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The Kuroshio in the East China Sea and the currents east of the Ryukyu Islands during autumn 1991

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Abstract : A modified inverse method is used to compute the currents in the East China Sea and to the east of the Ryukyu Islands with moored current meter records and hydrographic data collected during October-November, 1991. The volume transport of the Kuroshio is 27.4, 26.3 and $26.0\times10^6 m^3/s$ across three different sections. There are countercurrents east of the Kuroshio. There is a western boundary current, called "Ryukyu Current", east of the Ryukyu Islands. It has two cores of maximum speed east of Okinawa Island. One is located over the area of maximum slope of the bottom. Its maximum velocity is about 20cm/s, (between 500 and 600m levels). The other is located above 200m level further to the east. This current occupies mostly the upper 1400m. Its volume transport is about $21.4\times10^6 m^3/s$ east of Iriomotejima and Ishigakijima Islands and $12.4\times10^6 m^3/s$ east of Okinawa Island.

1. Introdduction

There have been many studies on the current structure and volume transport of the Kuroshio in the East China Sea. The computation methods used there are dynamic computation method (e.g., GUAN, 1988), diagnostic model (YUAN and SU, 1988), inverse method (e.g., YUAN *et al.*, 1990, 1991), modified inverse method (e.g., YUAN *et al.*, 1992) and prognostic model (YUAN, 1993). The average total volume transport (VT) through section PN in the East China Sea is around $29\times10^6 m^3/s$ (YUNA *et al.*, 1993).

In contrast there have been few studies on the western boundary currennt east of the Ryukyu Islands. For simplicity we will call it "Ryukyu Current" (WANG and SUN, 1990). YUAN *et al.* (1990, 1991) pointed out that this northeastward current often has two cores of maximum speed. One is always between 300 and 800m over the area of maximum slope of the bottom, and its maximum velocity was 25cm/s at the 700m level during Sept.-Oct. 1987. The other is located above the 200m level further to the east. Underneath the Ryukyu Current there is a southwestward current. To the east of it there is also a southwestward countercurrent. Probably because hydrographic sections did not extend over the whole Ryukyu Current, the computed volume transport of it showed a large variability with a maximum value comparable to the average VT of the Kuroshio in the East China Sea (YUAN *et al.*, 1993).

In order to inverstigate further the western boundary current on the both sides of the Ryukyu Islands, the first cruise was carried out in October 11 to November 15, 1991, as a part of a cooperative study between Chinese and Japanese scientists. Hydrograhic data were obtained during this cruise. Current meters were deployed to the southeast of Okinawa Island (Fig. 1) in November 1991 and recovered in September 1992. With the 1991 hydrographic data and the current meter records the modified inverse method proposed by YUAN *et al.* (1992) is used to compute the current structures and volume transports on both sides of the Ryukyu Islands.

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2. Numerical calculation

First we estimate the order of magnitude of

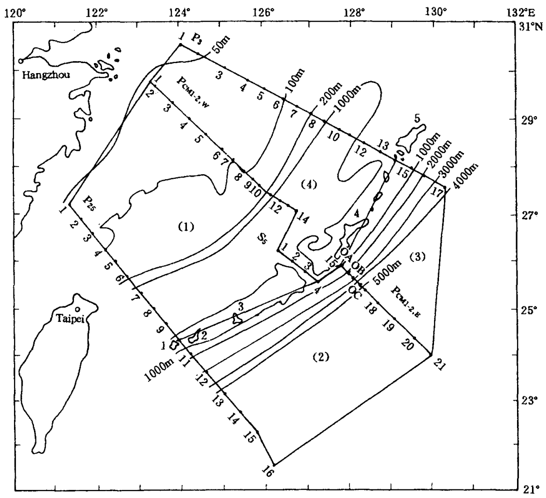

Fig. 1. Bottom topography (in meters), hydrographic sections, mooring stations OA, OB and OC and computation boxes in autumn 1991 (1: Iriomotejima I., 2: Ishigakijima I., 3: Miyakojima I., 4: Okinawa I., 5: Amamioshima I.).

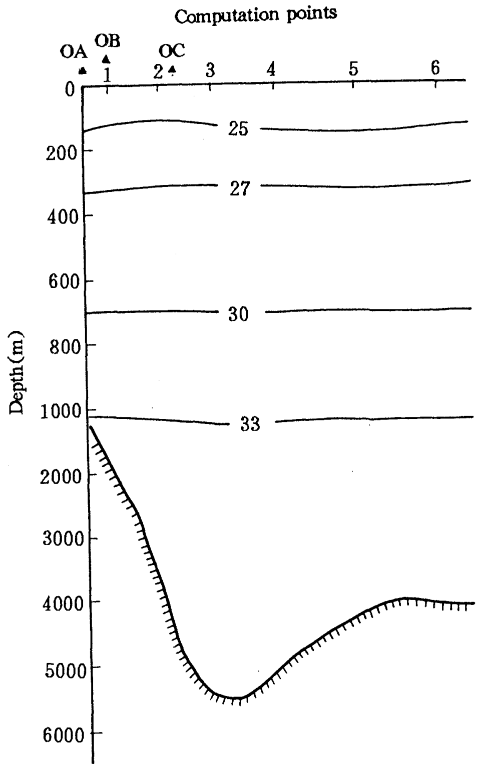

Fig. 2. Isopycnal levels along section PCM1-2E in autumn of 1991.

time change, nonlinear and horizontal eddy (HE) terms in the momentum equations. Based on velocity data obtained by moored current meters, the fluctuation of current on the slope in the East China Sea was found to have a predominant perid of 11–14 days (SUGIMOTO *et al.*, 1988). If the time and space scales T, L and the representative horizontal speed U_0 are taken to be 11 days (9.504×10^5s), 500km, and 1m/s. respectively, the Coriolis parameter f $7\times10^{-5}s^{-1}$, and the horizontal eddy coefficient A_H $10^3m^2/s$, we obtain the Rossby number $R_0=U_0/(fL)=3\times10^{-2}$, the ratio of the time change term to the Coriolis term $(Tf)^{-1}=2\times10^{-2}$, and the ratio of the HE to Coriolis terms $A_H/(fL^2)=10^{-4}$. Thus, the time change, nonlinear and HE terms are negligible in the momentum equations. In addition, previous studies (YUAN and SU, 1983; YUAN *et al.*, 1988) showed the HE term in the momentum equation is negligible, by comparing computed results between two cases, with and without the HE term. Thus, the modified inverse method described in YUAN *et al.* (1992) can be used to compute the current structures and volume transports in the survey area. Four boxes are set up: two in the East China Sea and the other two to the southeast of the Ryukyu Islands (Fig. 1). The computation points are the mid-points between neighboring hydrographic stations. For example, computation point 1 is between hydrographic points 1 and 2. Section S_5 is mostly located at a narrow gap over the Ryukyu Ridge.

All boundary sections of the computation boxes are divided into layers in the vertical according to isopycnal values of $\sigma_{t,p}$=25, 27, 30 and 33 (YUAN *et al.*, 1990). For example, at section PCM1-2E the four isopycnals lie between 130–150m, 330–345m, about 700m and 1200m, respectively (Fig. 2).

The average wind direction and speed observed on board the R/V Shijian were 42° (NE) and 8.6m/s during the autumn cruise in 1991. Because accurate wind data are not available, a steady uniform wind field with these values is assumed. The vertical eddy and diffusion coefficients are 10^{-2} m^2/s and 10^{-3} m^2/s, respectively, for the momentum and density equation (YUAN *et al.*, 1992).

Table 1. Time-averages of the low-passed current velocities during November 1991.

Mooring station	Water depth (m)	Period of averaging	Instrument depth (m)	V (cm/s)	θ	V′ (cm/s)
OA	1000	Nov. 4–11, 1991	570	21.7	66.8°	19.8
		Nov. 4–15, 1991	870	5.0	50.9°	5.0
OB	2020	Nov. 4–30, 1991	1890	4.4	253.0°	−3.8
		Nov. 4–15, 1991	1890	6.0	252.0°	−5.2
OC	4630	Nov. 14–30, 1991	700	10.1	330.4°	3.0
		Nov. 13–30, 1991	2000	4.2	225.0°	−4.2
		Nov. 13–30, 1991	4500	2.6	220.0°	−2.6

V: Speed.
θ: Direction measured clockwise from due the notrh.
V′: Velocity component normal to section PCM1–2E. Positive value: northeastward.

There were three moored stations, OA, OB and OC, located on section PCM1–2E (Fig. 1). Time-averages of low-passed current velocities during November 1991 are listed in Table 1. The period of averaging begins on the starting date of valid records and ends on either the final date of valid records or 30 November 1991 whichever comes earlier. The low-passed currents are rather steady during the periods of averaging (Fig. 3). Fig. 1 shows that stations OA and OC are not located on any computation points. Only station OB is located on computation point 1 at PCM1–2E. In order to discuss the dependence of computed results upon the velocity value prescribd at 1890m depth at OB, two different velocities, −3.8 and −5.2cm/s observed there (Table 1) are used as known values for the computation in two cases, which are referred to as CA–1 and CA–2. In addition, the velocity at 2000m level of computation point 2 (see Fig. 5 (b)) is interpolated from the average velocities observed at 1890m level at OB and 2000m level at OC to get a known value for the computation. Next we set up the third case CA–3, in which the velocity at 1890m depth at OB is unknown and to be obtained from our modified inverse method.

The FIADEIRO and VERONIS's method (1982) is used to determine an optimum reference level. An optimum reference level is obtained to be 2500m in our survey area. For computation points with water depth less than 2500m, the reference levels are reset to the local water depths.

Table 2 shows the results in the three cases in terms of the VT through a western part of P_{25} (points 1 to 9), a western part of P_3 (points 1 to 14) and the other two whole sections. The VT is very little different from each other between the three cases except the VT through PCM1–2E in case CA–3.

The velocity computed in case CA–3 is −1 cm/s and southwestward at 1890m depth at OB, which agrees in direction with the observation at OB but is much smaller than the observed magnitude, −3.8 cm/s or −5.2 cm/s. Since there is almost no difference between cases CA–1 and CA–2, only the result in CA–1 will be discussed below.

3. Velocity distribution during autumn of 1991

Figs. 4 to 7 show the velocity distribution at each section. It might be remarked that both horizontal and vertical scales are different from each other in these figures and that the vertical scale below 1000m is different from that above 1000m in each.

(1) Section P_{25}

Section P_{25} is divided into two parts; northwest of Iriomotejima Island (computation points 1–9) and southeast of it (computation points 10–15).

To the northwest of Iriomotejima Island the Kuroshio core is located over the continental slope (Fig. 4). The velocities are greater than 100 cm/s in the upper 150 m of computation point 6. Its maximum velocity is about 154 cm/s at the surface. Below 500 m level the location of maximum velocity moves eastward to the computation point 7, in agreement with previous studies (YUAN and SU, 1988). The

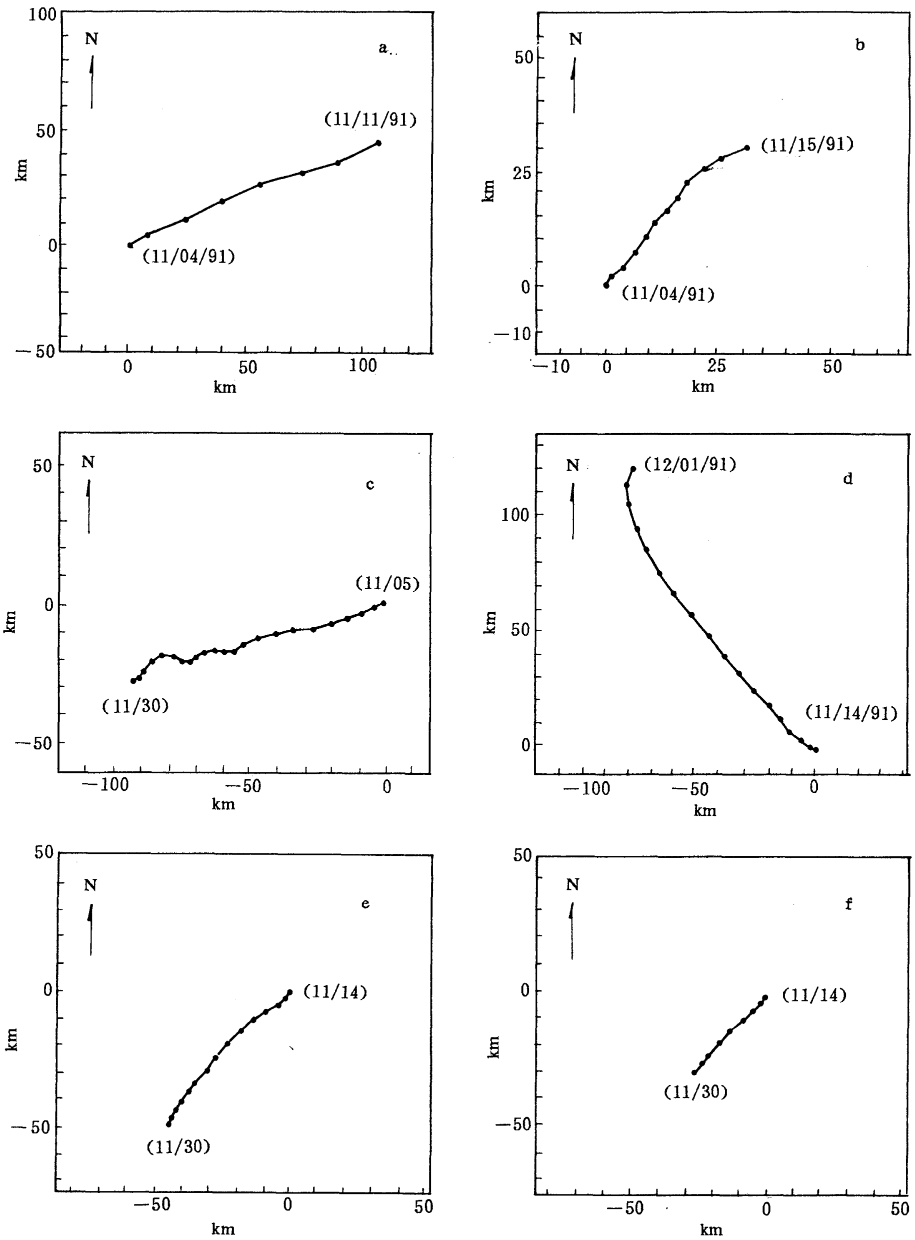

Fig. 3. Progressive vector diagrams of observed daily currents. (a), (b) 570m and 870m depths at OA; (c) 1890m depth at OB; (d), (e), (f) 700m, 2000m and 4500m depths at OC.

countercurrent is to the east of the Kuroshio. Its velocities are not small. The core of this flow lies between 700 and 1000m levels, and maximum velocity is about 21cm/s at 800m level (Fig. 4). There is a cold eddy over the shelf north of Taiwan and west of the Kuroshio, centered at about 122° 14.11′ E, 26° 8.72′ N. The temperature distribution at section P_{25} also depicts its existence, as discussed in previous studies (YUAN *et al.*, 1991). This cold eddy has been documented in many studies (e.g., UDA and KISHI, 1974; FAN, 1980; CHERN *et al.*, 1990). For

Table 2. Volume transports (VT) ($10^6 m^3/s$) through sections. NE: northeastward; SE: southeastward; SW: southwestward.

Cases	P_{25}	PCM1-2W	P_3		PCM1-2E	
	NE	NE	NE	SE	NE	SW
CA-1	27.5	26.1	25.8	−4.2	6.4	−5.8
CA-2	27.4	26.1	25.7	−4.3	6.1	−5.2
CA-3	27.5	26.1	25.8	−4.3	8.3	−6.1

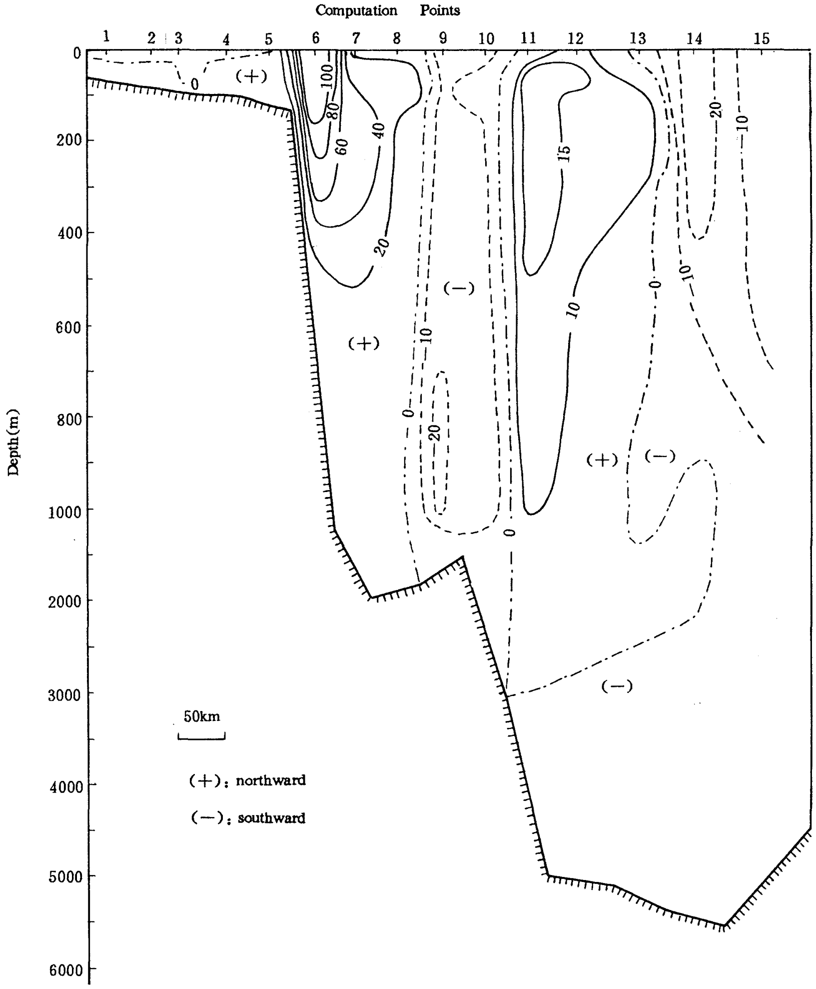

Fig. 4. Velocity distribution at section P_{25} during autumn of 1991. (positive: northeastward, units: cm/s)

example, on the basis of hydrographic data during Sept. 1987, CHERN *et al.* pointed out that next to the Kuroshio there was a distinct cold and high-salinity eddy on the shelf edge with minimum temperatures $<19°$ C and maximum salinities$>$ 34.6‰.

To the southeast of Iriomotejima Island, there is clearly a northeastward flow, i.e., the Ryukyu Current (Fig. 4). Its core is between 50 and 800m levels, located over the region of

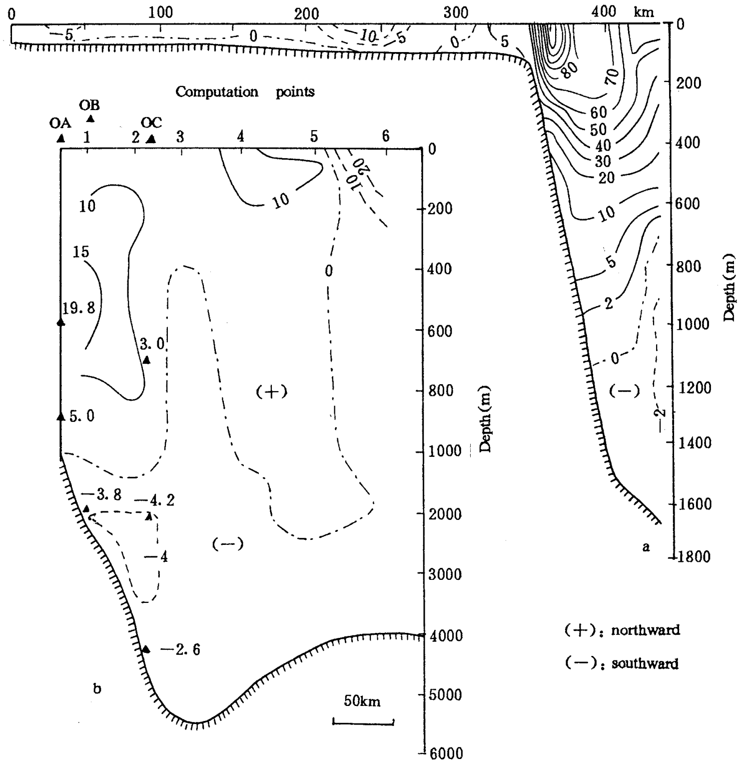

Fig. 5. Velocity distribution during autumn of 1991 at (a) section PCM1-2W, (b) section PCM-12E (positive: northeastward, units: cm/s). ▲ positions of the moorings.

maximum slope of the bottom. Inside this core the velocity varies slightly with depth, from 12 to 19 cm/s. Below this northeastward current the flow is southwestward. There is also a southwestward flow to the east of the Ryukyu Current. Its maximum velocity is close to 30 cm/s at the surface of computation point 14. At computation point 10 there is also a southwestward flow. This shows that flows on both sides of Iriomotejima Island have the same orientation (Fig. 4).

(2) Sections PCM1-2W, PCM1-2E and S_5

Fig. 5(a) shows the velocity distribution at section PCM1-2W. Similarly to section P_{25} the Kuroshio core is over the continental slope. Its maximum velocity is about 136 cm/s at 30m level. In the deeper layer there is a weak southwestward current. The countercurrent often existing east of the Kuroshio is not observed because this section does not extend across the whole Okinawa Trough.

Section PCM1-2E is located southeast of Okinawa Island. Fig.5(b) shows that the greater part of the section is occupied by a northeastward current with two cores of maximum speed. One is between 150 and 800 m levels over the area of maximum slope of the bottom, and its velocity is 16.3 and 16.1 cm/s, respectively, at 500 and 600m levels. The other is located above 200m level further to the east, and its maximum velocity is about 15.2 cm/s at 50m level. The average observed velocity component normal to section PCM1-2E at OA is 19.8 cm/s and 5 cm/s, respectively, at 570 and 870m levels (Table 1 and Fig. 5 (b)). Fig. 5(b) shows that the 570m current meter is in the core with speed greater than 15 cm/s, while the 870m current meter is between isotachs of 10 and 0 cm/s. The computed results agree fairly well with the observed values at OA. They agree with the observed values at OC, too (Fig. 5 (b)). Beneath the Ryukyu Current there is a southwestward flow. It is located below 1000 and 1400m levels

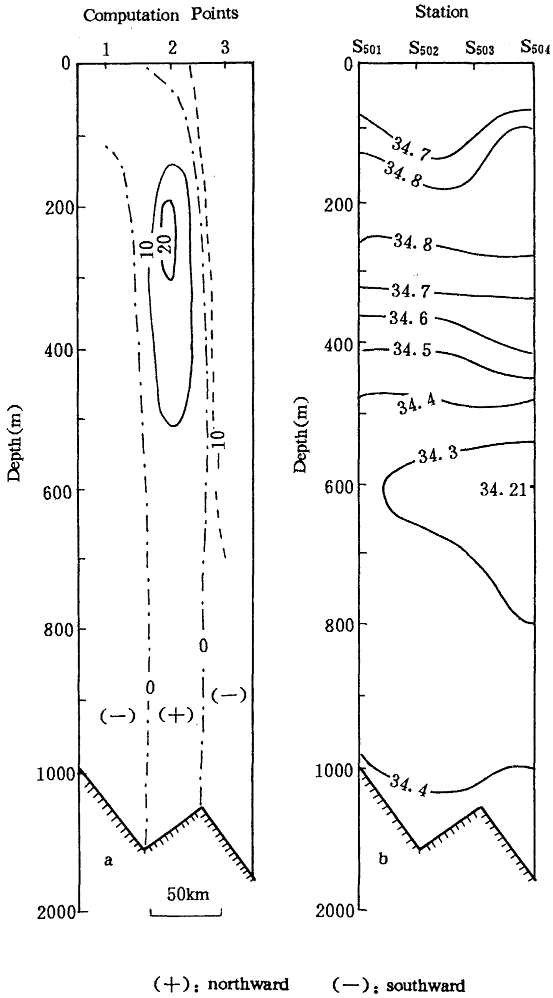

Fig. 6. Velocity (a) and salinity (b) distribution at section S_5 in autumn 1991. (positive: northeastward, units: cm/s and ‰)

at computation points 1 and 2, respectively. Its speed is about 4.2 and 4.1cm/s, respectively, at 2000 m level at computation points 1 and 2. The maximum speed is about 5.2 cm/s at 2500 m level. In the eastern part of section PCM1–2E there is also a southwestward flow, whose velocities are greater than 20 cm/s in the upper 150 m layer.

Finally, we note that the features of currents at section PCM1–2E as discussed above were also obtained at a section southeast of Okinawa Island in September–October, 1987 (YUAN *et al.*, 1990).

The velocity distribution at this section shows that there are southwestward flows at both its west and east ends and a northeastward flow at its central part (Fig.6 (a)). Fig.6 (b) shows that the low salinity water seems to intrude from the east to the west, in agreement with previous studies (Yu *et al.*, 1993).

(3) Section P_3

Section P_3 is divided into two parts (Fig. 1), i.e., the northwestern part (computation points 1–14) in the East China Sea just north of the regular survey line PN, and the southeastern part (computation points 14–17) southeast of Amamioshima Island.

The Kuroshio core at section P_3 is located over the continental slope (Fig.7). Its maximum velocity is about 92 cm/s at 100 m level of computation point 9, which is less than that at section P_{25} and PCM1–2W. Southeast of the Kuroshio there is a southwestward countercurrent. It extends all the way down to the bottom underneath the Kuroshio (Fig.7). Fig.7 also shows the appearance of a northeastward flow at computation point 13, the southeasternmost computation point inside the East China Sea, of which velocity is not large.

The southeastern part of section P_3 southeast of Amamioshima Island is of short length (Fig. 1). Fig. 7 shows a southwestward flow at computation point 15 and a northeastward flow at computation points 14 and 16. These flows all have subsurface cores and the southwestward flow is quite strong, with a maximum velocity of 72 cm/s at 250 m level.

4. Distribution of the volume transport during autumn 1991

Fig. 8 shows the distribution of the total volume transport in the computational region during autumn of 1991. In the East China Sea the net VT through the part of section P_{25} northwest of Iriomotejima Island is about $27.4\times10^6 m^3/s$. There is a core of higher temperatures (Fig. 9) and lower salinities in the deeper layer west of Iriomotejima Island, probably associated with an anticyclonic eddy with a total transport of $11\times10^6 m^3/s$ (Fig. 8). The northeastward VT is about $26.1\times10^6 m^3/s$ through section PCM1–2W, and about $25.8\times10^6 m^3/s$ through the northwestern part of section P_3. The transport of the

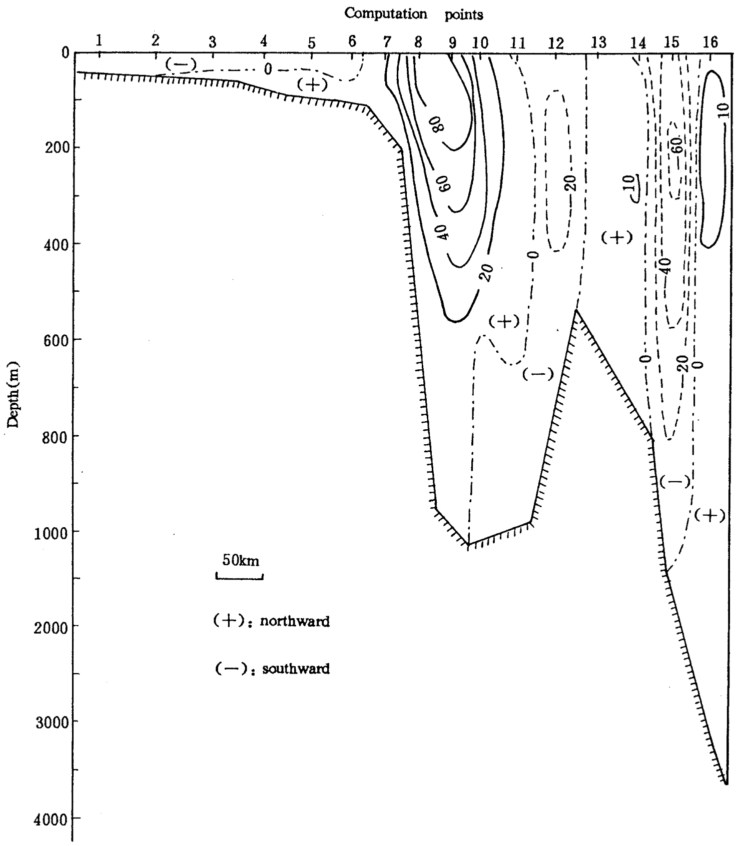

Fig. 7. Velocity distribution at section P_3 during autumn of 1991. (positive: northeastward, units: cm/s).

Kuroshio, i.e., the northeastward current next to the continental shelf of the Est China Sea, is 27.4, 26.3 and 26.0 × $10^6 m^3/s$, respectively, across sections P_{25}, PCM1–2W and P_3. These values are very close to the transport of the Kuroshio at section PN, 26.0×$10^6m^3/s$, during Oct. 1987 (YUAN *et al.*, 1990). Our computation cannot confirm the gradual decrease in VT along the downstream direction, because section PCM1–2W does not extend across the whole Okinawa Trough, as mentioned before.

In the following we shall discuss the volume transport in the area east of the Ryukyu Islands. Through the eastern part of section P_{25} the northeastward and southwestward total VT are 19.4 and 18.6× $10^6m^3/s$, respectively. The southwestward total VT is divided into two parts; one with 8.9×$10^6m^3/s$ is in the west and the other with 9.7×$10^6m^3/s$ in the east. The VT of the Ryukyu Current, i.e; the northeastward current east of Iriomotejima Island, is 21.4× $10^6m^3/s$. The northeastward and southwestward total VT through section PCM1–2E are 6.4 and 5.8×$10^6m^3/s$. The VT of the Ryukyu Current through section PCM1–2E is 12.4×$10^6m^3/s$ and the VT of the southwestward current beneath it is about 6.0×$10^6m^3/s$.

The VT of the northeastward and southwestward current through section P_3 east of the Ryukyu Islands are 9.1 and 8.2×$10^6m^3/s$, respectively.

There is a net eastward flow through the area between Okinawa and Miyakojima Islands with a VT of about 5.8×$10^6 m^3/s$.

5. Summary

Based on moored current meter records and hydrographic data during autumn of 1991, the modified inverse method is used to compute the Kuroshio in the East China Sea and the current

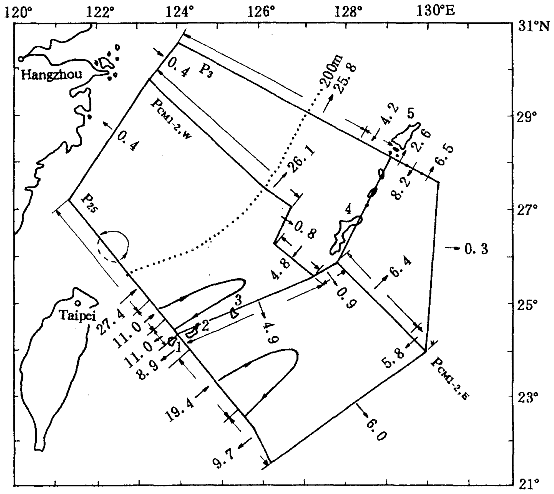

Fig. 8. Distibutions of the total VT during autumn of 1991 (units: $10^6 m^3/s$).

east of the Ryukyu Islands. It is found that:

1) The Kuroshio core is located over the continental slope. Its maximum velocity is 154, 136 and 92 cm/s, at sections P_{25}, PCM1-2W and P_3, respectively, during this cruise.

2) The transport of the Kuroshio is 27.4, 26.3 and $26.0 \times 10^6 m^3/s$, respectively, across sections P_{25}, PCM1-2W and P_3.

3) Beneath the Kuroshio there is a southwestward countercurrent. Southeast of the Kuroshio there is another countercurrent.

4) East of the Ryukyu Islands there is a western boundary current, called Ryukyu Current. It has two cores of maximum speed at section PCM1-2E. One is located over the area of maximun slope of the ocean bottom. Its maximum velocity is between 500 and 600m levels, and is about 20 cm/s. The other is located above 200m level further to the east.

5) Below the Ryukyu Current the flow is southwestward. Its maximum velocity at section PCM1-2E is about 5.2 cm/s at 2500 m level. There is another southwestward flow east of the Ryukyu Current.

6) The volume transport of the Ryukyu Current through sections P_{25} and PCM1-2E is 21.4 and $12.4 \times 10^6 m^3/s$, respectively.

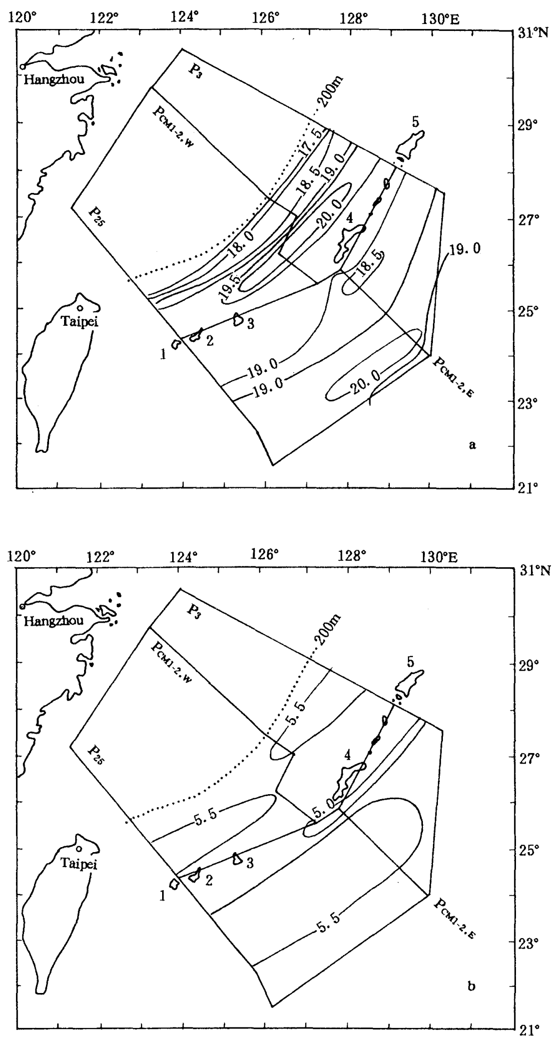

Fig. 9. Temperature distributions in autumn 1991 at (a) 200m level; (b) 800m level.

References

CHERN, C. S., J. WANG and D. P. WANG (1990): The exchange of Kuroshio and East China Shelf Water. J. Geophys. Res., **95**, 16017–16023.

FAN, K. L. (1980): On upwelling off northeastern shore of Taiwan. Acta Oceanogr. Taiwan, **11**, 105–117.

FIADEIRO, M. E and G. VERONIS (1982): On the determination of absolute velocities in the ocean. J. Mar. Res., **40**, suppl., 159–182.

GUAN, B. (1988): Major feature and variability of the Kuroshio in the East China Sea. Chin. J. Oceanol. Limnol., **6**, 35–48.

SUGIMOTO, T., S. KIMARA and K. MIYAJI (1988): Meander of the Kuroshio Front and current variability in the East China Ses. J. Oceanogr. Soc. Japan, **44**, 125–135.

UDA, M. and A. KISHI (1974): Cyclonic cold eddies along the edge of the Kuroshio current in the relation to the genesis and passage of cyclones, I. Waters north of Taiwan. The Kuroshio, III. Proceedings of the 3rd Symposium, Bangkok, Thailand, 1972, 199–218.

WANG, Y. and X. SUN (1990): A study on the features of the Ryukyu Current. Proc. Invest. the Kuroshio (II), China Ocean Press, Beijing, 237–245.

YU, H., J. SU and Y. MIAO (1994): Low salinity water centre of the Kuroshio in the East China Sea and intrusion of western boundary current east of the Ryukyu Islands. Proc. China Japan Joint Symp. Cooperative Study on the Kuroshio, 27–29 October 1992, Qingdao, China. (in press)

YUAN, Y. (1993): A prognostic model of three dimensional current in the East China Sea. Proc. Invest. the Kuroshio (V). China Ocean Press, Beijing, 311–324.

YUAN, Y., M. ENDOH and H. ISHIZAKI (1990): The study of the Kuroshio in the East China Sea and currents east of the Ryukyu Islands. *In*: Proc. Japan China Joint Symp. Cooperative Study on the Kuroshio, Science and Technology Agency, Japan & SOA, China, 39–57.

YUAN, Y., Z. PAN, I. KANEKO and M. ENDOH (1993): Variability of the Kuroshio in the East China Sea and the currents east of the Ryukyu Islands. Proc. the Kuroshio (V), China Ocean Press, Beijing, 279–297.

YUNA, Y. and J. SU (1983): A two-layer circulation model of the East China Sea. Proceedings of the International Symposium on the Continental Shelf, with special reference to the East China Sea, 364–374.

YUAN, Y. and J. SU (1988): The calculation of Kuroshio Current structure in the East China Sea – early summer. Progress in Oceanogr., **21**, 343–361.

YUAN, Y., J. SU and Z. PAN (1990): Calculation of the Kuroshio Current south of Japan during Dec., 1987–Jan., 1988. Proc. Invest. the Kuroshio (II), China Ocean Press, Beijing, 256–266.

YUAN, Y., J. SU and Z. PAN (1991): A study of the Kuroshio in the East China Sea and the currents east of the Ryukyu Islands in 1988. *In*: Oceanography of Asian Marginal Seas. K. Takano, ed., Elsevier Science Publishers, 305–319.

YUAN, Y., J. SU and Z. PAN (1992): Volume and heat transports of the Kuroshio in the East China Sea in 1989. La Mer, **30**, 151–162.

YUAN, Y., J. SU and W. ZHOU (1988): Calculation of the Kuroshio Current south of Japan in May–June 1986. Progress in Oceanogr., **21**, 503–514.