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# An Observation on the Cyclonic Eddy in the Coastal Side of the Non-large Meander Path of the Kuroshio

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**Abstract** : A weak cyclonic eddy exists in the coastal side of the non-large meander path of the Kuroshio south of Japan, while a large cyclonic eddy with a large cold water mass is accompanied by the large meander path of the Kuroshio. The CTD and ADCP observations were carried out in August 1999 and we observed a western part of the cyclonic eddy to the east of Kii Peninsula in non-large meander path of the Kuroshio. Main results of the observation are presented in this paper. It is shown that various horizontal intrusions of the less saline water with different potential density ( $\sigma_\theta$ ) are occurring in the salinity minimum layer. Less saline water accompanied by the cyclonic eddy in the coastal (northern) side of the main Kuroshio flow is relatively thin and covers a narrow range of $\sigma_\theta$ in the marginal area of the cyclonic eddy. Conversely, in the offshore (southern) side of the main Kuroshio flow, the horizontal intrusion of North Pacific Intermediate Water (NPIW) is thick and covers a wider range of $\sigma_\theta$. The origin of the less saline water accompanied by the cyclonic eddy on the coastal side of the main Kuroshio flow is discussed.

***Keywords :*** *Cyclonic eddy, Intermediate Oyashio Water, Salinity minimum layer*

## 1. Introduction

The Kuroshio south of Japan has bimodal path characteristics and a larger cyclonic eddy with a large cold water mass is formed in periods of large meander path (SHOJI, 1972; TAFT, 1972; ISHII *et al.*, 1983), while a weak cyclonic eddy is also observed in periods of non-large meander path. It is well known that the salinity minimum layer also exists on both sides of the main flow of the Kuroshio (e.g., SEKINE *et al.*, 1991; YANG *et al.*, 1993a,b and SENJYU *et al.,* 1998), while salinity in its minimum layer is relatively high in the mean flow of the Kuroshio. Both dominant salinity minimum waters have a potential density ( $\sigma_\theta$ ) of 26.7–26.9.

YASUDA *et al.* (1996) pointed out that on the eastern side of the Izu Ridge, the North Pacific Intermediate Water (NPIW) of salinity less than 34.1 psu is formed by mixing of the Kuroshio Water and Oyashio Water to the east of 150° E and this spreads southwestward up to 25° N to form a salinity minimum layer in the subtropical circulation. SEKINE *et al.* (2000) showed that the southwestward flow of NPIW is influenced by the topographic effect of the Izu Ridge and a westward shift of NPIW over the Izu Ridge into the Shikoku Basin is confined to the south of 30° N at a depth deeper than 2000 m, which is schematically shown in Fig. 1.

The Intermediate Oyashio Water (IOW) originated from the Oyashio Water (OW) flows southward along the east coast of Honshu and then reaches Sagami Bay (YANG *et al.*, 1993a,b; SENJYU *et al.*, 1998). SEKINE and UCHIYAMA (2002) detected the outflow of IOW from Sagami Bay to the Shikoku Basin through a southeastern channel off the Izu Peninsula. They also showed that a part of IOW to the south of the Boso Peninsula flows southward along the eastern side of the Izu Ridge, then flows into the Shikoku Basin through the gate channel of the main Kuroshio

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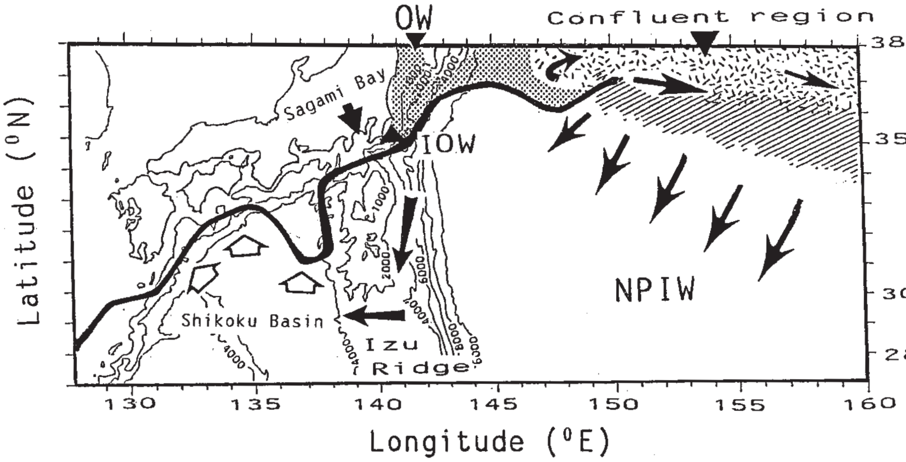


Fig. 1. Schematic view of the flow pattern of the NPIW formed by the mixing between the Kuroshio water and the Oyashio Water (OW) at the area with aslant lines (after, SEKINE and MIYAMOTO, 2002). The NPIW moves southwestward shown by the slant arrows. Near the Izu Ridge, the NPIW is influenced by the topographic effect of the Izu Ridge (SEKINE *et al.*, 2000) and further westward shift is possible to the south of 30° N, where depth of the Izu Ridge exceeds 2000 m. In the Shikoku Basin, the NPIW flows northward shown by the open arrows and essentially exists in the southern offshore side of the main Kuroshio axis. The OW flows along the Japanese Coast and ventilates to form the Intermediate Oyashio Water (IOW). The IOW reaches Sagami Bay, part of which flows out from Sagami Bay.

path over the Izu Ridge between Miyake-jima and Hachijo-jima islands. The schematic view of these results is also shown in Fig. 1.

Together with these observational evidences, it is inferred from Fig. 1 that two waters forming the salinity minimum layer are separated by the main Kuroshio flow. The NPIW is confined to the south of the main axis of the Kuroshio Extension (REID, 1965 and TALLEY, 1993, YASUDA *et al.*, 1996). Recently, SEKINE and MIYAMOTO (2002) showed a similar tendency on the western side of the Izu Ridge with the exception of the horizontal intrusion across the main Kuroshio axis to the northern coastal area during the decay period of the small meander of the Kuroshio in May 1992.

Based on these observational results, the origin and distribution of the salinity minimum water on the northern coastal side of the Kuroshio main axis in the Shikoku Basin should be examined with particulars. Here it is noted that because no less saline coastal and bay waters have a potential density greater than 26.0 owing to the characteristics of less saline water (e.g., SEKINE *et al.*, 1991), they can not be an origin of the salinity minimum water on the coastal side of Kuroshio. In this context, we could observe a western part of the cyclonic eddy in the coastal side of the main Kuroshio flow during non-large meander path by use of training vessel “Seisui-Maru” of Mie University on 26–31 August 1999. Composite of the satellite imageries of thermal infrared by NOAA 12, 14 and 15 during the observation are shown in Fig. 2. A cyclonic eddy is located at the Enshu-nada and accompanied warm water of the Kuroshio approaches to the Kii Peninsula. Therefore, we presents the main results of the observation in this paper.

## 2. Observation

CTD (Neil Brown Mark IIIB) observations along the observational lines shown in Fig. 3 were made by use of the Training Vessel “Seis ui-Maru” of Mie University during 26–31 August 1999. Five observational lines are set to observe the western part of the cyclonic eddy and its influence on the coastal area off Kii Peninsula. CTD observation began at Station 1 of Line 1 and ended at Station 16 of Line 5 along the continuous observational line shown Fig. 3.

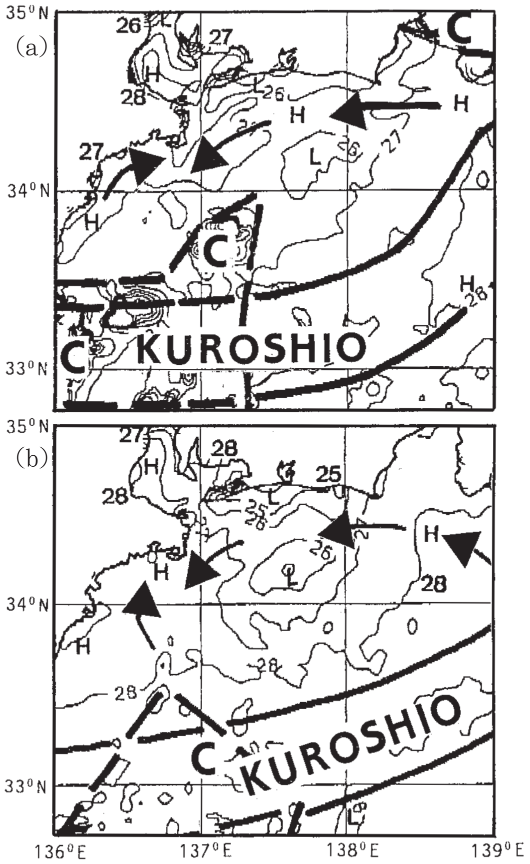


Fig. 2. SST (℃) shown by NOAA 12, 14 and 15 AVHRR composite on August 25 (after, Fisheries Research Institute of Mie, 1999). (a) 2 images composite from 3:15 to 6:03 (b) 3 images composite from 14:37 to 18:37. Arrows indicate direction of the shift of the warm water, estimated by the comparison of the sequential imagery map of SST. C shows the cloud area. H and L show the area with warmer and colder temperature, respectively.

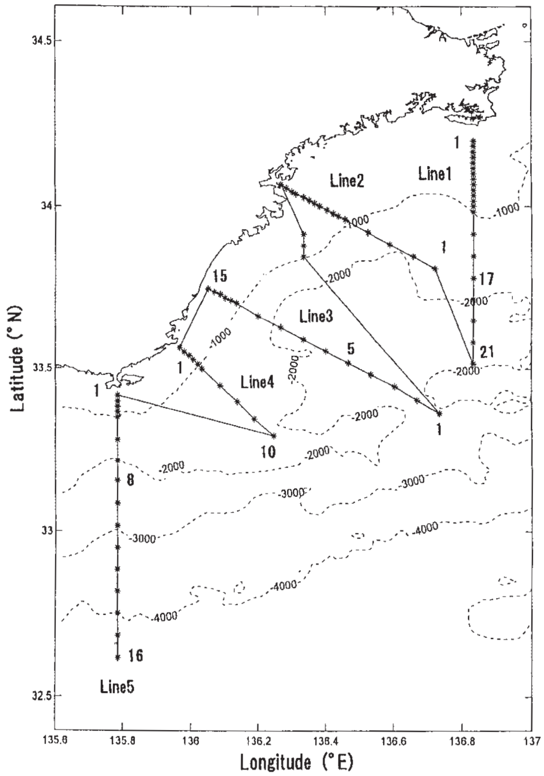


Fig. 3. Observational CTD points and ship track of the present study during August 26–31, 1999.

ADCP (CI–30 of Furuno Electric Inc.) observations at depths of 10 m, 50 m and 100 m were also carried out along these observational lines. Checks of the observed CTD data in comparison with standard salinity water were carried out at three observational points with about 10 layers and the worst-case accuracy of the observed CTD data was found to be 0.02 psu.

### 3. Results

Observed ADCP velocities are shown in Fig. 4. Because the ADCP velocity observed during CTD observation are omitted and those observed in constant ship velocity are employed, some downstream shifts of the observational points of ADCP velocity are recorded in the Kuroshio region with large eastward velocity. As indicated in Fig. 2, a southwestward counter current is observed along the Lines 1 and 2 and coastal sides of Lines 3 and 4, a western part of the cyclonic eddy is found in a western region of the Kii Peninsula. A strong eastward flow of the Kuroshio is observed in the southeastern area of lines 3 and 4. Furthermore, the eastward Kuroshio flow is dominant in all the range of Line 5.

Temperature, salinity and density ($\sigma_\theta$) fields along five observational lines are shown in Figs. 5, 6 and 7. As for Line 1 (Fig. 5a), isotherms, isohaline and isopycnal lines shift downward in the coastal region with the depths from 100 m to 900 m. Because the gradient of which is opposite to that in the region of the

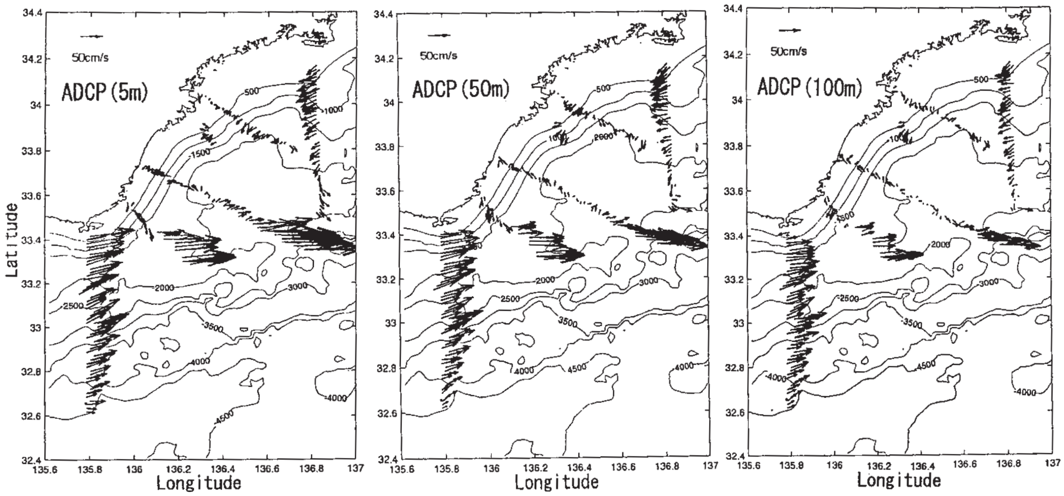


Fig. 4. Observed ADCP velocities at depths of 5 m (left), 50 m (center) and 100 m (right).

main flow of the Kuroshio, the westward flow is suggested from the geostrophic flow balance, which corresponds to the southwestward ADCP velocity shown in Fig. 4. Less saline water (<34.25 psu) is observed at the offshore stations south of Station 17, while it is not observed at the coastal area.

As the Line 2 is located at nearshore region (Fig. 4), the gradients of isotherms, isohaline and isopycnal lines in the coastal region are weak (Fig. 5b) and less saline water (<34.25 psu) is not observed. This suggests that the less saline water does not exist in the marginal region of the cyclonic eddy. However, the less saline water appears in an eastern offshore part of the Line 3 (Fig. 6a) with Stations of 1–5, which corresponds to the downstream part of the cyclonic eddy observed in the Line 1 shown in Fig. 5a. the Line 2 does not reach to this area. The opposite gradient of the isotherms, isohaline and isopycnal lines are detected at the offshore stations of the Line 3 in the upper layer shallower than 200 m (Fig. 6a) and it corresponds to the eastward strong main Kuroshio flow shown in Fig. 4.

As the offshore southern part of Line 4 is located at the Kuroshio region, the existence of the Kuroshio flow is clearly seen at the offshore stations by the gradient of isotherms, isohaline and isopycnal lines (Fig. 6b). The Subtrocpcal Mode Water ( > 34.8 psu) is seen in the upper layer shallower than 100 m, while it is not observed at the Line 3. Less saline water (< 34.25 psu) is not found in the Line 4.

More significant features of the eastward Kuroshio flow are seen at all the Stations of Line 5 (Fig. 7) by the prominent gradient of isotherms, isohaline and isopycnal lines. The Subtropical Mode Water is seen in the upper layer with depths of 100 m–300 m at Stations 6–16.

It is suggested from Figs. 2 and 4 that the main Kuroshio flow exists from Station 1 to Station 8 of the Line 5. Less saline water (<34.25 psu) in a lower part of the main thermocline is the NPIW and it occupies the Stations 9–16 (Fig. 7) in a southern area of the main Kurosho flow, which agrees with the fact that the NPIW is essentially confined to the southern offshore side of the main Kuroshio flow pointed out by SEKINE and MIYAMOTO (2002). It is also shown from Fig. 7 that the NPIW south of the main Kuroshio flow has vertically thick structures in comparison with those of the less saline water in the coastal side of the main Kuroshio flow shown in Figs. 5 and 6.

In order to see the water characteristics, T-S diagram of the stations with less saline water (<34.25 psu) of Lines 1,3 and 5 are shown in Fig. 8. The ordinary T-S distribution of the Kuroshio water in the Shikoku Basin is totally

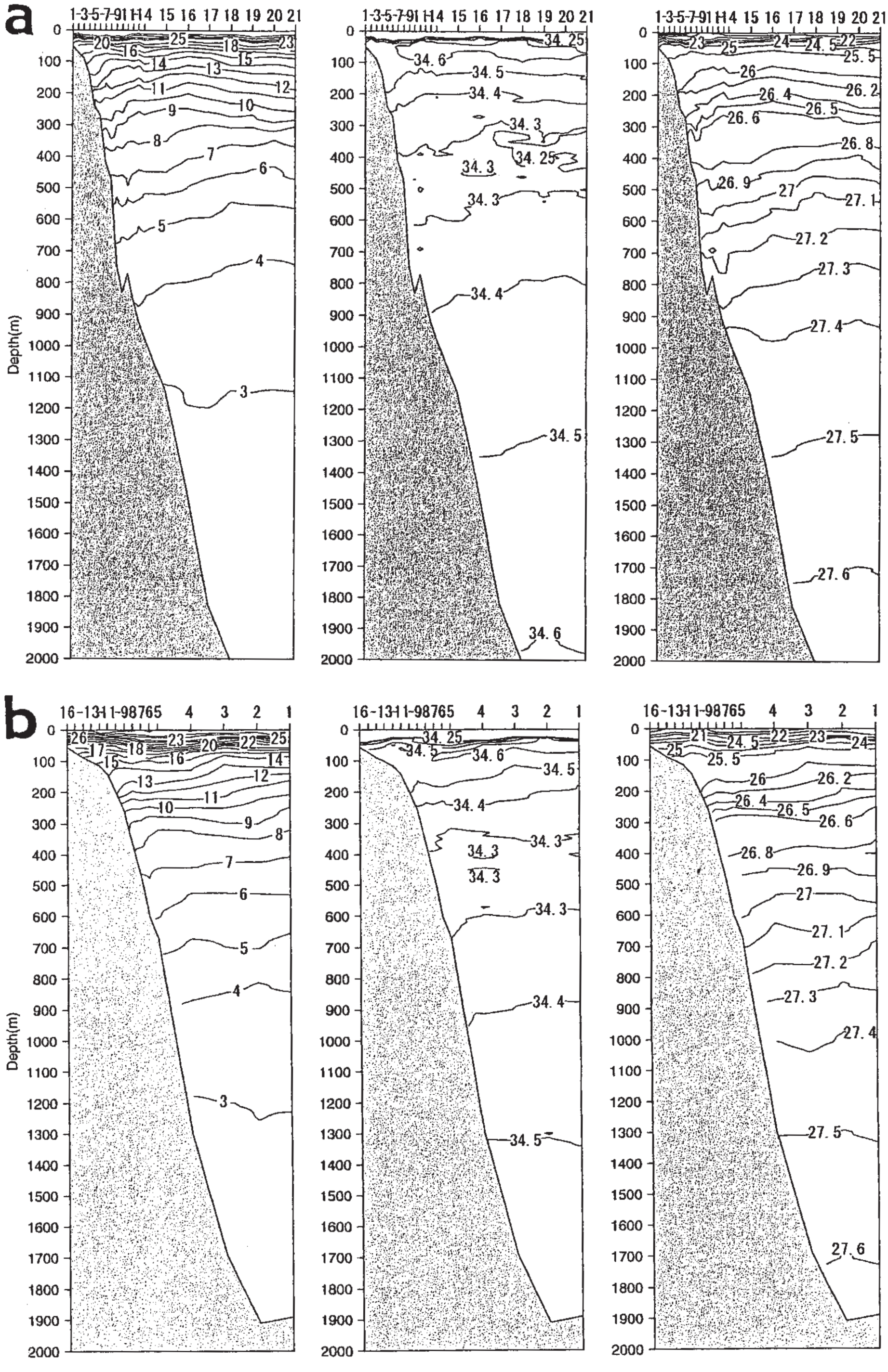


Fig. 5. Observed temperature (℃) (left), salinity (psu) (center) and density ($\sigma_\theta$) (right) fields along Line 1 (a) and Line 2 (b). Numerals at the top of each panel show the observational stations shown in Fig. 3.

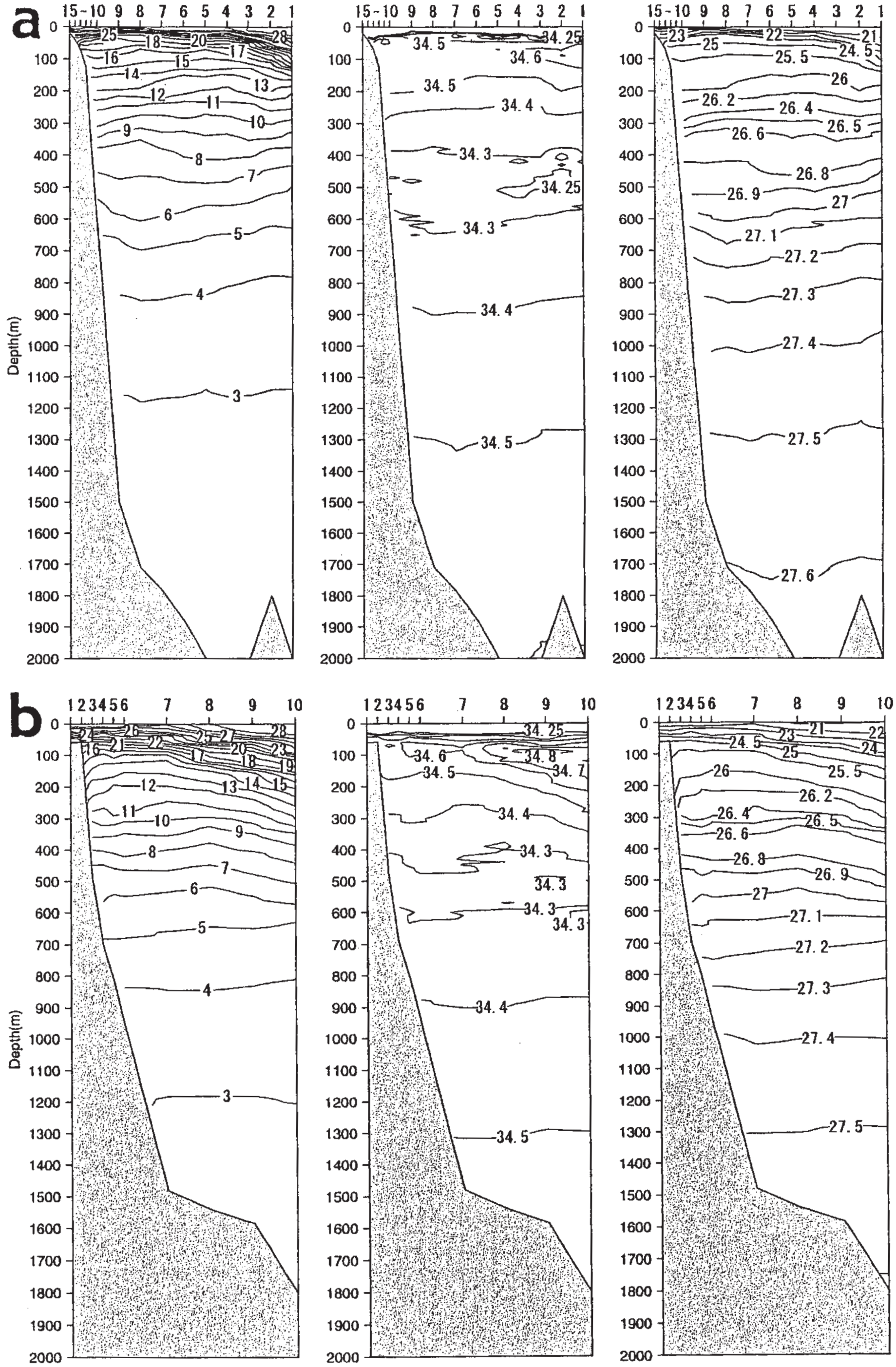


Fig. 6. Same as in Fig. 5 but for the (a) Line 3 and (b) Line 4.

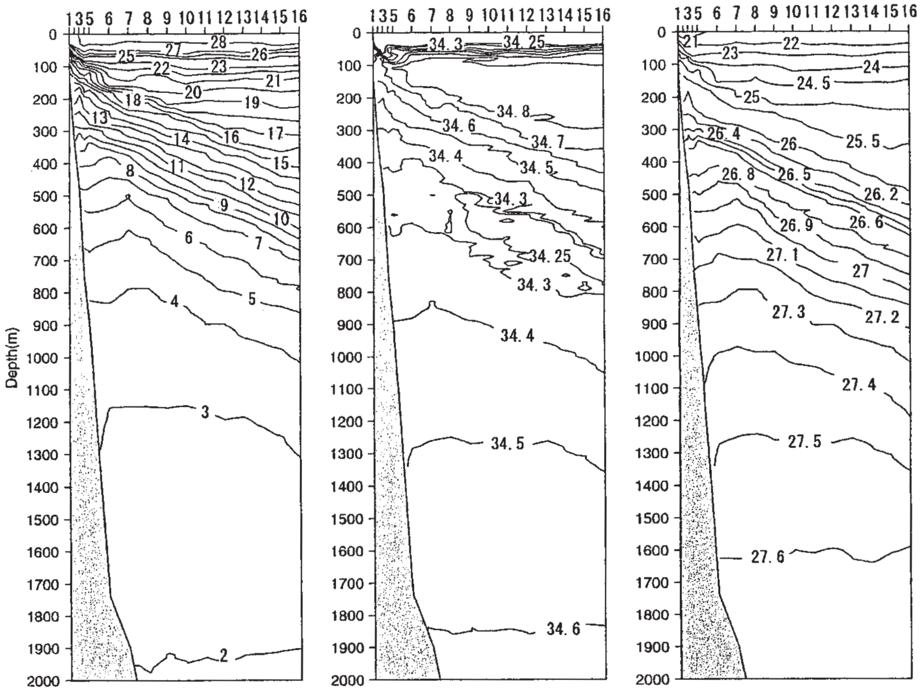


Fig. 7. Same as in Fig. 5 but for the Line 5.

suggested (Ishii *et al.*, 1983). It is noted that there exists a splitting of the T-S lines near the salinity minimum layer, which suggests the horizontal intrusion of less saline water in this level.

To see this more clearly, salinity distribution on potential density ($\sigma_\theta$) coordinate is shown in Fig. 9. It is found that the horizontal intrusions are not carried out along an equal $\sigma_\theta$ surface and some minimum peaks of less saline water exist in the salinity minimum layer, which implies the occurrence of various kinds of less saline water intrusion with different $\sigma_\theta$ in the salinity minimum layer. Since almost similar $\sigma_\theta$ range of the intruding salinity minimum layer is found between Station 21 of Line 1 and Station 2 of Line 3, it is suggested that both Stations are commonly located at the western part of the cyclonic eddy. As for Line 3, $\sigma_\theta$ range of the intruding less saline water is relatively narrow and the peak of the salinity minimum becomes weak, if we go to the coastal side (from Station 2 to Station 5). In contrast to this, the horizontal intrusion of the less saline water is significant in all southern stations

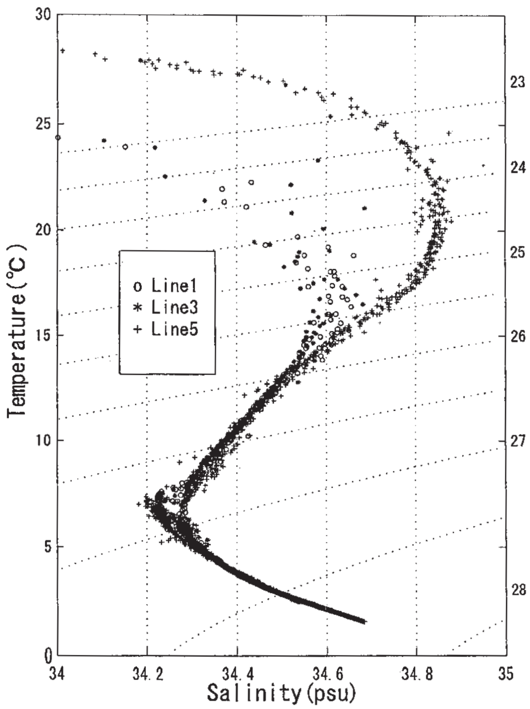


Fig. 8. T-S diagram of Lines 1, 3 and 5. Here, only data at Stations with less saline water (<34.3 psu) shown in Fig. 9 are plotted.

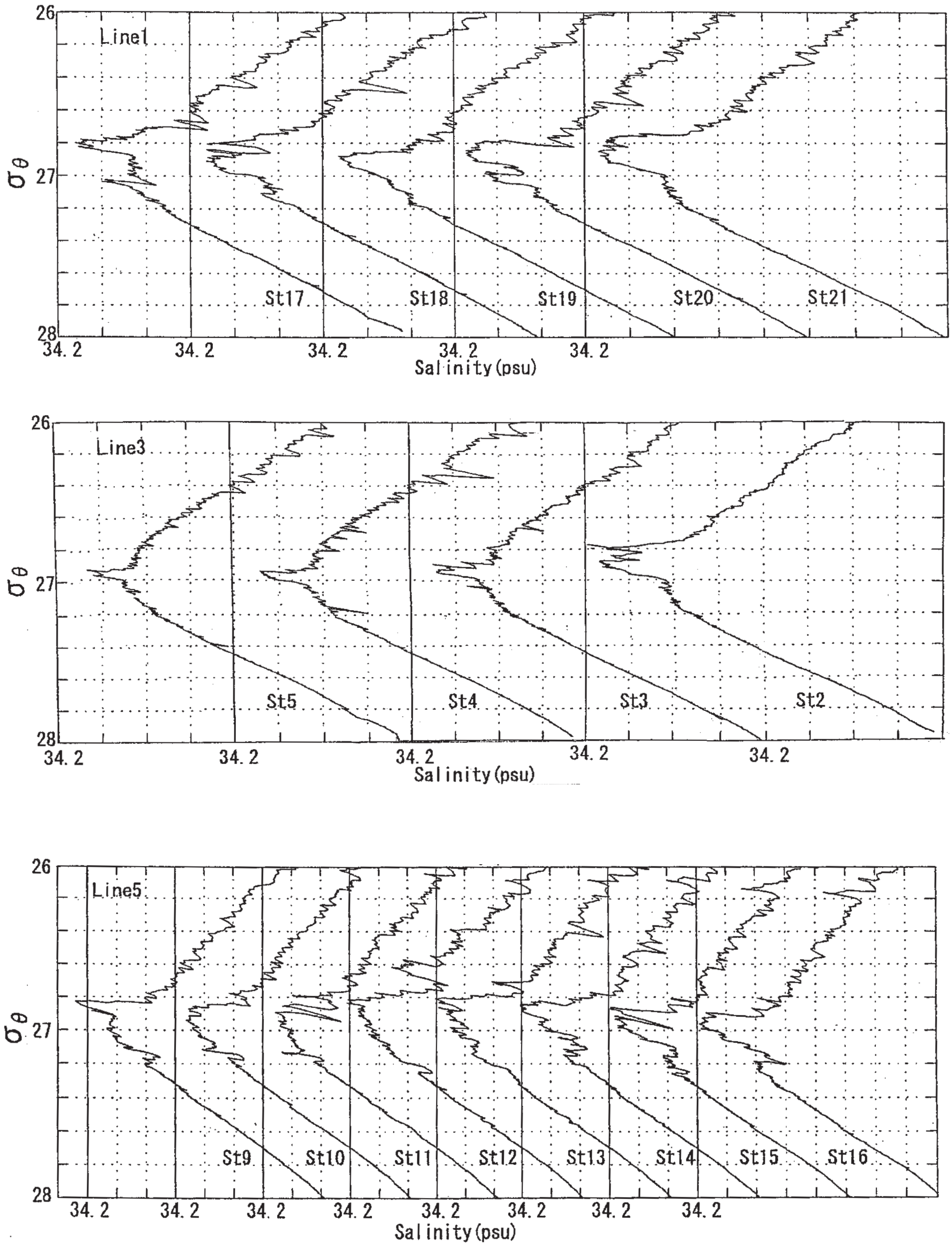


Fig. 9. Salinity distribution on $\sigma_\theta$ coordinates. Line 1 (top), Line 3 (middle) and Line 5 (bottom). One vertical scale mark corresponds to 0.05 psu and the next scale mark to 34.2 psu shown by solid line is 34.25 psu.

of Line 5 and various minimum peaks with wide range of $\sigma_\theta$ are detected.

## 4. Discussion

We could observed a western part of the cyclonic eddy in the coastal side of the non-large meander path of the Kuroshio by use of training vessel "Seisui-Maru" of Mie University in August of 1999. It is shown that there exist various horizontal intrusions of the less saline water with different potential density ($\sigma_\theta$) in the salinity minimum layer. Less saline water accompanied by the cyclonic eddy in the coastal side of the main Kuroshio flow is relatively thin and covers a narrow range of $\sigma_\theta$ in the marginal area of the cyclonic eddy. Conversely, in the offshore side of the main Kuroshio flow, the horizontal intrusion of NPIW is thick and covers a wider range of $\sigma_\theta$.

It is suggested from these results that origin of the less saline water in the coastal side of the main Kuroshio flow is the intermediate Oyashio Water (IOW) that comes from Sagami Bay and/or gate area over the Izu Ridge between Miyake-jima and Hatijou-jima to the Shikoku Basin. Because NPIW in southern offshore side of the main Kuroshio axis has very weak tendency to go northward crossing the Kuroshio flow (SEKINE and MIYAMOTO, 2002), the NPIW has little possibility to be the origin of the less salinity in the northern side of the Kuroshio. No less saline coastal and bay waters have a potential density greater than 26.0 (e.g., SEKINE *et al.*, 1991), they can not be the origin of less salinity water with $\sigma_\theta > 26.7$. Therefore, it is suggested that the less saline water on the coastal side of the main Kuroshio flow is originated from IOW flows out from Sagami Bay and/or the gate area of the Kuroshio over the Izu Ridge. However, these discussion has few quantitative characteristics, to draw firm conclusion, more dense observations are needed for the less saline water on the coastal side of the main Kuroshio flow in the Shikoku Basin.

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