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Observation on the ADCP Velocity of the Kuroshio South of Japan

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Abstract

In order to see horizontal distribution of the velocity across the western boundary current, we have made six ADCP observations across the Kuroshio south of Japan over the period from July 1992 to August 2001. Observed ADCP velocity distribution across the Kuroshio is given in the present paper. It is shown that almost all the observed ADCP velocities decreased significantly in the nearshore coastal regions of Japan, which suggests that the viscous coastal boundary condition for numerical models of the Kuroshio is more suitable than some slippery conditions with the maximum velocity at the coastal boundary, such as the slip boundary, superslip and hyperslip boundary conditions. It is also shown that in August 2001, a prominent time change in the velocity distribution south of the mean flow of the Kuroshio was observed during only two days, in which the strong topographic effect of the Izu Ridge on the variation in the Kuroshio main axis is detected. The topographic effect of the Izu-Ogasawara Trench is shown to be small, and a barotropic current from the continental slope of the Nansei Islands to south of the Izu Ridge at latitude of 31^0 N is suggested. On the basis of the observed ADCP data, the dominant appearance of the offshore non-large meander path of the Kuroshio since 1992 is discussed.

Key Words: Kuroshio, current velocity, horizontal velocity shear

1. Introduction

It has been pointed out by many numerical studies that the flow pattern of the western boundary current is much influenced by coastal boundary conditions[1)-3)]. If a slip boundary condition is assumed, a western boundary current flowing along coastal boundary is formed, but a separation of the western boundary current is enhanced in case with a viscous boundary condition. Furthermore, if the superslip condition without gradient of relative vorticity at coastal boundaries or the hyperslip boundary condition without gradient of the potential vorticity is assumed, a strong coastal current with very large volume transport is formed and no westward intensification is detected[3)]. However, because clear observational results of the horizontal velocity distribution of the western boundary current have not been obtained, detailed discussion on this problems can not be made.

In order to see horizontal distribution of the velocity across the western boundary current, we have made six ADCP and CTD observations across the Kuroshio south of Japan over the period from July 1992 to August 2001, following the previous seventeen observations made from May 1983 to October 1988,

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temperature and salinity data of which were reported by Sekine et al.[4] and geostrophic velocity data by Sekine et al.[5].

As for the observational data of the six observations since July 1992, the temperature, salinity and density distribution were presented by Sekine (2002a)[6], while the observed geostrophic flow of the Kuroshio observed during the same cruises was reported in Sekine (2002b)[7]. It was shown by Sekine (2002a)[6] that the salinity minimum layer is unclear under the mean flow of the Kuroshio and the less saline water is separated to the coastal and offshore sides of the Kuroshio main axis in the western region of the Izu Ridge. It is also shown by Sekine (2002a)[6] that the opposite temperature gradients to the mean flow of the Kuroshio are commonly observed in south to the mean Kuroshio flow, which implies the existence of counter currents forming anti-cyclonic circulation in the offshore region.

On the basis of these previous results, we have analyzed the horizontal distribution of the ADCP velocity of the Kuroshio south of Japan. A basic velocity distribution is presented in this paper. Details of the ADCP observation will be mentioned in section 2. Results of the observation will be shown in section 3 and discussion will be made in section 4.

2. Observations

Six cruises of shipboard ADCP (CI-30 of Furuno Electric Inc.) observations together with the CTD (Mark III System of Neil Brown Instrument Systems, Inc.) observation during the period from July 1992 to August 2001 were carried out by the training vessel Seisui-Maru of Faculty of Bioresourse of Mie University. All the observational lines including the CTD stations are shown in Fig. 1 and Table 1.

The mean Kuroshio flow during the six observations are also shown in Fig. 1. As the large meander path has not been formed after 1992, the offshore non-large meander path is mainly observed except for the nearshore non-large meander path in July 1994 (Fig. 1c).

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	2 upper
92 JUL	Line 2	10-13 Jul. 1992	2 upper
93 JUL	Line 1	5- 7 Jul. 1993	2 lower
93 JUL	Line 2	8-11 Jul. 1993	2 lower
94 JUL	ASUKA	7- 9 Jul. 1994	4 upper
94 JUL	Line 1	14-16 Jul. 1994	3 upper
94 JUL	Line 2	17-19 Jul. 1994	3 upper
95 JUL	ASUKA	6-12 Jul. 1995	4 lower
95 JUL	Line 1	14-16 Jul. 1995	3 lower
95 JUL	Line 2	17-19 Jul. 1995	3 lower
98 AUG		19-22 Aug. 1998	5
01 AUG		12-14 Aug. 2001	6

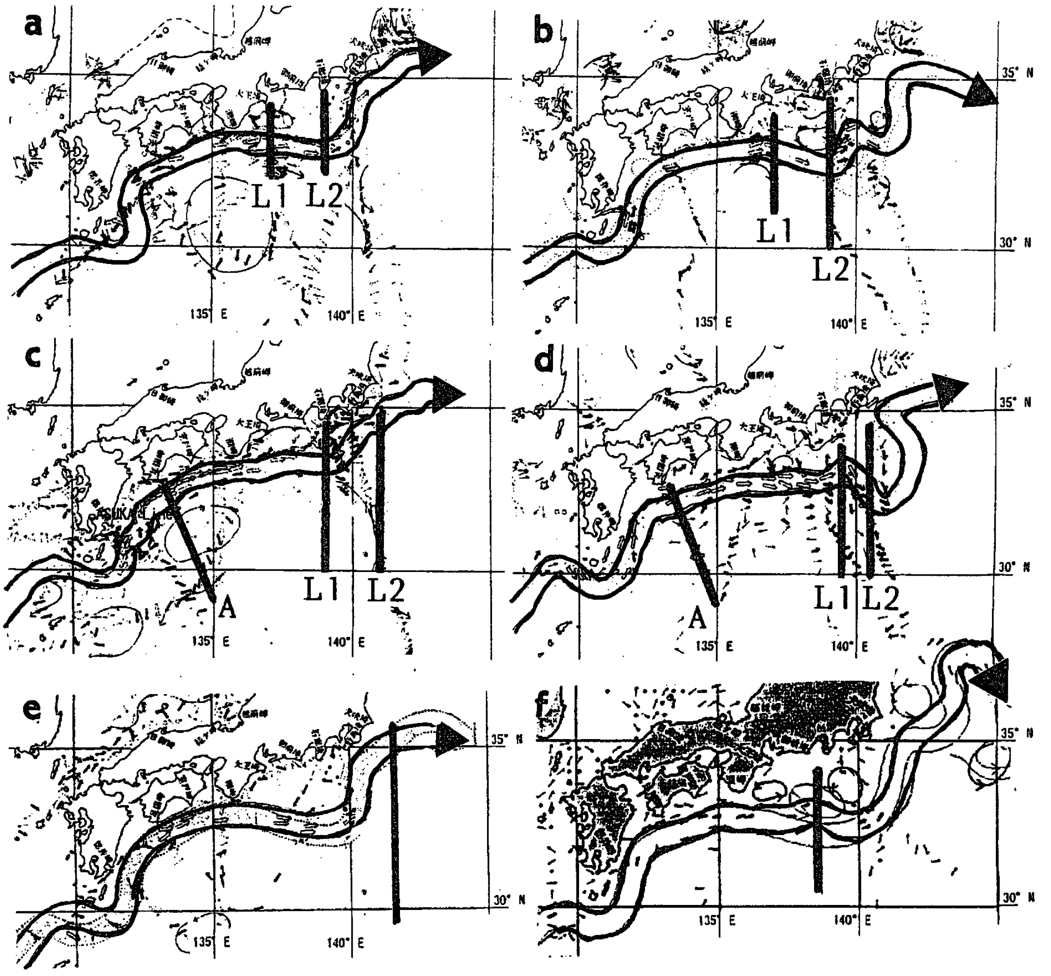

Fig. 1 Observational line of ADCP by use of the training vessel Seisui-maru of Mie University during July 1992 to August 2001. (a) 92 JUL, (b) 93 JUL, (c) 94 JUL, (d) 95 JUL, (e) 96 JUL, (f) 98 AUG and (g) 01 AUG. Also shown are locations of the Kuroshio flow and directions of its velocity proposed by the Hydrographic Department[17] during each observational period.

3. Results

All the observed ADCP velocity distribution across the Kuroshio main axis is shown in Figs. 2-6. As indicated from zonal flow of the Kuroshio over the Izu Ridge (Fig. 1a), a prominent zonal ADCP velocity is observed in 92 JUL (Fig. 2 upper). Vertical change of the zonal mean flow of the Kuroshio is unclear. In contrast to this, a prominent vertical change is detected in a westward flow in north of the main Kuroshio axis. Namely, northern-westward coastal flow along Line 2 shows a gradual decrease as we go to deeper layers, while the westward coastal flow along Line 1 is relatively clear at a depth of 100 m. These results indicate that the coastal counter flow has a large vertical shear.

The vertical velocity difference of the main Kuroshio axis is observed in case of 93 JUL (Fig. 2 lower). Largest velocity is found at a depth of 50 m, but it decreases at 100 m. The mean flow of the Kuroshio is furthermore decreased at a depth of 200 m and the flow direction is significantly changed. It should be noticed that at a depth of 200 m the mean flow goes over the shallower region of the Izu Ridge near the

Hachijou-Jima shown by the bottom contour of 500 m, and the large topographic effect of the Izu Ridge is suggested. Relatively large westward flow is observed in a southern part at depths of 50 m and 100 m of Line 2, while it is changed to southward flow at a depth of 200 m.

A coastal mean flow is observed in 94 JUL (Fig. 3 upper) and a vertically coherent flow is perceived. Northeastward flow of Line 1 goes to the shallow region of the Izu Ridge. Large topographic effect of the Izu Ridge is suggested. Although southern westward flow of Line 1 at latitude of 32° N is vertically coherent, the westward flow of Line 2 is relatively large at a depth of 50 m, but it is weakened at depths of 100 m and 150 m.

As for the velocity distribution of 95 JUL (Fig. 3 lower), a large change in the current direction is seen between Lines 1 and 2. Eastward flow is observed at Line 1 but it turns southward at Line 2, total feature of which is shown by Fig. 1d. Large topographic effect of the Izu Ridge is also suggested here and it will be discussed in section 4 with special reference with the bimodal path characteristics of the Kuroshio south of Japan. Vertically coherent westward flow is detected at south of 30.5° N of both observational lines. It is recognized that the westward flow runs along bottom contour of 2000 m. Sekine et al. (2000)[8] pointed out that the North Pacific Intermediate Water (NPIW) formed in the confluent region of the Oyashio and the Kuroshio Extension shifts southwestward and goes over the south of the Izu Ridge at 30° N with the depth deeper than 2000 m. Therefore, this westward coherent flow may correspond to shallower part of NPIW.

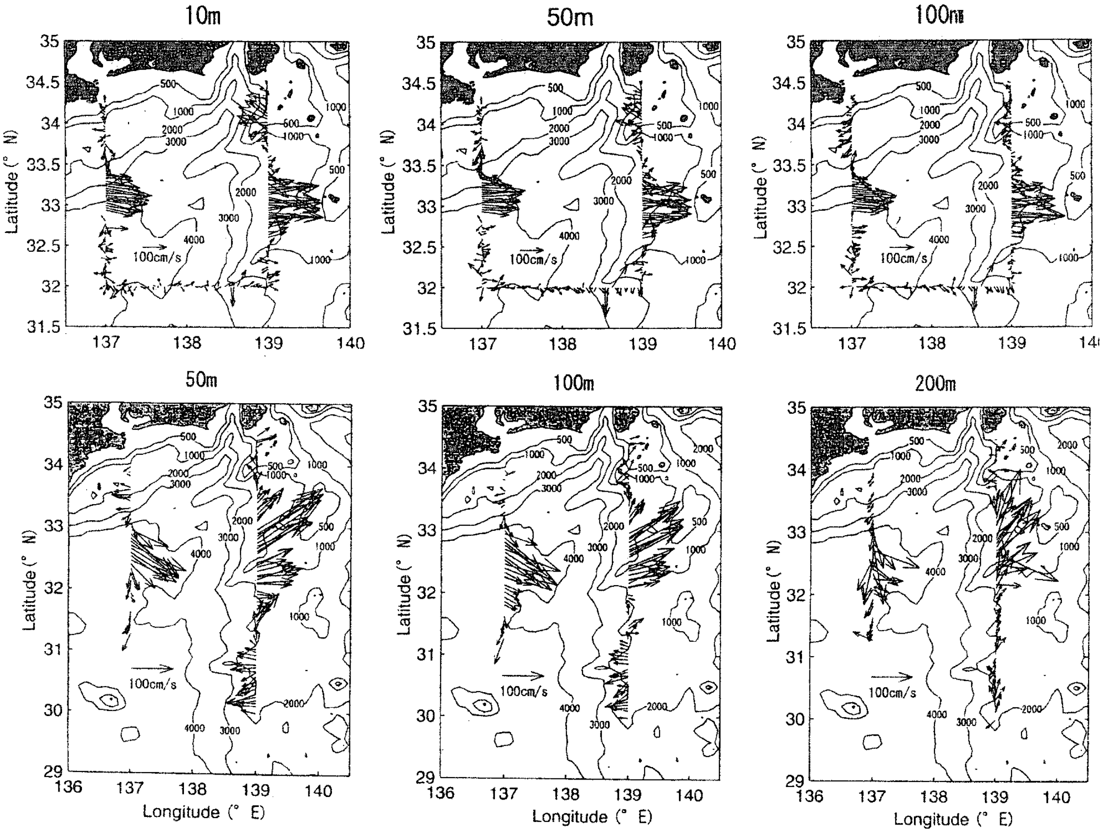

Fig. 2 Distributions of the observed ADCP velocity along Lines 1 and 2 in 92 JUL (upper) and Lines 1 and 2 in 93 JUL. Observed depths of ADCP velocities are shown in the top of each panel and depth contours (in meter) are also shown.

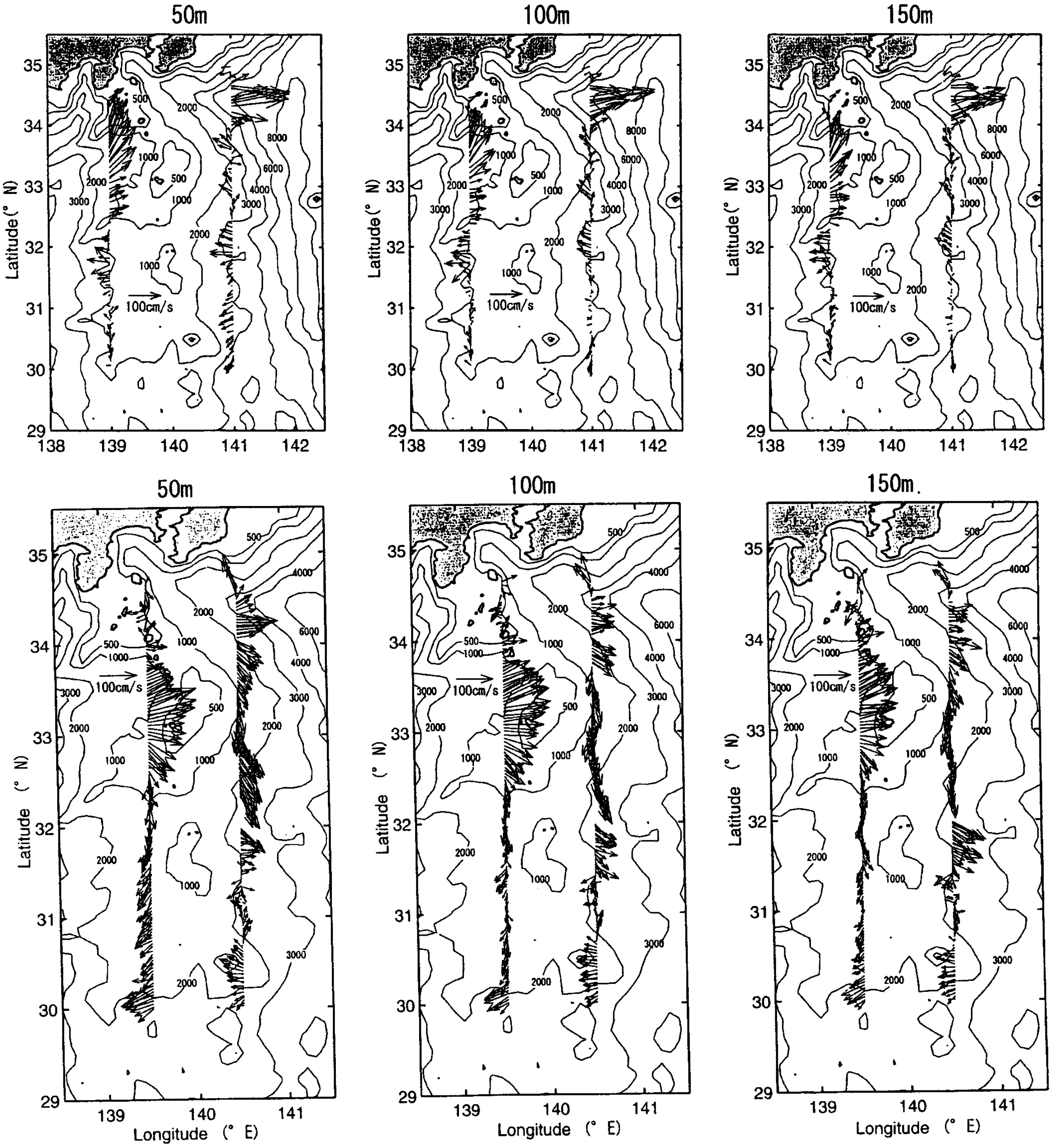

Fig. 3 Same as in Fig. 2, but for Lines 1 and 2 of 94 JUL (upper) and Lines 1 and 2 of 95 JUL.

Almost essentially similar velocity distribution is observed along ASUKA Line (Fig. 4). It is commonly detected that almost all ADCP velocities including ASUKA line have a tendency to decrease significantly in northern nearshore coastal region of Japan. Therefore, the viscous coastal boundary condition is more stable for numerical model of the Kuroshio, but some slippery conditions with a maximum velocity at a northern margin, such as the slip boundary, superslip and hyperslip conditions are unsuitable.

It is also shown from Fig. 4 that wider and weaker mean Kuroshio flow is observed in 94 JUL (upper panel), while narrower and strong mean flow is observed in 95 JUL (lower panel). A clear westward counter current in south to the mean Kuroshio flow is seen in both cases and it is a part of anti-cyclonic eddy in the subtropical circulation. This suggests that the Kuroshio is a western boundary current with strong

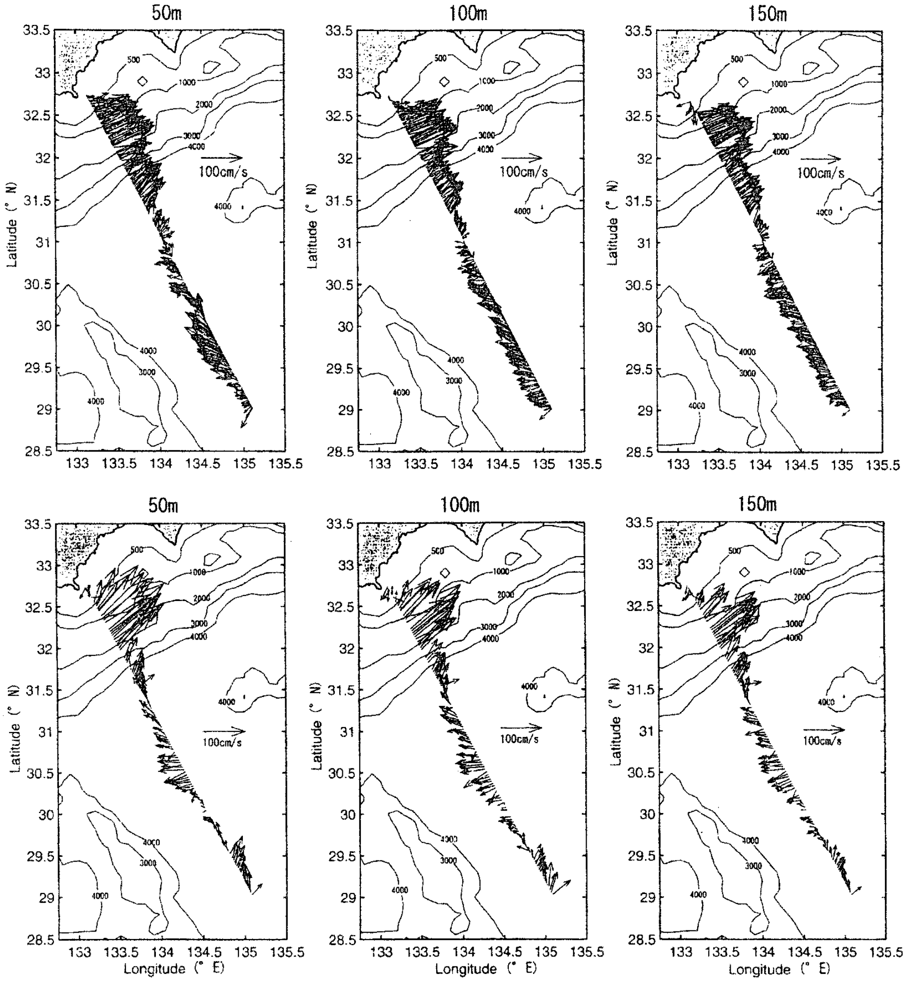

Fig. 4 Same as in Fig. 2, but for ASUKA Line of 94 JUL (upper) and 95 JUL (lower).

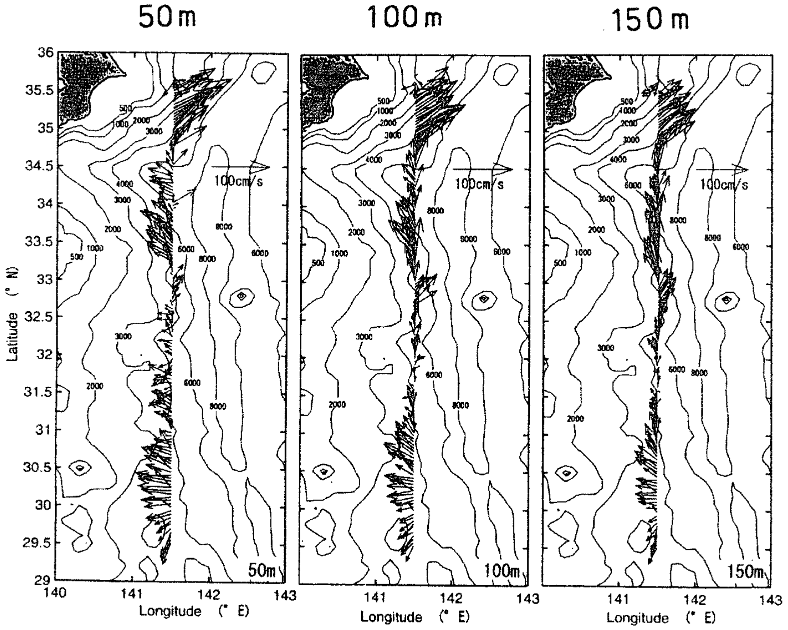

Fig. 5 Same as in Fig. 2, but for the observational line of 98 AUG.

nonlinearity in which anti-cyclonic eddy is formed in southeast of the western boundary current[1)-3)].

A mean flow of the Kuroshio Extension is located at a northern part of the observational line of 98 AUG (Fig. 5), in which weak vertical velocity change is detected. A northwestward flow in south of the mean flow is observed at a depth of 50 m, while it changed northward at depths of 100 m and 150 m. This northwestward and northward flows are part of anti-cyclonic eddy located at south of the mean flow (Fig. 1e). Although current is weak at latitudes of 32^0-33^0 N, a strong westward flow exists south of 31^0 N. This large westward flow is commonly observed in cases of 93 JUL (Fig. 2 lower), and 95 JUL (Fig. 3 lower). Although a barotropic current has strong tendency to flow along the contour of f/h, where f is the Coriolis parameter and h is a depth of ocean, the dominant westward flow suggests that the topographic effect of the Izu-Ogasawara Trench is weak and a water over the trench is able to go over it forming the westward flow.

A remarkable time change in velocity is observed in 01 AUG (Fig. 6), in which southward and northward

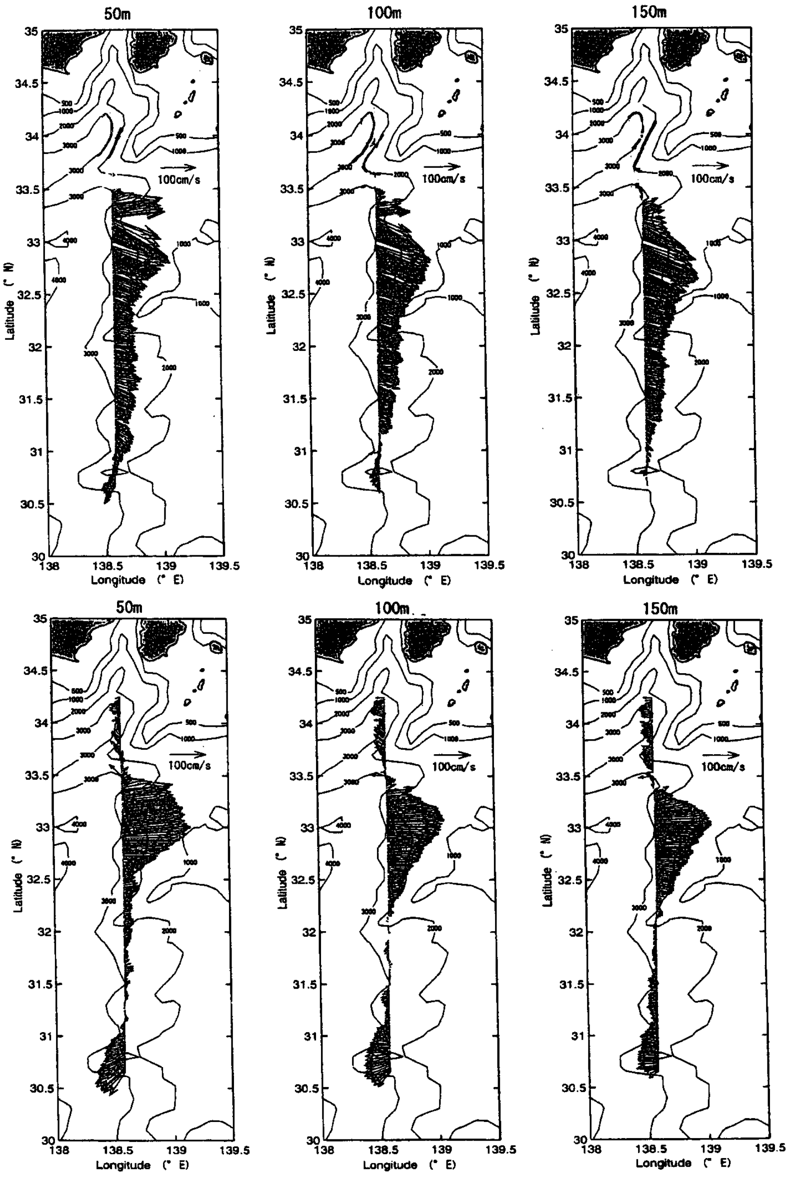

Fig. 6 Same as in Fig. 2, but for the observational line of 01 AUG during the southward period (upper) and northward period (lower).

cruise take about 2 days and 7 hours. Namely, Southward cruise (Fig. 6 upper) was carried out from noon of August 12 and the northward cruise (Fig. 6 lower) began at 19 o'clock of August 13 and ended at 19 o'clock of the next day. Northward shift of the mean flow is detected between the two data and a strong eastward flow in south of mean flow in southward cruise disappears in the northward cruise. Furthermore, westward flow at the souther region is observed in the northward cruise. The observational period is in the transitional process from the offshore non-large meander path (Fig. 1f) to the nearshore non-large meander path. Decay of the eastward flow in south to the mean flow and the appearance of the southern westward flow in the northward cruise indicate the northward shift of the main Kuroshio flow. There exists no vertical velocity change and the large topographic effect of the Izu Ridge is also suggested.

4. Discussion

The large topographic effect of the Izu Ridge on the Kuroshio is suggested from the gross feature of the observed ADCP velocity. Firstly, we discuss the dominant appearance of the offshore non-large meander path after 1992 (Fig. 1). Since the volume transport of the Kuroshio has a tendency to increase after 1990[9)], the large meander part is advected downstream to the western part of the Izu Ridge. Therefore, offshore non-large meander path is formed and the large meander path is not formed by the large topographic effect of the Izu Ridge. It is shown by some numerical experiments that the topographic effect of the Izu Ridge on the large meander path with a cyclonic eddy is significant and the large meander path decays in a short time over the Izu Ridge[10), 11)]. However, this suggestion should be checked more quantitatively, some numerical experiment will be carried out with reference to the observational feature why offshore non-large meander path is formed in spite of nearshore non-large meander path.

The prominent westward flow has been shown to dominate in south to 31^0 N, which implies that the topographic effect of the Izu-Ogasawara Trench is weak and the barotropic Rossby wave is not trapped along the eastern side of the Trench. As for the seasonal variation in subtropical circulation, a barotropic western boundary current has been predicted on the continental slope of Nansei Islands[12), 13)]. Kawabe (2001)[9)] also concluded the barotropic flow off Nansei Islands by the consideration of westward propagation of the barotropic Rossby wave. Since Kawabe (2001)[9)] considered the topographic effect of the Izu-Ogasawara Trench, existence of the the subtropical counter current[14)] is pointed out. However, the topographic effect of the Izu-Ogasawara Trench is shown to be weak in this study, a zonal eastward flow from continental slope off Nansei Islands to south of the Izu Ridge is suggested.

The dynamics of this current from off Nansei Islands to south of the Izu Ridge is essentially common to the subtropical circulation in southern hemisphere including the Agulhas Current in east of Africa and Brazil Current. As the coastal topographic effect of the Africa corresponds to that of Izu Ridge[15), 16)], similar current system is indicated in the Shikoku Basin. More detailed studies on this current will be made in near future.

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日本南岸の黒潮のADCP流速観測

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西岸境界流の水平流速分布を知るために，1992年7月から2001年8月までに日本南岸の黒潮を横切るADCP観測を6回行った。この論文ではこれらの観測で得られたADCP流速の分布を提示する。日本南岸の岸近くでは黒潮流速が顕著に減少することが共通して観測され，数値モデルについては粘性の境界条件が適切であり，非粘性境界条件や超非粘性境界条件さらに極粘性境界条件のような岸近くで最大速度となる条件は不適切であることが示された。2001年8月にはわずか2日の間に極めて著しい流れの変化を観測し，黒潮に及ぼす顕著な伊豆海嶺の地形効果が示唆された。順圧流に対して伊豆小笠原海溝の地形効果は小さく，南西諸島東の陸棚斜面から北緯31度の伊豆海嶺の南端を結ぶ海流の存在が示唆された。これらの観測結果を基礎に，1992年以降の観測期間では離岸型非大蛇行流路が卓越することの背景を議論した。