 1 to March 24 1981 are shown in Fig. 2. A sharp salinity front runs eastward from off Cape Inubo (36 ° N) roughly along the meandering path of the Kuroshio or Kuroshio Extension. In the north north of this front, the horizontal salinity gradient is large, and the isohaline contours runs east-west except near a fresher water tongue extending southeastward. The salinity value tends to increase southward. This region corresponds to the Mixed Water Region, and the first letter M in the line name shows that the line is located in this region. The salinity gradient in the region south of the front is considerably weak. The salinity value tends to increase from east to west or from southeast to northwest. We may call this region as the Kuroshio Region or the Subtropical Water Region. The first letter K in the line name indicates that the line is located in this region. The second letter in the name shows the relative position of the line aligned from southwest to north alphabetically. If the direction of salinity increase in salinity minimum layer is a measure of that of the water movement near this year, there is a great difference in the advecting manner of the intermediate water between the regions North of and south of the front.

3. Water type distribution along the line KJ

The observation line KJ extending southeast from off the tip of the Boso Peninsula is located just to the south of the boundary between the Mixed Water Region and the Kuroshio Region. The variation of the position of the Kuroshio axis is large when the flow crosses over the Izu-Ogasawara Ridge, but it is small near the line KJ. We may select this line as a reference, and analyze firstly the water type distribution along this line.

All data obtained at six observation points on the line KJ in 14 years from 1973 to 1986 are plotted in a T-S plane and shown in Fig. 3. The large scattering of the data points in the domain of $\delta_T>250$ cl/t represents seasonal variations in the surface layer, and we consider only the domain of $\delta_T<250$ cl/t in the following discussions. We defined three characteristic curve to represent the distribution nature of the water type as shown in Fig. 3; Curve I is the envelope of the fresher side of data points, Curve II the fresher side boundary of the domaim where data points are distributed almost continuously, and Curve III the envelope of the saline side of the data points. These curves

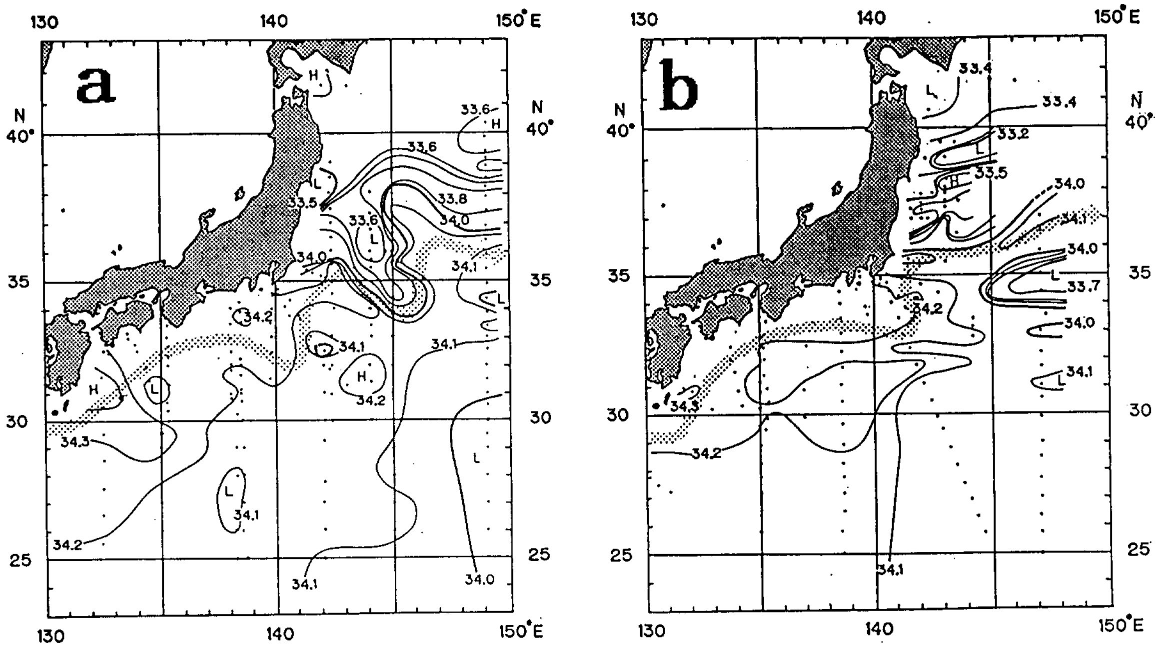

Fig. 2. Salinity distribution (in ‰) on the salinity minimum surface of July 7-September 16 1965(a) and February 1-March 24 1981(b). The position of the current zone of the Kuroshio is cited from the Quick Bulletin of Oceanic conditions published by Maritime Safety Agency, and is shown with dotted band area.

exhibit clear salinity minimum layer butween δ_T=100 cl/t and 140 cl/t. It should be noted that the scattering of the data points are larger near the salinity minimum in comparison with those of shallower or of the deeper depth.

The fluctuation of the Kuroshio path is small near the line KJ, and the position of each observation point relative to the current zone of the Kuroshio is almost fixed; KJ-1 the nearest to the coast is located shoreward of the Kuroshio, and the second point KJ-2 inside of the current zone. The offshoremost point KJ- 6 is usually located in weak current zone, the outside of the Kuroshio. The scattering diagrams of water type for these six staions are shown in Fig. 4a through Fig.4f, respectively. The distributions in these figure are similar to each other, except fresher side near the salinity minimum: no data appears between Curve I and II in the distribution at KJ-2 (inside of the current zone), while many data points can be seen in the distributions at KJ-1 and KJ-6.

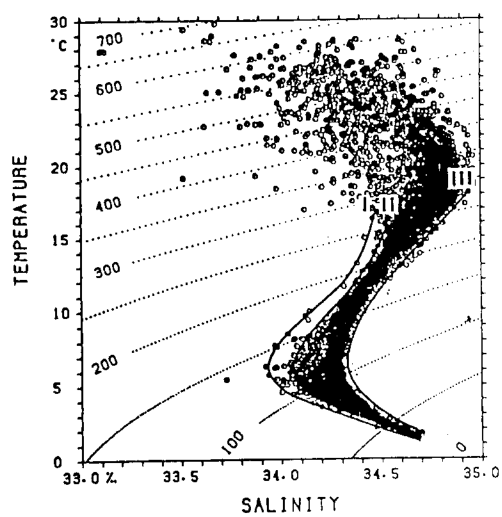

Fig. 3. Scattering diagram of water type is found along the line KJ in the period from 1973 to 1986. Three characteristic curves are defined: Curve I is the envelope of fresh side of the data points, Curve II the fresh side boundary of the domain where the data points are distributed almost continuously, and Curve III the envelope of saline side of the data points. The dotted lines represent the isopleths of thermosteric anomaly in cl/t.

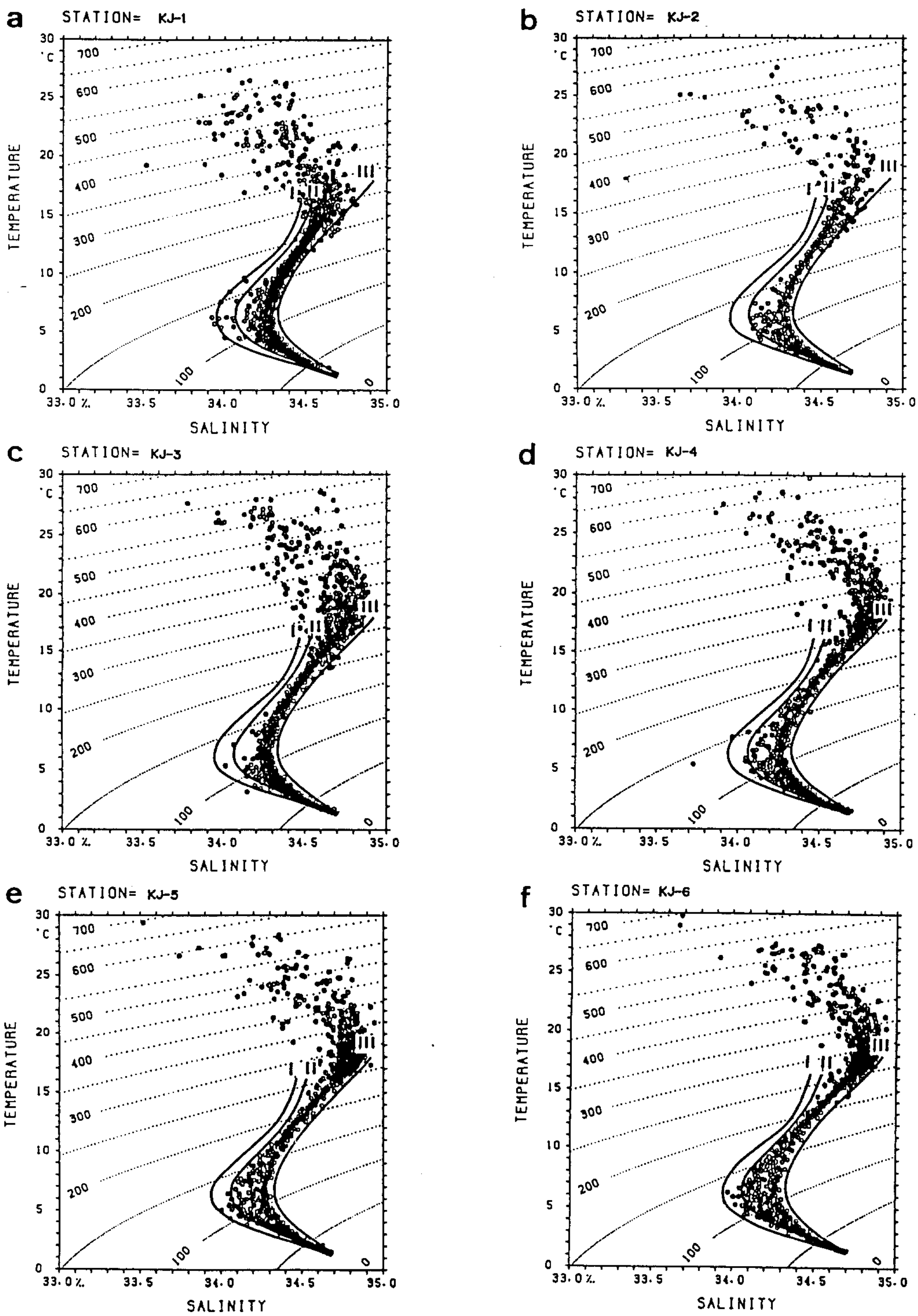

Fig. 4. Scattering diagrams of water type at three stations on the line KJ: (a) station KJ-1 which is located nearest to the coast, (b) the second station KJ-2, (c) the third station KJ-3, (d) the forth station KJ-4, (e) the fifth station KJ-5 and (f) the sixth and offshoremost station KJ-6. KJ-2 is usually located inside of the current zone of the Kuroshio.

Yang et al. (1993a and b) analyzed the cross-sectional features along the line KJ, and found that a core of the salinity minimum is always found just near to the coast. This coastal salinity minimum layer water is clearly separated from the offshore salinity minimum layer by the relatively saline salinity minimum water beneath the Kuroshio. They also pointed out that the intermediate Oyashio Water often intrudes along the coast of the Boso Peninsula into Sagami Bay.

The difference in the distributions among the stations in each line may give some information on oceanic conditions there. However, due to large temporal variability of the oceanic condition it is hard to find significant difference from statistical analysis except for the line KJ, and we shall lay our attention only the differences in distribution natures among the observation lines in the following discussions.

4. Spatial variation of the water type distribution in the seas adjacent to Japan.

The water type distributions in T-S plane for the lines KB, KD, KF, KG, ML and MM in 26 years from 1960 to 1985 are shown Fig. 5 through Fig. 11. The characteristic curves defined for the distribution for the line KJ, Curve I, Ccrve II and Curve III, are reproduced in each figure for comparison.

The distribution patterns obtained in the Kuroshio Region (Fig. 5 through Fig. 8) are very similar to each other in comparison with those taken in the Mixed Water Region. However, there is clear tendency that the distribution pattern shifts gradually form fresher side to saline side. The most remarkable change in the Kuroshio Region can be seen between the line KB in the East China Sea and the line KD in the Pacific Ocean to the southeast of Kyushu.

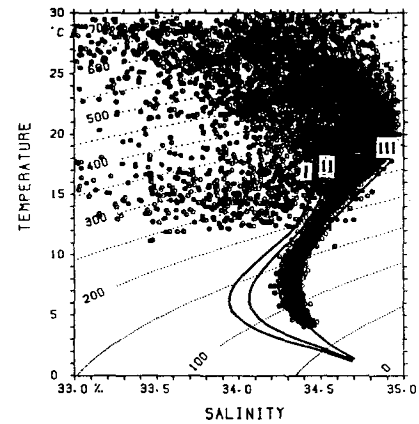

Fig. 5. The same as in Fig. 3 except for along the line KB. Three characteristic Curves I, II and III defined for the line KJ (Fig. 3) are also shown for comparison.

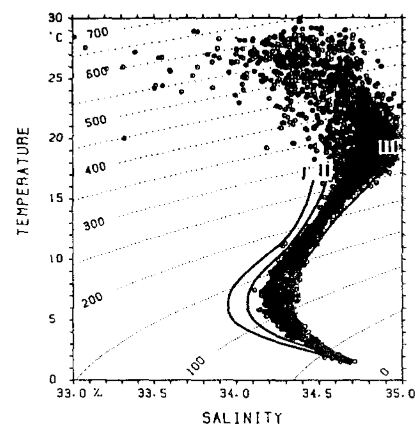

Fig. 6. The same as in Fig. 5 except for the line KD.

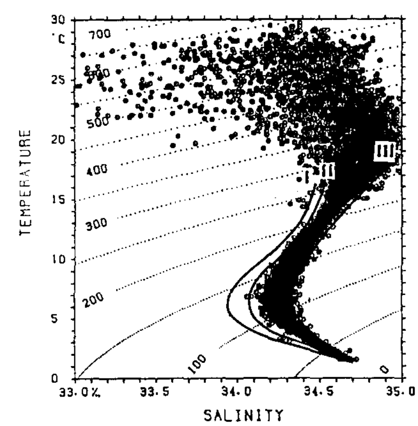

Fig. 7. The same as in Fig. 5 except for the line KF.

The Kuroshio flows out into the Pacific Ocean through the shallow Tokara Strait, the depth of which is less than 500 m. As the water near the salinity minimum is completely separated by the ridge, the difference between KB and KD is not surprising. The water near the salinity minimum at KB has considerably higher salinity value, and may represent the condition of the intermediate layer of the farther upstream region.

It should be noted that the water types between Curve I and II does not appear near the salinity minimum layer for the distributions of the south of the line KG. This suggests that the intermediate water in the Kuroshio Region does not receive direct influence from the Oyashio Water or the Mixed Water, except near the line KJ or near its northern boundary adjacent to the Kuroshio Extension.

The distributions in the Mixed Water Region exhibit much wider scattering of the water type, and scattering width increase rapidly as the line moves north. The path of the Kuroshio or Kuroshio Extension exhbits large meandering and many of warm- core rings are cut off from the meandering. The warm-core rings usually propagate northward, reach off Hokkaido, and sometimes penetrate into the Oyashio Region. Also the Tsugaru Current supplies saline water into this region. So, the saline water which indicates the influence of the subtropical Water can be seen even in the northernmost line MM. On the other hand, the cold fresh Oyashio Water intrudes near to Cape Inubo as the First Branch of the Oyashio. Thus, the cold fresh water similar to the Oyashio Water can be observed in the southernmost line MK. However, both the envelops of saline side and of cold fresh side move clearly from saline side to fresh and cold side as the line moves north.

In order to illustrate the spatial change of the distribution, we defined Curves I, II and III for each distribution in Figs. 5- 11 by the same criterion made for the distribution of KJ in Fig. 3. The Curves I, Curves II and Curves III for

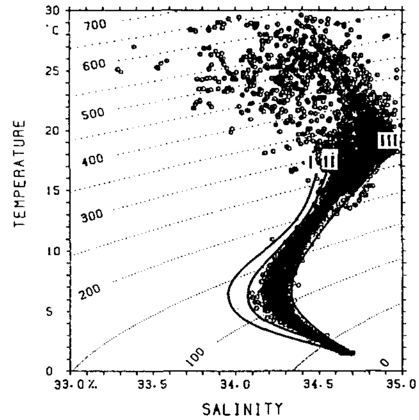

Fig. 8. The same as in Fig. 5 expect for the line KG

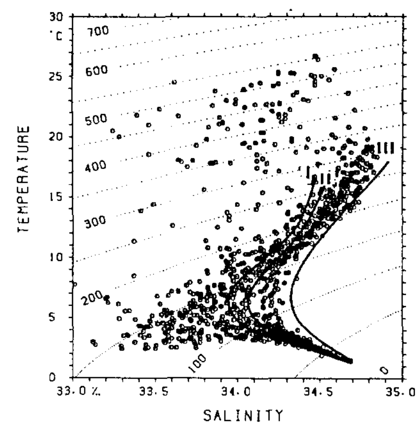

Fig. 9. The same as in Fig. 5 expect for the line MK.

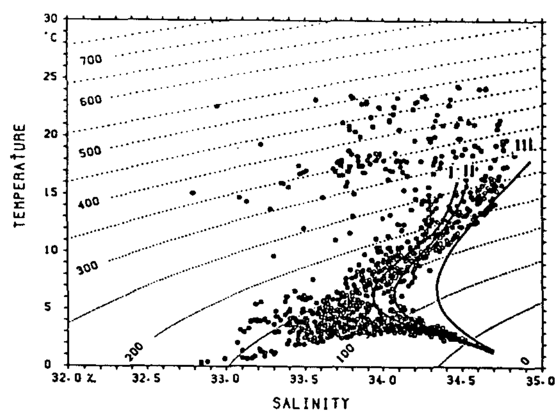

Fig. 10. The same as in Fig. 5 expect for the line ML.

the lines KB through MM are shown in Fig. 12 through Fig. 14, respectively. We adopted the envelope of cold side (Curve I) of the distribution for the line MM as a water mass representative to the Oyashio Water, and the envelope of saline side (Curve III) for the line KD as a water mass representative to the Kuroshio water to the south of Japan(Due to the above mentioned gap between oceanic condition between the lines KB and KD and due to the lack of deeper profile for the line KB, we chose the line KG as a reference.). If the water columns of these two water are mixed gradually along each isopycnal surface, the water mass in the transition region would follow the curve that results in by mixing of two waters with some fixed rate, and the rate of the Oyashio Water mixed would decrease gradually southward. The curves corresponding to several mixing ratios are also shown in each figure.

The difference between the Kuroshio Region and the Mixed Water Region is most clearly for the envelope of fresh and/or cold side (Curve I in Fig. 12). Especially, in shallower layers near δ =200 cl/t, the water type of the line KJ is almost identical to those of the lines to the south. This means that the southern boundary of the Mixed Water Region would be clearly determined by the Kuroshio Front defined in the surface layer. However, the water type taken near the salinity minimum at the line KJ, which is located a little south of the Kuroshio Front, is considerably more saline than those for the lines to the south, and indicates the influence of the Oyashio Water. As pointed out by Yang et al. (1993a and b), the Oyashio Water in the intermediate layer appears easily intrude southward than that in the surface layer not only in the region shoreward of the Kuroshio but also in the region offshoreward of the Kuroshio.

The shift of each characteristic curve towards fresher and/or colder side as the line moves from southwest to north along Japanese coast can be clearly seen in all of these figures.

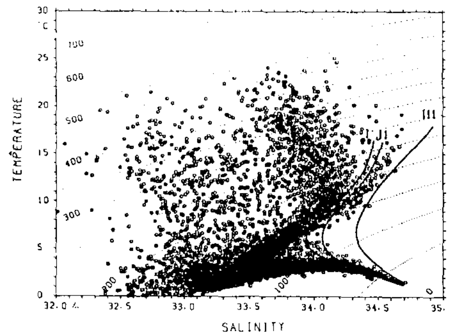

Fig. 11. The same as in Fig. 5 expect for the line MM.

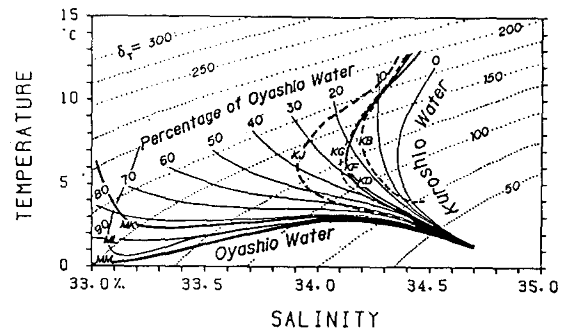

Fig. 12. Spatial variation of the envelope of fresh and/or cold side in the water type distribution (Curve I). The thin full lines with numerals indicate T-S curves for the water mass which may be created if the water columns of the typical Oyashio Water and of the typical Kuroshio Water are mixed with a fixed ratio along each isopycnal surface, and the attached numerals indicate the percentage of the Oyashio Water mixed. The thin dotted lines represent the isopleth of thermosteric anomaly in cl/t.

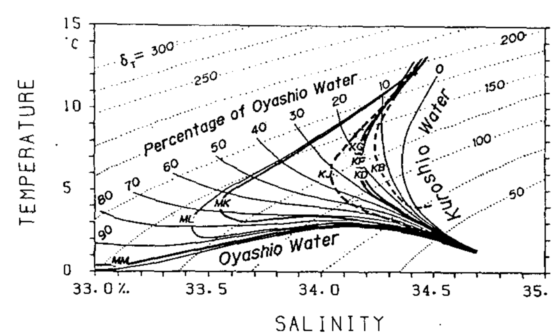

Fig. 13. The same as in Fig. 12, except for the fresh side boundary of the domain where data points are distributed almost continuously (Curve II).

It should be noted that the density of the salinity minimum changes considerably line by line. For each characteristic curve, the density of the salinity minimum tends to increase from north to south. Fujimura and Nagata (1991) analyzed the spatial change of the vertical salinity profile in and near the Mixed Water Region, and showed that the southward increase of the density at the salinity minimum is recognized in their snapshot type observations. They also pointed out that a local minimun of the salinity minimum density at the current zone of the Kuroshio or the Kuroshio Extension. Unfortunately, such a detailed structure cannot be detected in our statistical results due to large variability of the data and due to coarse intervals between the observation lines used.

In deeper layers below the salinity minimum, all of the characteristic curves in Figs. 12-14 follow roughly the curves produced by the fixed rate mixing between the Oyashio and the Kuroshio Waters. This indicates that the water type distribution of the waters in these deeper layers can be explained by the slow and steady mixing along isopycnal surfaces. The characteristic curves near the salinity minimum layer, however, cross the curves of the fixed rate

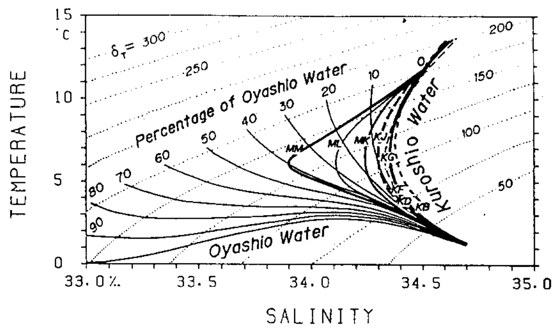

Fig. 14. The same as in Fig. 12, except for the envelope of saline side of the water type distribution (Curve III).

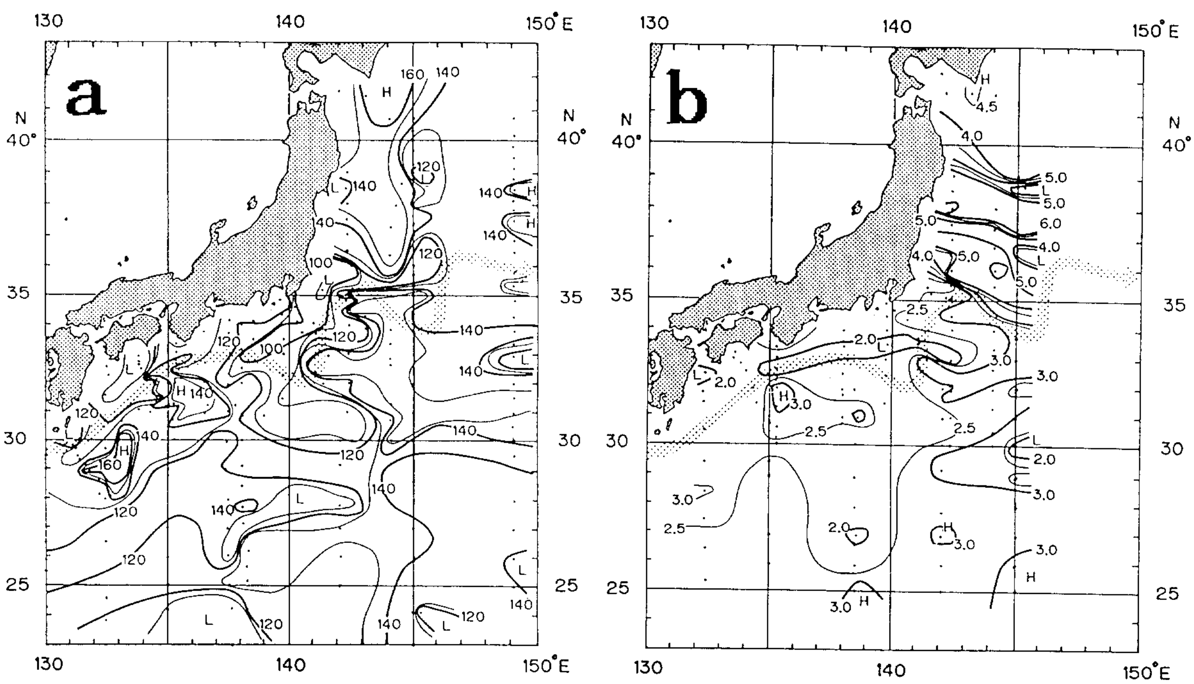

Fig. 15. Horizotal distribution for (a)the thermosteric anomaly (in cl/t) and (b)the dissolved oxyzen(ml/l) on the salinity minimum surface of July 7-September 16 1965.

mixing with large angles. This could be explained by isopycnal mixing only. As pointed out by Fujimura and Nagata(1992), microstructure activity is high in the salinity minimum layer indicating that severe mixing processes take place there. If we take into account the southward increasing tendency of the salinity minimum density, it is plausible that very active water mass modification is occurring in the salinity minimum layer in the Mixed Water Region. The southward increasing of the density at salinity minimum appears to be explained by the erosion of the upper part of the salinity minimum layer while the water in and below the salinity minimum layer moves slowly southward. The salinity minimum would be considered as a boundary between two waters aligned vertically as pointed out by Hasunuma (1978): the upper layer which is receiving severe modification and the lower layer which is produced by slow and steady mixing. If the salinity minimum layer is a boundary of two waters, the horizontal density distribution on the salinity minimum surface would show a complicated pattern, as the mixing processes in the upper layer would be changeable in time and space. An example of the thermosteric anomaly and the Dissolved Oxygen(ml/l) distribution on the salinity minimum surface is shown in Fig. 15. The complicated distribution in the figure may support our argument.

Acknowledgment

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북서태평양에서의 북태평양중층수

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북서태평양에 위치한 일본근해의 수괴분포에 대한 특성을 중층수에 중점을 두어 일본 해상기상청이 관측한 정기 해양관측정선에서 얻어진 자료를 사용하여 검토하였다. 쿠로시오해역의 T-S도상에서 분산은 비교적 작게 나타나고 있다. 쿠로시오해역에서 고온, 고염분측에 분산하던 수형이 남서해역에서 북서해역으로 관측정선이 이동함에 따라 고온, 고염분측에서부터 저온, 저염분측으로 이동하고 있다. 혼합해역에서 수형의 분산은 북으로 이동함에 따라 고염분측의 이동보다 저온, 저염분측으로 급격히 증가하고 있다. 염분극소층에서 해수의 써모스태릭 아노말리(thermosteric anomaly)는 해양관측정선이 북에서 남으로 이동함에 따라 감소하고 있다. 이러한 사실은 해수가 염분극소층을 따라 남하하는 것이 아니고, 염분극소층이 두 해수의 수직적인 경계임을 제시하고 있다. 여기서 오야시오수와 쿠로시오수의 두 전형적인 수괴를 정의하고 있다. 염분극소층보다 깊은 부분의 T-S도는 전형적인 오야시오수와 쿠로시오수가 같은 양으로 혼합하는데 대해, 염분극소층보다 상층에서는 전혀 다른 양상을 나타내고 있다. 염분극소층 해수의 써모스테릭 아노말리가 북에서 남으로 이동함에 따라 뚜렷이 감소해 간다. 이러한 사실은 왜 염분극소층에서 써모스테릭 아니말리의 값이 북에서 남쪽으로 이동함에 따라 감소하는지를 설명해 주고 있다.