Bull. Fac. Bioresources, Mie Univ.
No.29 : 63 − 74
November 15, 2002

Temperature and Salinity Distribution across the Kuroshio in the Shikoku Basin

Yoshihiko SEKINE*
Faculty of Bioresources Mie University, 1515 kamihama-cho, Tsu, Mie 514-8507, Japan

Abstract

Temperature and salinity observations across the Kuroshio in the Shikoku Basin have been made seven times during the period from July 1992 to August 2001 by use of the training vessel Seisui-maru of Mie University. Focus is placed on the temperature structure in the strong Kuroshio flow as a western bounndary current and the salinity distribution in the salinity minimum layer with the North Pacific Intermediate Water. All the observed temperature and salinity distribution across the Kuroshio mean flow is presented in this paper. It is shown that the salinity minimum layer is unclear under the mean flow of the Kuroshio and the less saline water is separated towords the coastal and offshore sides of the Kuroshio main axis in the western region of the Izu Ridge. It is also shown that sources of the salinity minimum water in the coastal and the offshore sides are Intermediate Oyashio Water and North Pacific Intermediate Water, respectively. Opposite temperature gradients associated with the mean flow of the Kuroshio are commonly observed to the south of the mean Kuroshio flow, which implies the existence of counter currents forming anti-cyclonic circulation in the offshore region. It is geophysically indicated that the formation of the anti-cyclonic circulations is associated with the high nonlinearity of the Kuroshio south of Japan.

Key Words: North Pacific intermediate water, intermediate Oyashio water, salinity minimum layer, the Kuroshio

1. Introduction

Some zooplanktons ordinarily living in the Oyashio water such as Copepoda calanus and Sagitta elegans are found from the salinity minimum layer to the bottom layer of the Sagami Bay[1)-3)], which suggests that the Intermediate Oyashio Water (IOW) intrudes southward to Sagami Bay. Sekine and Uchiyama[4)] examined the southward intrusion conditions of the IOW to the south of Boso Peninsula and concluded that southward shift of the main axes of the Kuroshio and the Kuroshio Extension is a more favorable condition than the intensity of the southward shift of the Oyashio Water (OW), which sometimes intrudes significantly southward up to the offshore of a southern area of Ibaragi Prefecture[5)-7)], although its mean southward limit is off Sendai Bay at the latitude of 38° − 39°N.

In the eastern side of the Izu Ridge, there are two dominant salinity minima on both sides of the main flow of the Kuroshio and the Kuroshio Extension[8)-11)]. Both of these salinity minimum waters have a potential

Accepted: September 8, 2002
* For correspondence (e-mail: sekine@bio. mie-u. ac. jp)

density (σ_θ) of 26.7−26.9. Yasuda et al.[12] 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 (KW) and the OW to the east of 150° E and the NPIW spreads southwestward up to 25° N. They also pointed out that less saline water on the northern side of the Kuroshio Extension west of 150° E is the OW and some parts of NPIW flow into the confluent region of KW and OW. Sekine et al.[13] indicated that the southwestward flow of the NPIW is influenced by topographic effects 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 2000m.

In order to examine salinity distribution in the western side of the Izu Ridge in the Shikoku Basin, seven observational cruises were carried out by use of the training vessel Seisui-maru of Mie University, during the period from July 1992 to August 2001. In this paper, the temperature and salinity distribution across the mean Kuroshio flow is presented. Main observational results of the Kuroshio by the training vessel Seisui-maru before 1988 were reported by Sekine et al.[8),14)].

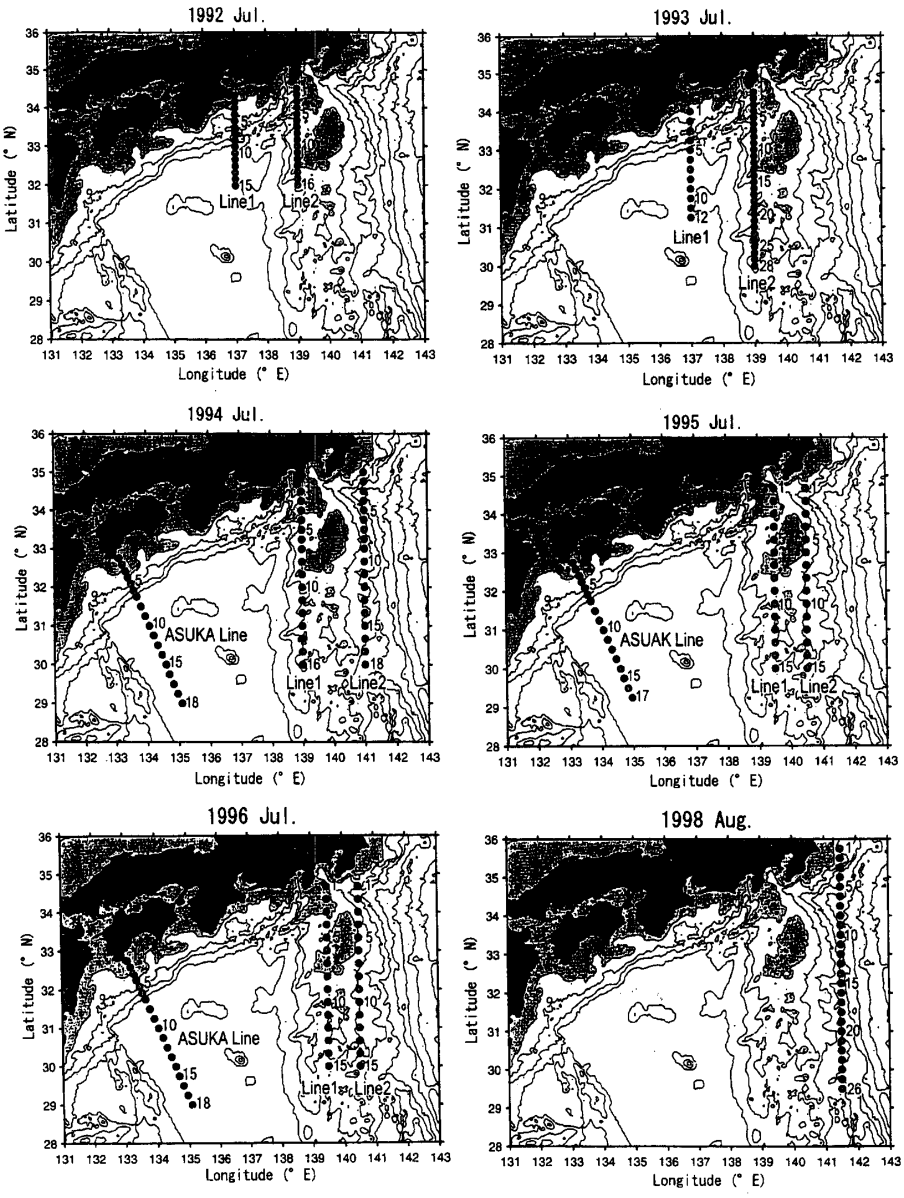
2. Observations

CTD (Mark III System of Neil Brown Instrument Systems, Inc.) observations during the period from July 1992 to August 2001 were carried out by the training vessel Seisui-maru of Mie University. All observational stations of CTD are shown in Fig. 1, and observational lines and periods are listed in Table 1.

In comparison with standard salinity data, observed salinity data were checked at about 10 levels of three observation stations for every cruise. Accuracy of the observed CTD data was found to be within 0.03 psu even in the worst-case. The density (σ_t) is calculated by use of international formula[15].

Table 1 Observations made by the Seisui-maru for the present study

Cruise name	Obs. line	Periods of Observation	Figures.
92 JUL	Line 1	7 − 9 Jul. 1992	3a
92 JUL	Line 2	10 − 13 Jul. 1992	3b
93 JUL	Line 1	5 − 7 Jul. 1993	4a
93 JUL	Line 2	8 − 11 Jul. 1993	4b
94 JUL	ASUKA	7 − 9 Jul. 1994	6
94 JUL	Line 1	14 − 16 Jul. 1994	5a
94 JUL	Line 2	17 − 19 Jul. 1994	5b
95 JUL	ASUKA	6 − 12 Jul. 1995	7a
95 JUL	Line 1	14 − 16 Jul. 1995	8a
95 JUL	Line 2	17 − 19 Jul. 1995	8b
96 JUL	ASUKA	6 − 8 Jul. 1996	7b
96 JUL	Line 1	13 − 14 Jul. 1996	9a
96 JUL	Line 2	15 − 16 Jul. 1996	9b
98 AUG		19 − 22 Aug. 1998	10a
01 AUG		12 − 14 Aug. 2001	10b



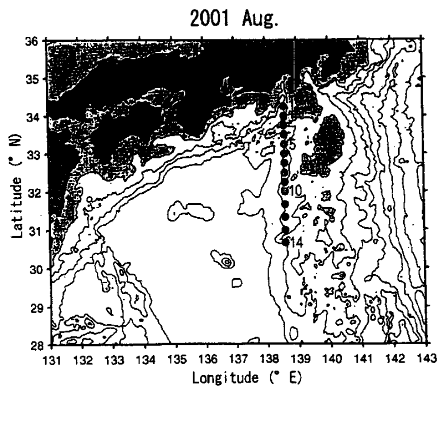


Fig. 1 CTD stations observed by the training vessel Seisui-maru of Mie University during July 1992 to August 2001. Dots in the observational lines show the CTD stations. Depth contours are also shown and the regions with a depth shallower than 1000m are stippled.

The mean flow of the Kuroshio during seven observational periods are shown in Fig. 2. As the long-period large meander path has not been formed after 1992, non-large meander path is observed during the observational periods. Non-large meander path is classified into two types, nearshore non-large meander path and offshore non-large meander path, on the basis of offshore distance of the Kuroshio main axis over the Izu Ridge[17]. It is shown from 2 that offshore non-large meander paths are dominantly detected except for in July 1994 (Fig. 2c).

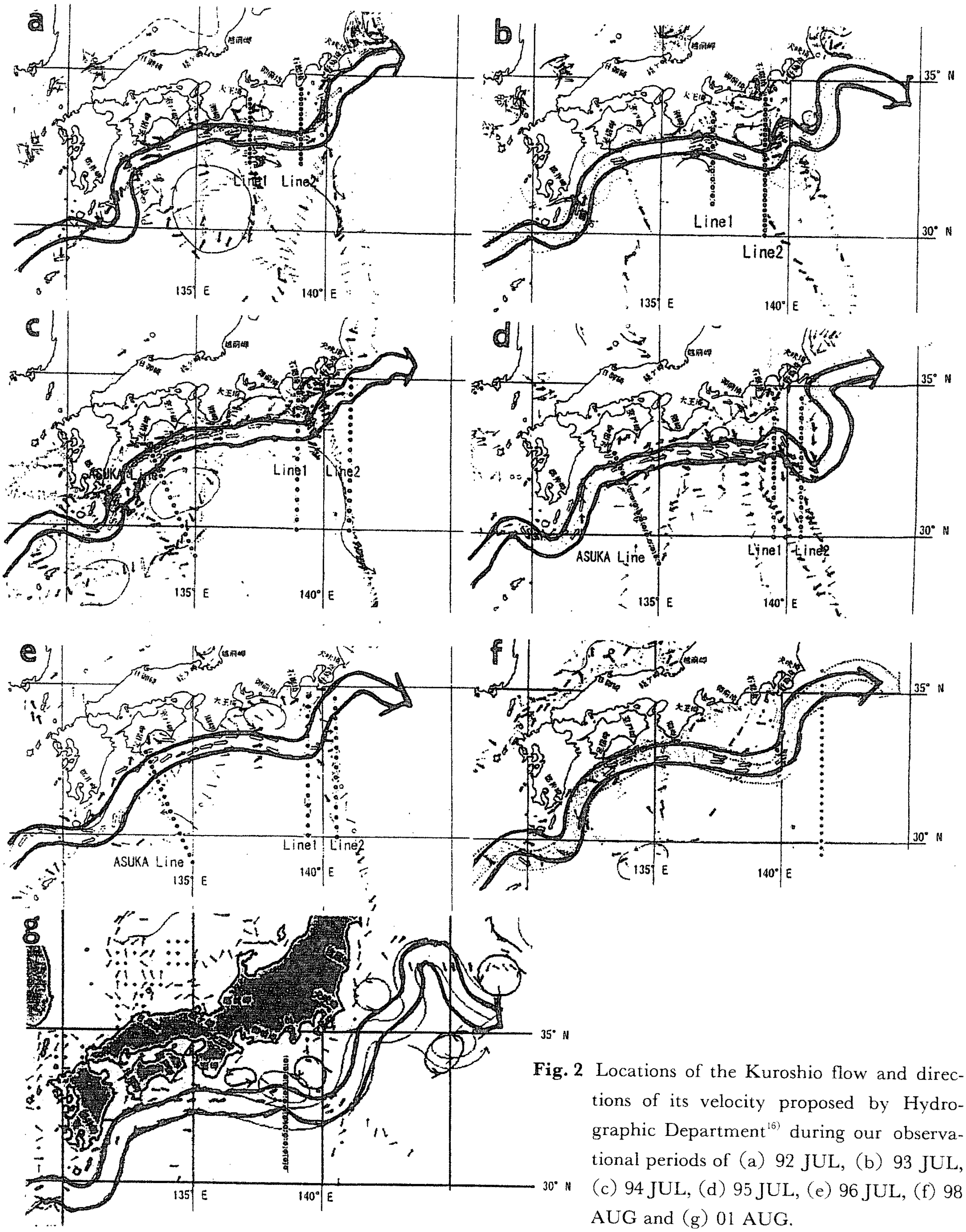


Fig. 2 Locations of the Kuroshio flow and directions of its velocity proposed by Hydrographic Department[16] during our observational periods of (a) 92 JUL, (b) 93 JUL, (c) 94 JUL, (d) 95 JUL, (e) 96 JUL, (f) 98 AUG and (g) 01 AUG.

3. Distribution of temperature and salinity

Distribution of the observed temperature, salinity and density during 92 JUL is shown in Fig. 3. Temperature and density gradients are relatively small along Line 1, which suggests the baroclinic Kuroshio flow is small. A less saline water (<34. 2 psu) is confined to the south of the Kuroshio main axis located

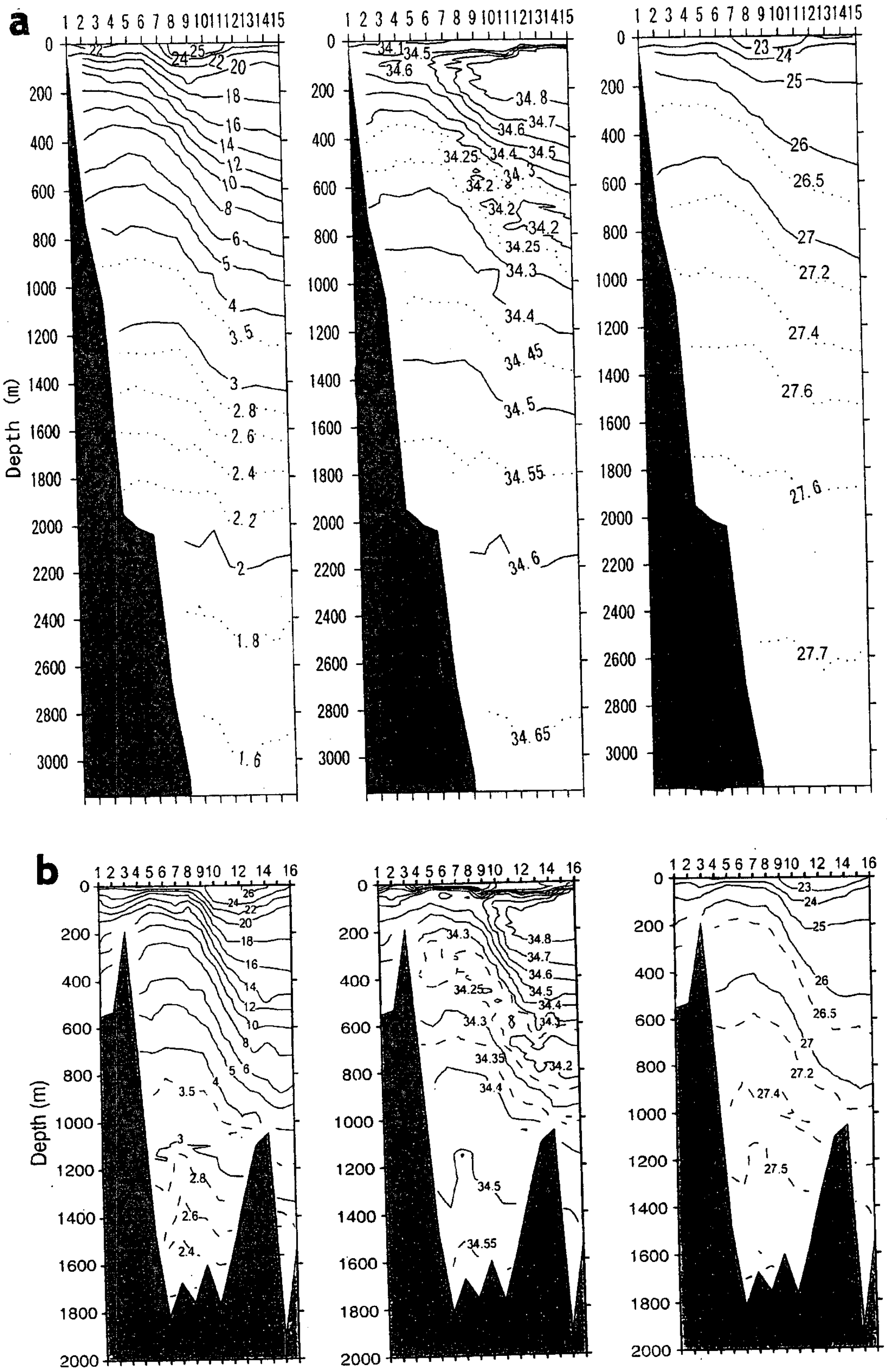


Fig. 3 Distributions of temperature (℃) (left), salinity (psu) (middle) and density (σ_t) (right) along (a) Line 1 and (b) Line 2 in 92 JUL.

at station 9 (Fig. 3a). Relatively large gradients of temperature and density are observed along Line 2 (Fig. 3b). The less saline water is located at the south of Station 10 in the Kuroshio main axis. Because the domelike upwelling structures of the three panels are detected at depths of 100m−600m of the Stations 4 − 9, the existence of the cold water mass with the cyclonic circulation is expected in the coastal side of the Kuroshio main axis. Upwelling of the lower layer water is perceived up to near the bottom. As the density fields are significantly similar to those of temperature, density fields will not be shown in the following.

The distribution of temperature and salinity observed during 93 JUL is shown in Fig. 4. As for Line 1, the temperature distribution is almost similar to that of Line 1 of 92 JUL (Fig. 3a). However, a cold water dome is under a depth of 1700 m as shown by by the upward shift of isotherms. Less saline water (<34.2 psu) is observed at Stations 3 and 4 in the coastal side of the Kuroshio main axis.

In relation to this, it should be noticed that the less saline water (<34.2 psu) is observed at Stations 1 and 3 − 4 of Line 2 of 93 JUL (Fig. 4b). Since the less saline water at Station 1 is isolated from the other southern stations, the less saline water flows out from Sagami Bay to the Shikoku Basin through a southeastern channel off the Izu Peninsula. The latter less saline water at Stations 3 and 4 exists in south-east to Miyake-jima, which is also separated from further southern less saline water south of the mean Kuroshio flow. The less saline water at Stations 3 and 4 flows out into the Shikoku Basin through the gate area of the main Kuroshio path over the Izu Ridge between the Miyake-jima and Hachijo-jima islands (for details of the water characteristics of the less saline water, see Sekine and Uchiyama[4)]). It is inferred that the IOW to the south of the Boso Peninsula is separated into two branches, and one branch is to Sagami Bay and the other branch is to the gate region over the Izu Ridge.

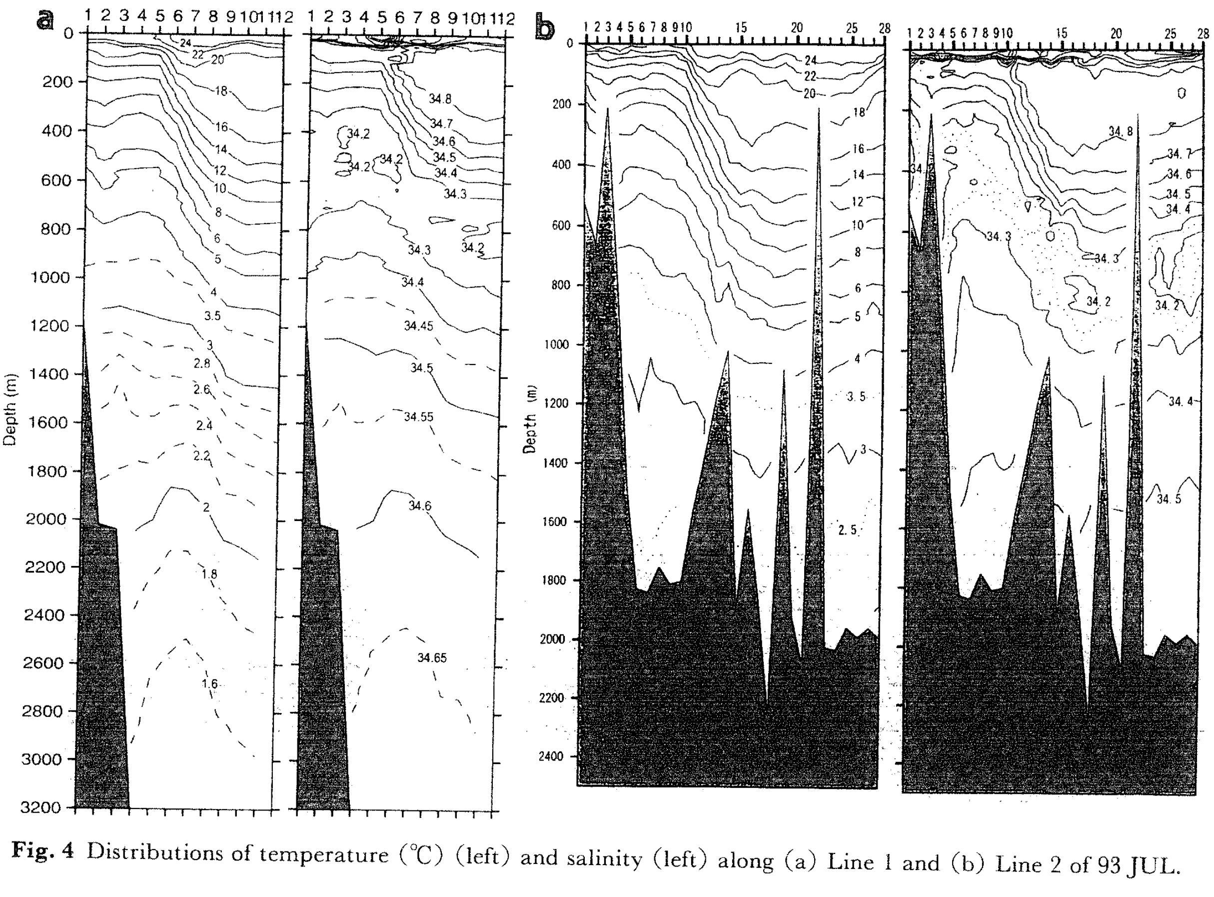


Fig. 4 Distributions of temperature (℃) (left) and salinity (left) along (a) Line 1 and (b) Line 2 of 93 JUL.

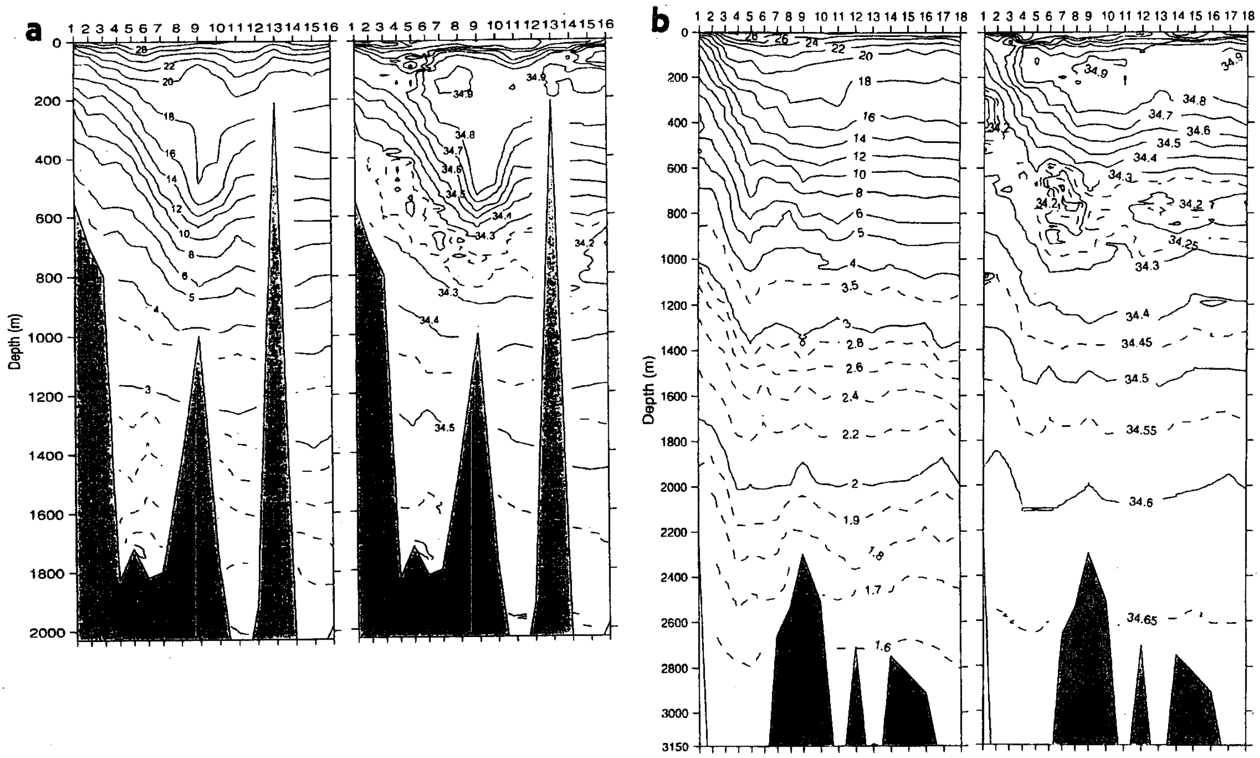


Fig. 5 Same as in Fig. 4, but for (a) Line 1 and (b) Line 2 of 94 JUL.

As for the temperature fields of Line 1 of 94 JUL (Fig. 5a), an downward shift of the isotherms of which center is located around Station 9 is found. Because the downward shifts of temperature and salinity are the characteristic distribution of the anti-cyclonic circulation and because the common seasonal change in the upper layer (<100m) that shows the long lifetime of the eddy, it is inferred to be a part of anti-cyclonic eddy off Shikoku, forming a recirculation of the subtropical circulation. In the eastern side of the Izu Ridge (Line 2 shown in Fig. 1), less saline water is separated into the northern and the southern sides of the Kuroshio main axis located around Stations 3 and 4 (Fig. 5b). Since Line 2 is in the eastern side of the Izu Ridge, the northern and southern less saline waters are the IOW and NPIW)[4),9),12)], respectively. The less saline water sepa-

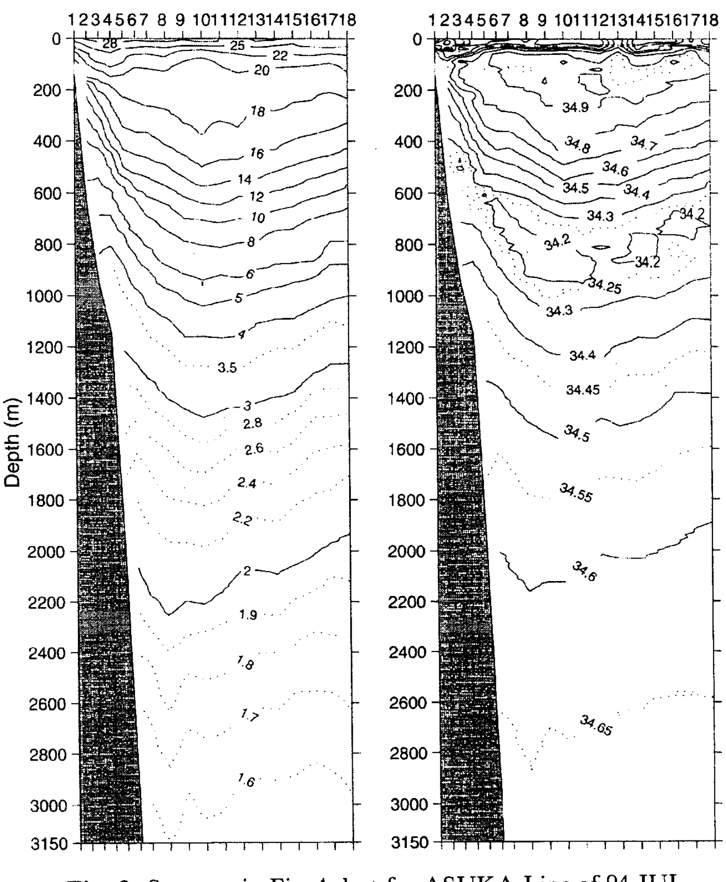


Fig. 6 Same as in Fig. 4, but for ASUKA Line of 94 JUL.

rated by the mean flow of the Kuroshio is observed in the eastern region of the Izu Ridge, Line 2 of 95 Jul (Fig. 7b), 96 Jul (Fig. 8b) and 98 AUG (Fig. 9a).

In the western side of the Izu Ridge, it is commonly detected that the salinity decrease in the salinity minimum layer is relatively unclear under the main axis of the Kuroshio and weakly less saline water is found in the coastal side of the Kuroshio (Line 1 of 95 JUL (Fig. 8), 96 JUL (Fig. 9a) and 01 AUG (Fig. 10b)). Source of these two salinity minimum water in the western side of the Izu Ridge will be discussed in the next section.

The temperature gradients in the nearshore region off Shikoku are commonly observed along the ASUKA line (94 JUL (Fig. 6), 95 JUL and 96 JUL (Fig. 7)), which means that the Kuroshio flow approaches to the coast of Shikoku, as also shown by the mean Kuroshio flow during the observational periods (Fig. 2). Because of the wide continental slope off Shikoku, the Kuroshio flow has a tendency to flow along the continental slope, as predicted by numerical models with the continental slope[18), 19)].

It is commonly seen from Figs. 6, 7 and 8 that there are opposite gradients of the temperature to those in the coastal area corresponding to the mean Kuroshio flow. The opposite gradients suggest a counter current of the Kuroshio forming an anti-cyclonic circulation in the southern area of the mean Kuroshio flow. As discussed in the next section, the formation of the recirculation implies the strong nonlinear characteristics of the Kuroshio, a western boundary current in the North Pacific.

4. Discussion

In the western side of the Izu Ridge, a similar structure of the salinity minimum layer to the eastern side of the Izu Ridge[8)-11)] is observed, and NPIW on the offshore side of the Kuroshio main axis can not go northward under the mean flow of the Kuroshio. It is thus concluded that salinity minimum water on the offshore southern side of the Kuroshio is NPIW. On the other hand, because less saline coastal water can not go southward under the mean flow of the Kuroshio, and because an outflow of IOW from Sagami Bay

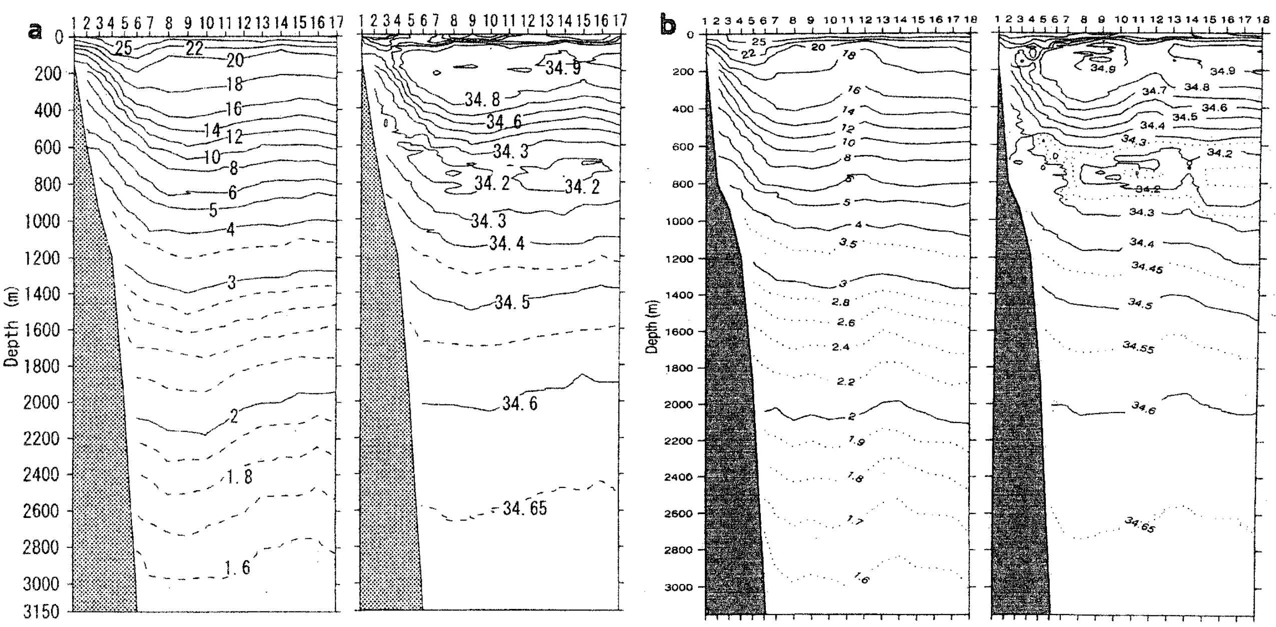


Fig. 7 Same as in Fig. 4, but for the ASUKA Line of (a) 95 JUL and (b) 96 JUL.

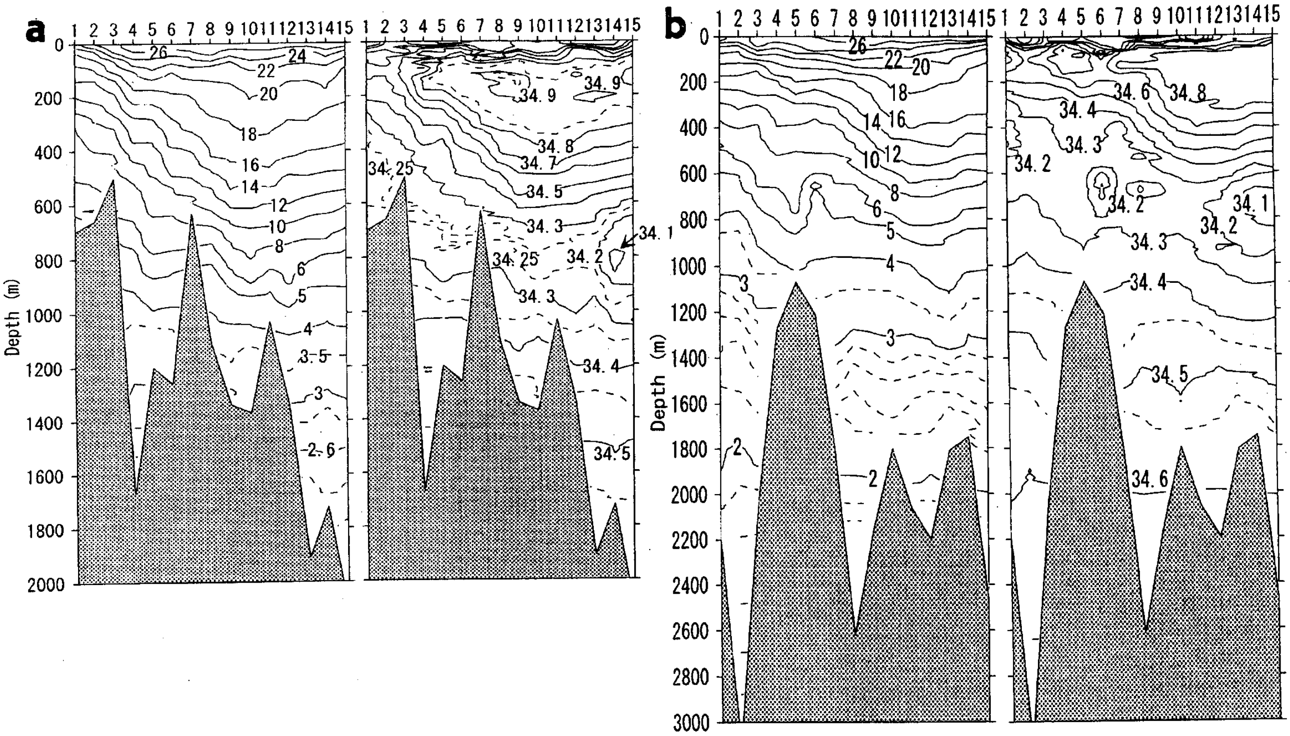


Fig. 8 Same as in Fig. 4, but for (a) Line 1 and (b) Line 2 of 95 JUL.

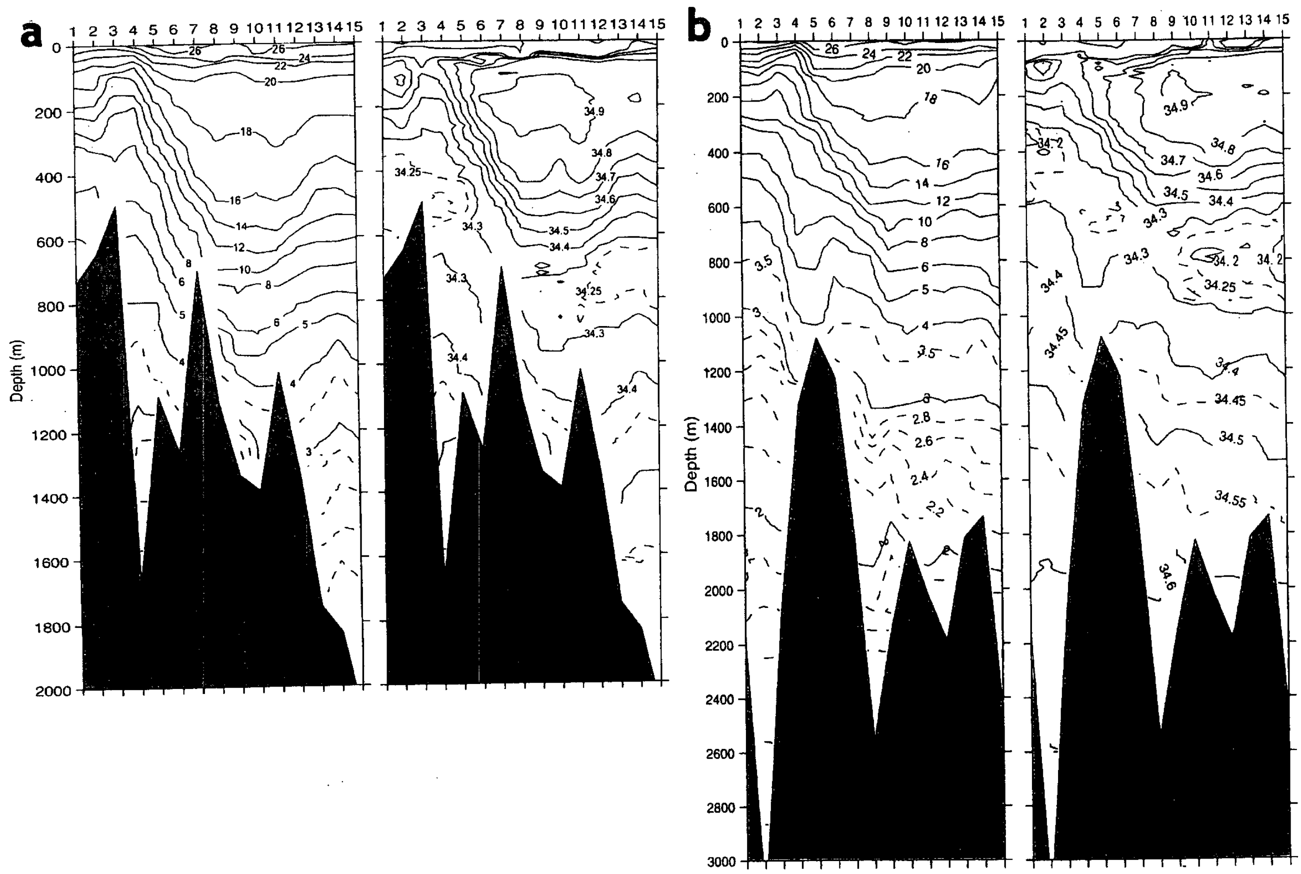


Fig. 9 Same as in Fig. 4, but for (a) Line 1 and (b) Line 2 of 96 JUL.

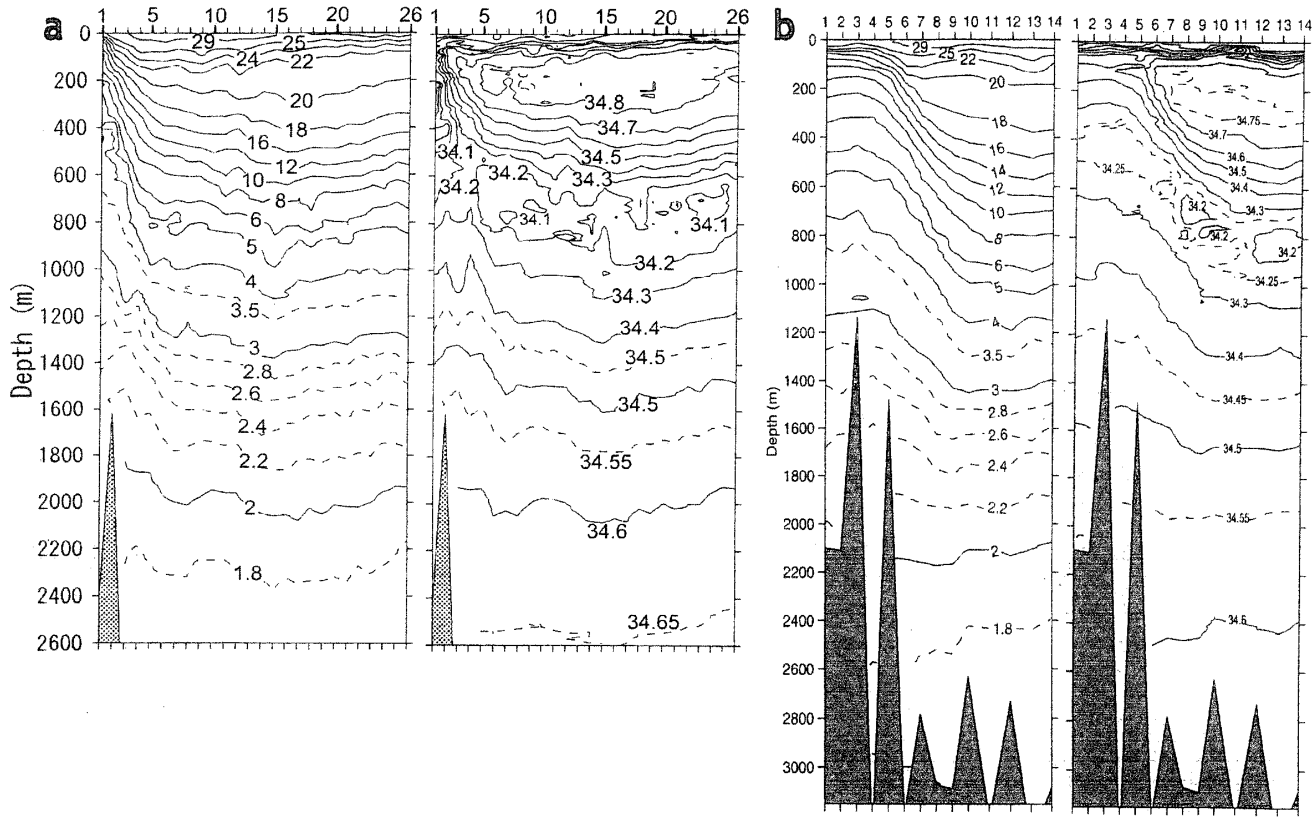


Fig. 10 Same as in Fig. 4, but for (a) 98 AUG and (b) 01 AUG.

and from the gate area over the Izu Ridge (Fig. 4b) is observed in this study, the coastal northern less saline water is IOW.

The opposite temperature gradient to that associated with the mean Kuroshio flow implies a westward flow forming anti-cyclonic recirculation in the offshore side of the Kuroshio. It is shown by historical studies on western boundary currents[20),21)] that the anti-cyclonic recirculation accompanied by the western boundary current is enhanced, if nonlinear effect is large, while the recirculation is very weak in linear models such as well-known Stommel and Munk models. Therefore, it is pointed out that the actual Kuroshio flow is accompanied with anti-cyclonic recirculation and nonlinear effect is important for dynamics of the Kuroshio. This gives some important information for the numerical modeling of the Kuroshio. The existence of the anti-cyclonic circulation make estimation of the volume transport complex. If the counter current is not accurately estimated to its southernmost latitude, the net volume transport of the Kuroshio is not estimated.

Acknowledgments

We would like to thank Captain I. Ishikura and all the officers and crews of the training vessel Seisui-maru of Mie University for their skillful assistance during the observations. Thanks are extended to all past and present members of the under graduate course and post graduate course of my laboratory for their help in the observations of CTD. Especially, I thank Mr. D. Kitayama for his help in drawing figures.

Reference

1) OMORI, M. Calanus cristatus and submergence of the Oyashio water. Deep-Sea Res., **14**: 525-532 (1967).

2) OMORI, M. and O. TANAKA. Distribution of some cold-water species of copepods in the Pacific water off east-central Honshu, Japan. J. Oceanogr. Soc. Japan, **23**: 63-73 (1967).

3) SEKIGUCHI H. Distributional expansion of the pelagic copepod in relation to its large-scale ontogenetic vertical migration. Bull. Fac. Fish, Mie Univ., **2**: 19-28 (1975).

4) SEKINE, Y. and K. UCHIYAMA. Outflow of the Intermediate Oyashio Water from Sagami Bay. J. Oceanogr. **58**, 531-537 (2002).

5) SEKINE, Y. Anomalous southward intrusion of the Oyashio east of Japan. I. Influence of seasonal and interannual variation in wind stress over the North pacific. J. Geophys. Res., **93**: 2247-2255 (1988).

6) SEKINE, Y. A numerical experiment on the anomalous southward intrusion of the Oyashio. J. Oceanogr. Soc. Japan, 44: 60-67 (1988).

7) SEKINE, Y. Anomalous southward intrusion of the Oyashio east of Japan. II. Two layer numerical model. J. Geophys. Res., **104**: 3049-3058 (1999).

8) SEKINE, Y., Y. SATO and I. SAKAMOTO. Observation on the salinity minimum layer in the Shikoku Basin South of Japan. Bull. Fac. Biores. Mie Univ., No. **6**, 83-108 (1991).

9) YANG, S.K., Y. NAGATA, K. TAIRA and M. KAWABE. Southward intrusion of the intermediate Oyashio water along the east coast of the Boso Peninsula. I. Coastal salinity-minimum-layer water off the Boso Peninsula. J. Oceanogr., **49**, 89-114 (1993a).

10) YANG, S.K., Y. NAGATA, K. TAIRA and M. KAWABE. Southward intrusion of the intermediate Oyashio water along the east coast of the Boso Peninsula. II. Intrusion events into Sagami Bay. J. Oceanogr., **49**, 173-191 (1993b).

11) SENJYU, T., N. ASANO, M. MATSUYAMA and T. ISHIMARU. Intrusion events of the intermediate Oyashio Water into Sagami Bay, Japan. J. Oceanogr., **54**, 29-44 (1998).

12) YASUDA, I., K. OKUDA and Y. SHIMIZU. Distribution and modification of North Pacific Intermediate water in the Kuroshio-Oyashio interfrontal zone. J. Phys. Oceanogr., **26**, 448-465 (1996).

13) SEKINE, Y., S. WATANABE and F. YAMADA. Topographic effect of Izu Ridge on the distribution of the north pacific Intermediate water south of Japan. J. Oceanogr., **56**, 429-438 (2000).

14) SEKINE, Y., Y. SATO, H. TAKAMORI and I. SAKAMOTO (1991a): Observation on the volume transport of the Kuroshio south of Japan. Bull. Fac. Biores. Mie Univ., No. **6**, 57-82 (1991b).

15) UNESCO. Background papers and supporting data on the international equation of state of sea water 1980, UNESCO Technical Papers in Marine Science, No. 38, 192 pp. (1981).

16) Hydrographic Dept. Maritime Safety Agency of Japan. The Prompt Report of Oceanographic condition (1992 – 2001).

17) KAWABE, M. Sea level variations at the Izu Islands and typical stable paths of the Kuroshio. J. Oceanogr. Soc. Japan, **41**, 307-326 (1985).

18) SEKINE, Y. A numerical experiment on the path dynamics of the Kuroshio with reference to the formation of the large meander path south of Japan. Deep-Sea Res., **37**, 359-380 (1990).

19) AKITOMO, K., T. AWAJI and N. IMASATO (1991): Kuroshio path variation south of Japan. 1 Barotropic inflow-outflow model. J. Geophys. Res., **96**, 2549-2560.

20) PEDLOSKY, J. Geophysical fluid dynamics. Springer-Verlag, New York, Heidelberg, Berlin, 624 pp (1979).

21) GILL, A. E. Atmosphere-ocean dynamics, Academic Press, 662 pp (1982).

四国海盆内部の黒潮を横断する水温と塩分分布

関 根 義 彦

四国海盆内部の黒潮を横断する水温と塩分分布の7回の観測を，1992年7月から2001年8月までに三重大学生物資源学部の練習船『勢水丸』を用いて行った。観測はとりわけ西岸境界流としての黒潮強流帯の水温構造と塩分極小層内部の塩分分布に注目した。この論文では観測された黒潮を横断する水温と塩分分布を提示した。観測結果の解析により，黒潮の強流帯の下で塩分極小層が不明確で，伊豆海嶺の西側でも塩分極小層は黒潮の陸側と沖側に分離することが示された。また，陸側と沖側の塩分極小層を成す海水がそれぞれ親潮中層水と北太平洋中層水であることが示された。黒潮の関連する水温躍層の傾きと反対方向の水温躍層の傾きが南の沖側で観測され，黒潮の沖側に西向きの反流を伴う高気圧循環が存在することが示され，日本南岸の黒潮は非線形効果の卓越した西岸境界流であることが示唆された。