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Geostrophic Velocity of the Kuroshio South of Japan

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Abstract

It has been pointed out by many studies that current velocity is an important parameter of the bimodal path characteristics of the Kuroshio south of Japan. However, clear relationships between the observed current velocity and the selection of the bimodal Kuroshio path have not been fully discussed. From this point of view, seven hydrographic observations of the Kuroshio south of Japan have been made over the period from July 1992 to August 2001, in addition to 22 observations from May 1983 to October 1988. An estimated geostrophic velocity referred to 1500 db is presented in this paper. As the reference level of 1500 db has no theoretical background, the estimated geostrophic velocity is compared with that referred to the observed shipboard ADCP velocity in the upper layer. It is shown that there exist large differences between both the geostrophic velocities, which implies that the reference level of the geostrophic flow estimation should be more carefully assumed. The dependence of the bimodal Kuroshio path on the geostrophic flow and seasonal variation in the geostrophic current are also discussed.

Key Words: Kuroshio, geostrophic balance, geostrophic velocity and reference level

1. Introduction

So far, many theoretical studies on the bimodal path dynamics of the Kuroshio have been made. In the early studies[1)-3)] showed that the Kuroshio takes the large meander path when the volume transport and/or the velocity of the Kuroshio is relatively small, because the large meander of the Kuroshio is considered essentially as a stationary Rossby wave in the zonal eastward mean flow. However, some later studies[4)-7)] have demonstrated that if the inclination of the northern coastal line from zonal direction and the continental slope are included in the numerical model, the large meander path is formed when the volume transport is relatively large.

To clarify dynamics of the Kuroshio, we should know the true relationship between the intensity of volume transport and the selection of the bimodal path. Therefore, we have carried out 22 hydrographic observations on the Kuroshio during the period from May 1983 to October 1988[8)] and showed that the geostrophic transport referred to 1500 db is relatively larger during the period with non-large meander path (70.5 ± 9.82 Sv; 1 Sv = 10^6 m^3 sec^{-1}) than during that with large meander path (61.8 ± 20.0 Sv). Recently, detailed observations along ASUKA line have been carried out[9)]. However, as the large meander

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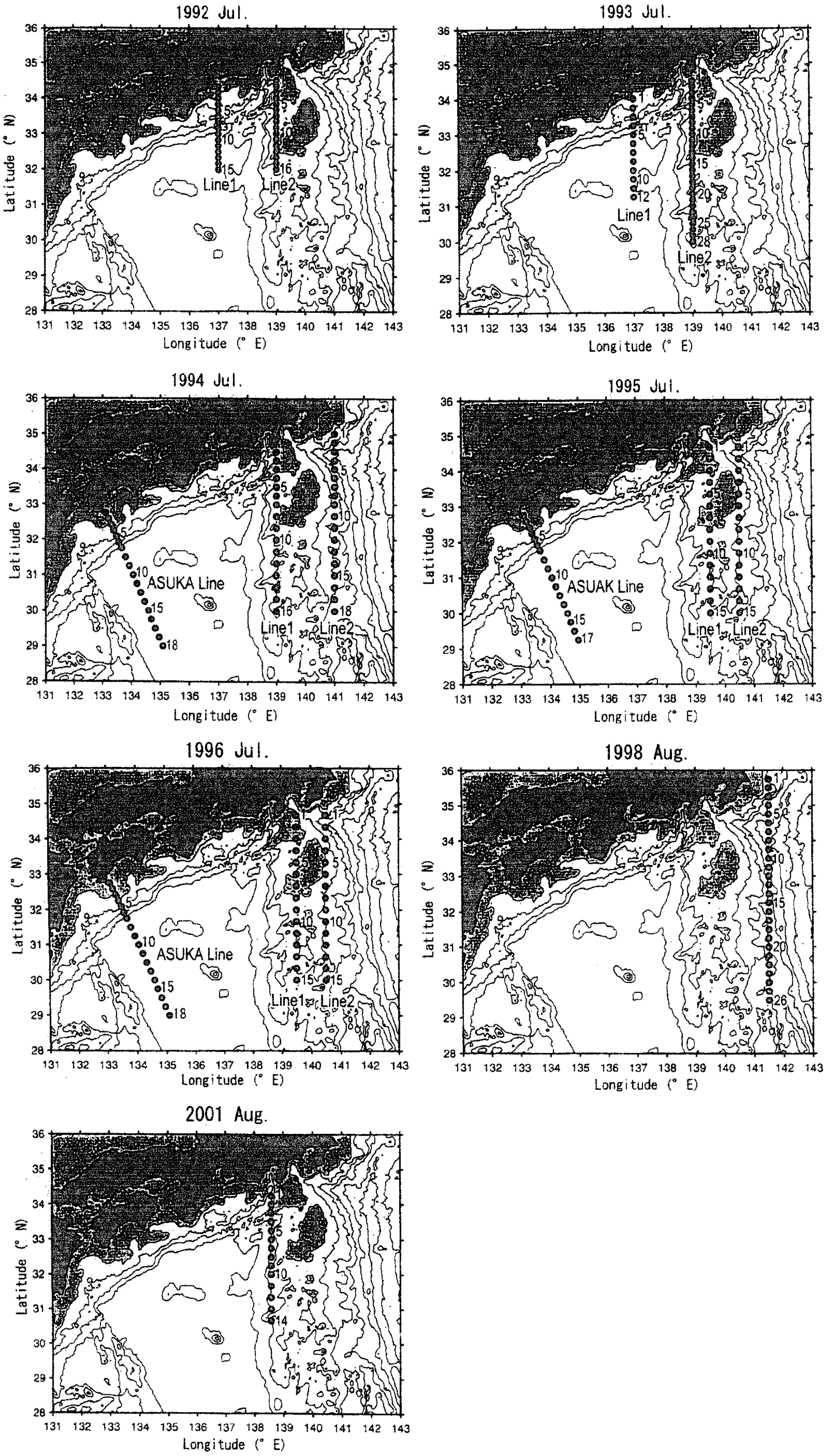

Fig. 1 Observational lines for the geostrophic flow estimation. Dots in the observational lines show CTD stations by use of the training vessel Seisui-maru of Mie University during the periods from July 1992 to August 2001. Depth contours are also shown and the regions with the depth shallower than 1000m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

path is not formed after 1992, differences in volume transport between the large meander path and non-large meander path can not be discussed.

Some numerical studies[10),11)] examined seasonal variations in volume transport of the Kuroshio, focussing upon the JEBAR effect. It should be noticed that as the barotropic response is dominant for the seasonal change in the wind stress with the strongest maximum in winter and weakest minimum in summer, the large volume transport in winter is not well evaluated by the geostrophic flow estimation with the assumption of no motion depth. In particular, the late winter strong western boundary current along eastern continental slope off Nansei Islands are predicted[12),13)]. From these points of view, it is very important to estimate the level of no motion for the geostrophic flow observation.

In order to study variations in volume transport south of Japan, seven hydrostatic observations (Fig. 1) were carried out and the obtained geostrophic velocities referred to 1500 db are compared with those referred to the shipboard ADCP velocities. In this paper, two observed geostrophic flows are presented and the difference is discussed with reference to the level of no motion. Detailed shipboard ADCP velocity, temperature & salinity fields will be presented elsewhere[14)−15)].

2. Observations

Seven cruises of CTD (Mark III System of Neil Brown Instrument Systems, Inc.) and the shipboard ADCP (CI-30 of Furuno Electric Inc.) observations south of Japan were carried out by the training vessel Seisui-maru of Faculty of Bioresourse of Mie University during the period from July 1992 to August 2001. All the observational stations and details are shown in Fig. 1 and Table 1. Unfortunately, the ADCP velocity data in July 1996 were not obtained due to the empirical trouble.

Accuracy of the ADCP velocity is 3cm sec^{-1}. The density needed to estimate geostrophic flow is calculated by use of international formula[16)]. The mean Kuroshio flows during the seven observational periods are shown in Fig. 2. It should be noticed that a large meander path has not been formed after 1992. As the non-large meander path furthermore devided into offshore non-large meander path and nearshore non-large meander path depending the offshore distance over the Izu Ridge[17)]. The offshore non-large meander path is mainly observed in the observationa periods, except for the nearshore non-large meander path in July 1994 (Fig. 2c).

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

Cruise name	Periods of Observation	Observational lines *
92 Jul	7 − 13 Jul. 1992	CS, WI
93 Jul	5 − 11 Jul. 1993	CS, WI
94 Jul	7 − 19 Jul. 1994	AS, WI, EI
95 Jul	7 − 13 Jul. 1995	AS, WI, EI
96 Jul	5 − 11 Jul. 1996	AS, WI, EI
98 Aug	7 − 19 Aug. 1998	E I
01 Aug	12 − 14 Aug. 2001	WI

* CS, AS, WI and EI correspond to the observational line across the Kuroshio main axis along 139° E, the international cooperative observational ASUKA Line[9)], a western side of the Izu Ridge and an eastern side of the Izu Ridge, respectively.

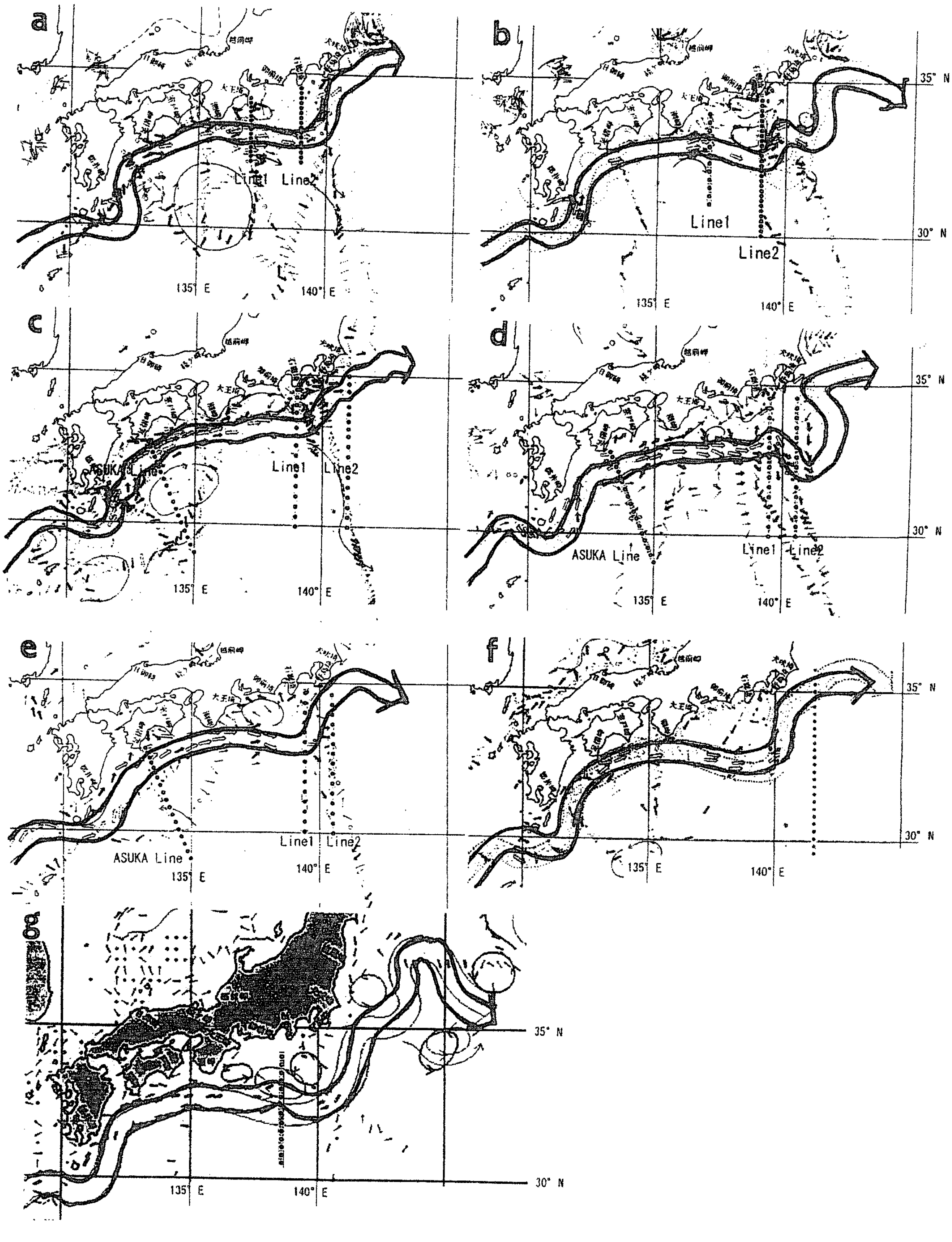

Fig. 2 Locations of the main Kuroshio flow and direction of the velocity presented by Hydrographic Department[18] during our observational periods of (a) 92 JUL, (b) 93 JUL, (c) 94 JUL, (d) 95 JUL, (e) 96 JUL, (f) 98 AUG and (g) 01 AUG.

3. Observed geostrophic flow of the Kuroshio

All the observed geostrophic velocity distribution across the Kuroshio main axis referred to 1500 db (hereafter, 1500 db case) and those referred to the observed shipboard ADCP velocity (ADCP case) are shown in Figs. 3 – 9. Here, the ADCP velocity used as the reference velocity is estimated as the averaged ADCP velocities at the deepest level between the two CTD stations, of which the observed temperature and salinity are used in the geostrophic flow estimation.

As a whole, it is shown from Figs. 3 – 10 that there exist three typical patterns of the two estimated geostrophic flow distribution of 1500 db case and ADCP case, if we focus on the region of the mean Kuroshio flow. The first pattern is a relatively common distribution between 1500 db case and ADCP case, which corresponds to Line 2 of 93JUL (Fig. 4b) and ASUKA Line of 94JUL and 95JUL (Fig. 6). The geostrophic flow estimation with the assumption of level of no motion is reasonable in this case.

The second pattern is that the constant difference is found in almost all the depth due to difference of the level of no motion, which corresponds to Lines 1 and 2 of 92JUL (Fig. 3), Line 1 of 93JUL (Fig. 4a), Lines 1 and 2 of 94JUL (Fig. 5) and 95JUL (Fig. 7b), 98 AUG and 01 AUG (Fig. 10). In this case, assumption of the reference level of 1500 db is shown to be unsuitable and causes errors of the volume transport of the

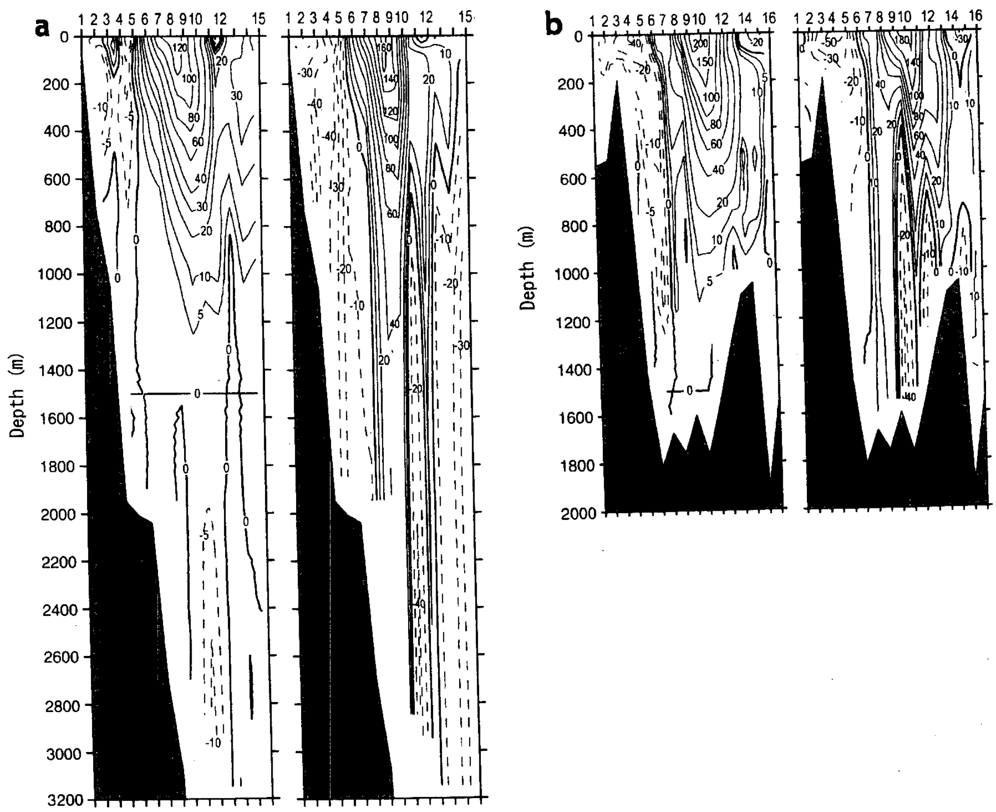

Fig. 3 Distribution of the geostrophic velocity (in cm sec^{-1}) along (a) Line 1 and (b) Line 2 in 92 JUL. Left and right panels in (a) and (b) show the geostrophic velocity referred to 1500 db and that referred to ADCP velocity, respectively. Dotted contours show the area of the counter current to the Kuroshio and the location of the observational stations is shown at the top of each panel.

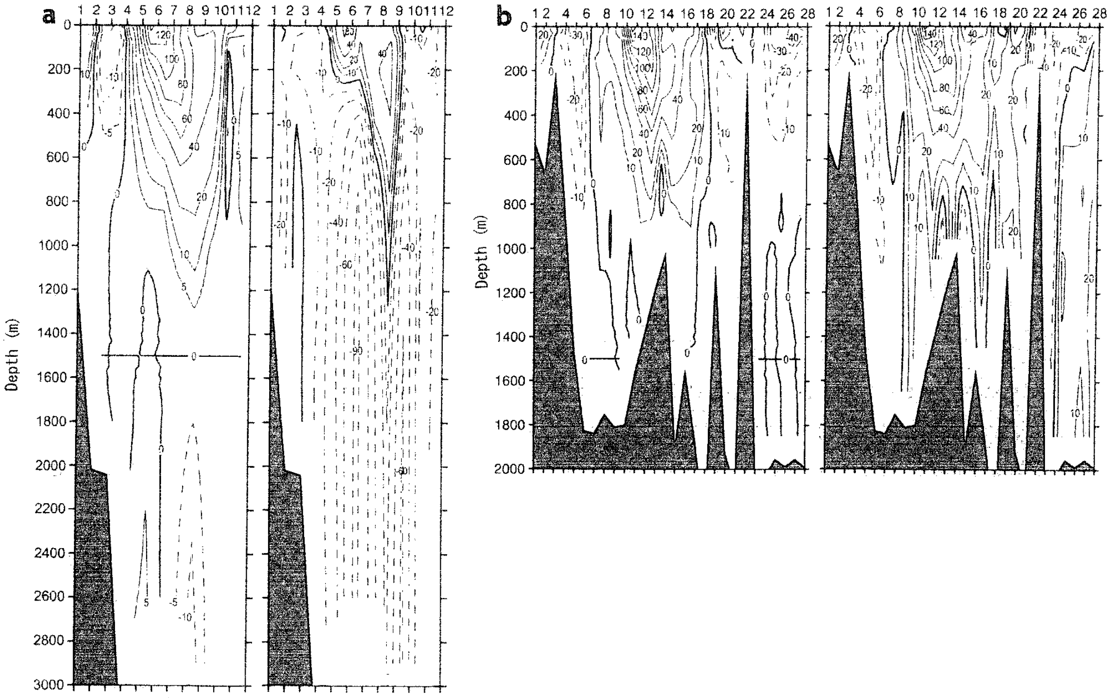

Fig. 4 Same as in Fig. 3, but for (a) Line 1 and (b) Line 2 of 93 Jul.

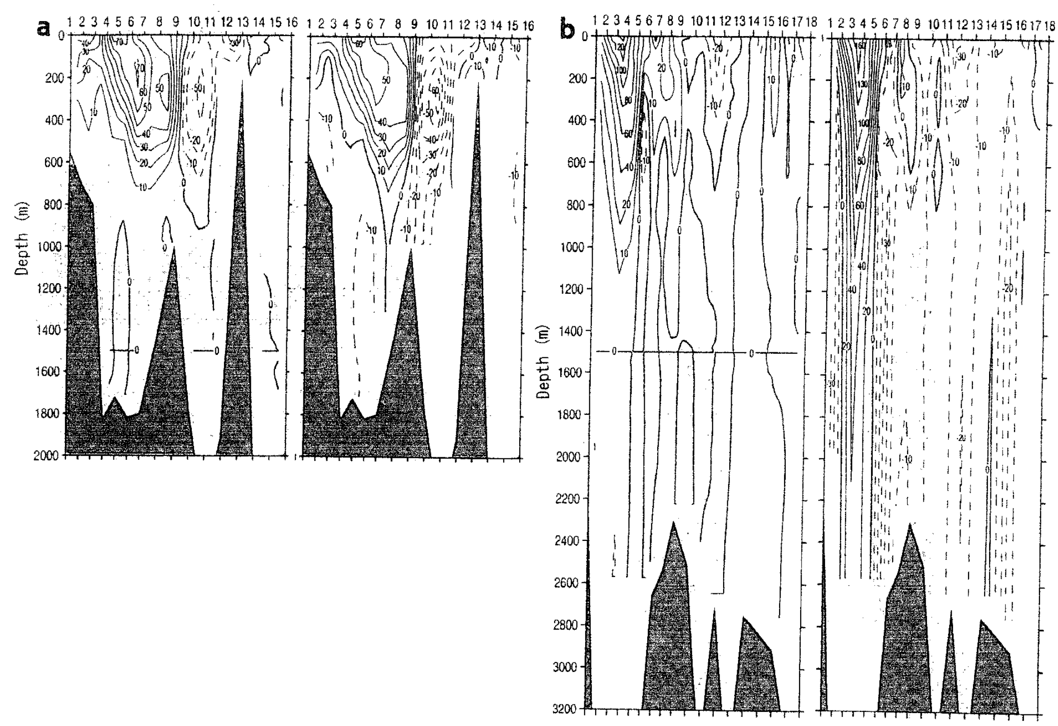

Fig. 5 Same as in Fig. 3, but for (a) Line 1 and (b) Line 2 of 94 Jul.

Table 2 Observed volume transport (in Sv = $10^6 m^3 sec^{-1}$)

Cruise name	Observational Line	1500 db case	ADCP case
92 Jul	Line 1	55.5	58.2
	Line 2	53.5	57.8
93 Jul	Line 1	64.9	42.9
	Line 2	57.7	66.2
94 Jul	ASUKA	63.4	71.8
	Line 1	50.1	36.3
	Line 2	56.4	91.0
95 Jul	ASUKA	53.7	54.9
	Line 1	42.0	67.4
	Line 2	31.5	39.4
96 Jul	ASUKA	43.3	–
	Line 1	51.6	–
	Line 2	61.6	–
98 Aug		60.0	18.7
01 Aug		84.0	248.4 (67.8*)
	mean	55.3 ± 11.9	71.1 ± 75.8 (59.8 ± 19.3*)

* the ADCP velocity observed in the northward cruising period is used and ± in the bottom shows the standard deviation.

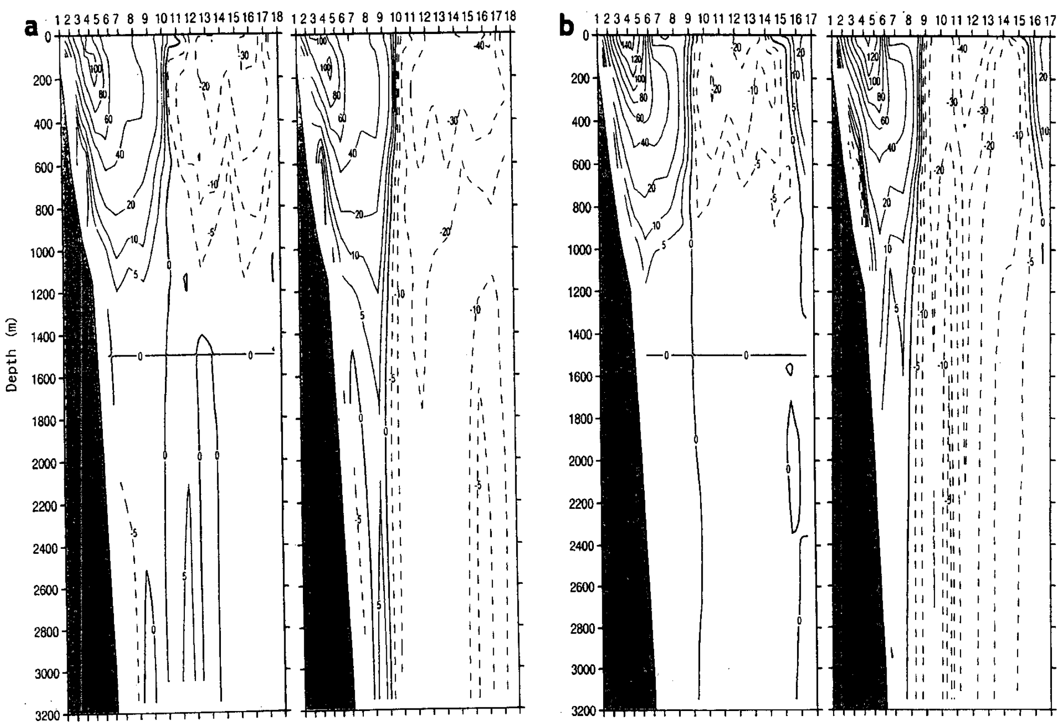

Fig. 6 Same as in Fig. 3, but for the ASUKA Line of (a) 94 Jul and (b) 95 JUL.

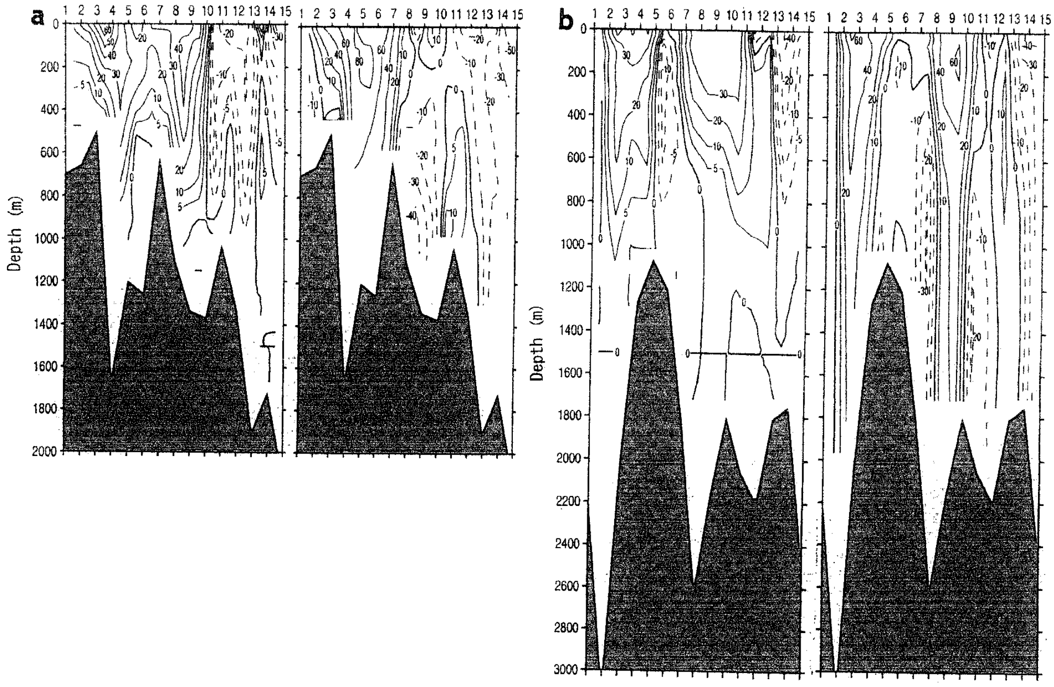

Fig. 7 Same as in Fig. 3, but for (a) Line 1 and (b) Line 2 of 95Jul.

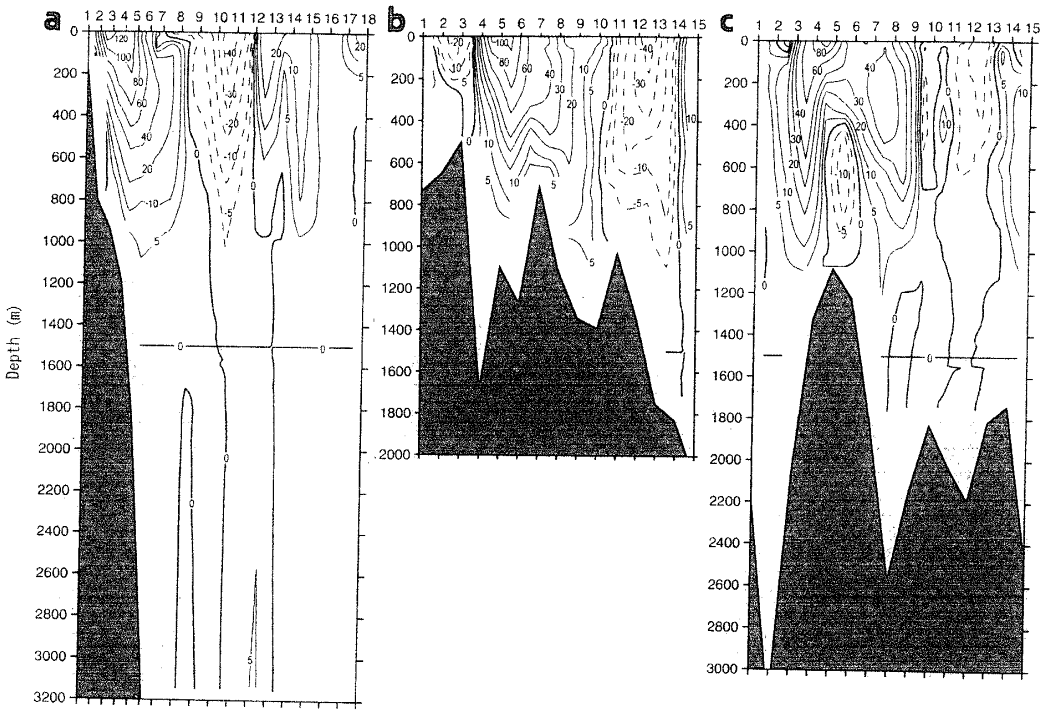

Fig. 8 Distribution of the geostrophic velocity referred to 1500 db of 96Jul. (a) ASUKA Line, (b) Line 1 and (c) Line 2.

geostrohic flow. In particular, a significant large difference in the volume transport is detected in 01 AUG, which will be discussed below.

The third pattern shows no common feature between the two cases, corresponding to Line 1 of 95 JUL. It is suggested that there exists an ageostrophic vertical shift of the density fields owing to the internal wave and/or a dominant ageostrophic ADCP velocity, such as tidal currents. Attainment of the geostrophic flow balance should be carefully checked in the geostrophic flow estimation.

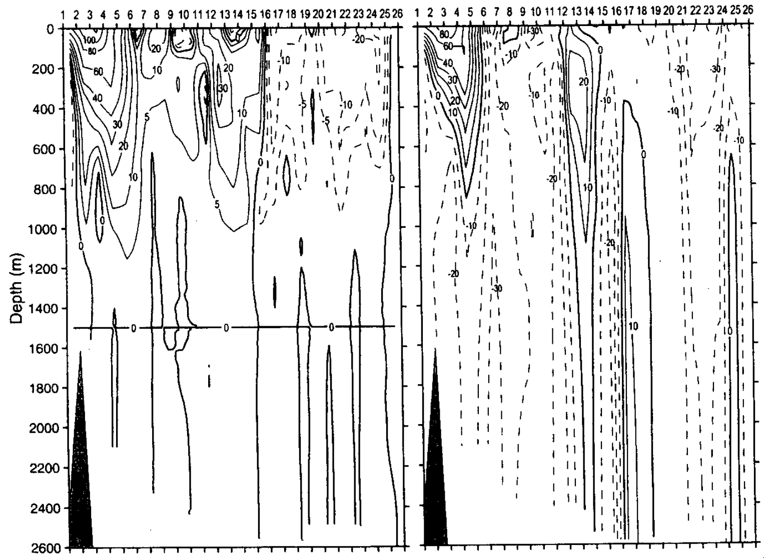

Fig. 9 Same as in Fig. 3, but for 98 AUG.

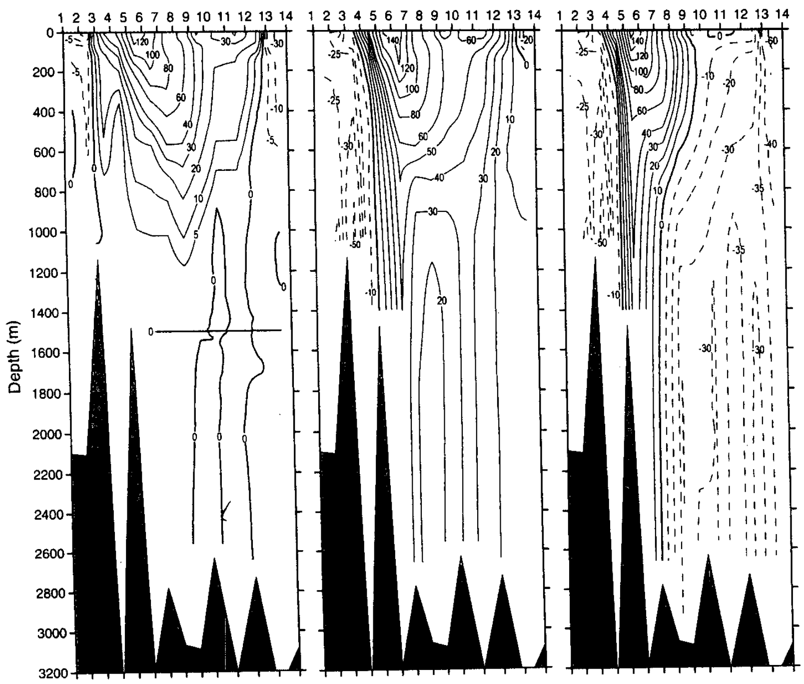

Fig. 10 Distribution of the geostrophic velocity of 01AUG. (a) Case of referring to 1500 db, (b) Case of referring to ADCP velocity during southward cruise and (c) that of northward cruise.

The observed volume transport of the Kuroshio is shown in Table 2. Here, the transport is defined as that accompanied by the mean Kuroshio flow with the maximum downstream geostrophic velocity, while that of counter upstream current is not subtracted. Larger transport with large variable range is found in ADCP case. Namely, mean transport of ADCP case is 71.1 ± 75.8 Sv (1 Sv = $10^6 m^3 sec^{-1}$), while that of 1500 db case is 55.3 ± 11.9 Sv. Here, a remarkable difference between the two volume transport is found in case of 01 AUG (Fig. 10). The volume transport referred to the ADCP velocity during the CTD observation toward south is 248.4 Sv. However if the ADCP velocity observed in the northward cruise along the same observational line is used, the volume transport is decreased to 67.6 Sv. The difference is due to the difference in ADCP velocity in the southern region: Because the large eastward flow is observed at Stations 10−12 (Fig. 10 middle), and because the internal pressure compensation by the gradient of the density fields is not sufficient, the large eastward flow is estimated in the deeper layer. On the other hand, such a large eastward flow is not observed in the northward cruise (Fig. 10 right) and the large volume transport in the deeper layer is not observed.

The geostrophic transport in period of the large meander path (64.6 ± 16.9 Sv) is relatively larger than in non-large meander path period (58.8 ± 11.4 Sv). This tendency is opposite to that obtained by Sekine et al.[8], mentioned in Introduction. As the large meander path is not observed after 1992, the opposite tendency is due to the relatively small volume transport after 1992 listed in Table 3. It is also shown from Table 3 that the geostrophic volume transport has a maximum in spring and minimum in winter. Because of relatively less observational data in winter, more frequent observations are needed.

4. Discussion

Firstly, we discuss the difference in the volume transport among the three patterns of the geostrophic flow classified by the similarity between the 1500 db case and ADCP cases. The averaged difference in the two geostrophic volume transport between the 1500 db and AVCP cases (Table 2) is 6.0 Sv for the first pattern with similar distribution. However, the difference is 36.4 Sv for the second pattern with the constant difference in all the depth. Even if the ADCP velocity of the northward cruising period is used, the averaged difference is 17.9 Sv, which is still much larger than that of first pattern.

It is detected that a small difference in the volume transport is found in 92 JUL (Fig. 3) of the second pattern. It is due to the fact that the difference in horizontal width of the Kuroshio flow is compensated by the difference in the vertical distribution, accordingly the calculated volume transport approximately

Table 3 Mean volume transport (in Sv) from May 1983 to August 2001

	Number of Observational line	Transport*
Periods of Large meander path	16	64.6 ± 16.9
non-large meander path	30	58.8 ± 11.4
Spring (from March to May)	9	66.6 ± 16.8
Summer (from June to August)	24	60.4 ± 13.6
Autumn (from September to November)	11	60.6 ± 10.6
Winter (from December to February)	2	49.6 ± 0.6

* Because there is no ADCP velocity data before 1989, the geostrophic velocity referred to 1500 db is used and ± shows the standard deviation.

equals. A complicated error is included in the volume transport estimation. The third pattern is only one (Line 1 of 95JUL) and its difference between the 1500 db and ADCP cases is 25.4 Sv (Table 2). It is thus concluded that the difference is small in the first pattern and the volume transport can be also suitably estimated, while the second and third patterns introduce larger errors. Since the accidental small difference occurs in the volume transport of 92JUL, it is pointed out that the comparison of the distribution of two geostrophic flow velocities should be made in every geostrophic flow estimation.

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日本南岸の黒潮地衡流流速

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従来の多くの研究により，黒潮流速が黒潮の二つの安定流路選択の重要なパラメータであることが指摘されている。しかし，はっきりした観測される黒潮流速の大小とその時の黒潮流路の選択の関連は十分に議論されていない。このような観点から，1983 年 5 月から 1988 年 10 月までの 22 回の観測航海に続き，1992 年 7 月より 2001 年 8 月にかけて 7 回の黒潮流速の観測を行った。この論文では 1500 db を無流面とする観測された地衡流の分布を提示する。1500 da の無流面の仮定には何の根拠もないので，船底設置の ADCP 流速計の観測流速に準拠した地衡流流速も提示して比較した。その結果，1500 da を無流面とした地衡流流速と ADCP 流速に準拠した地衡流流速はかなり一致する場合もあるが，大きな違いが生じる場合が多いことがわかり，無流面の設定には十分な注意が必要であることが示された。黒潮流路の選択や流量の季節変動特性についても議論した。