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The western boundary current east of the Ryukyu Islands [*1]

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Abstract: With hydrographic data in Sept. 1992 and moored current meter records from Nov. 1991 to Sept. 1992, a modified inverse method is used for computing the western boundary current east of the Ryukyu Islands (WBCE) and the Kuroshio in the East China Sea. The WBCE has two cores, of which the depths vary seasonally. There is a southwestward abyssal boundary current under it throughout the year. Through a transect southeast of Okinawa, the volume transport (VT) of the WBCE is $30.8\times10^6 m^3/s$ and the VT of the southwestward current is $6.0\times10^6 m^3/s$, so that the net northward VT is $24.8\times10^6 m^3/s$. Through a transect northwest of Okinawa the total VT of the Kuroshio and Taiwan Warm Current is $32.1\times10^6 m^3/s$ and the VT of a southwestward countercurrent is $3.7\times10^6 m^3/s$, so that the net northeastward VT is $28.4\times10^6 m^3/s$, slightly larger than the VT southeast of Okinawa. The amount of water exchanged between the east and west sides of the Ryukyu Islands is discussed. The salinity minimum water in the mid-layer flows northwestward from the east of the Ryukyu Islands to the East China Sea through a gap of the Ryukyu Ridge. Its VT west of Okinawa is about $2.4\times10^6 m^3/s$.

1. Introduction

The current east of the Ryukyu Islands, sometimes called the Ryukyu Current (WANG and SUN, 1990), was first discussed by NITANI (1972). He pointed out that a narrow countercurrent flows just southeast of the Ryukyu Islands, on the offshore side of which flows a northeasterly current. However, so far there have been few studies on it.

YUAN *et al.* (1991*a, b*) first showed the subsurface core structure of the Ryukyu Current, a southward undercurrent below it and a southward countercurrent to its east, which is often associated with a mesoscale anticyclonic eddy. The volume transport (hereafter abbreviated to VT) of the Ryukyu Current was computed with the inverse method (YUAN *et al.*, 1991*a, b*) and the modified inverse method (YUAN *et al.*, 1992, 1993*a, b, c*).

The study on the Ryukyu Current is of primary importance for understanding the western boundary current system in the northwestern Pacific Ocean, especially because it is one of the principal sources of the Kuroshio transport southeast of Kyushu (YUAN *et al.*, 1991; YUAN *et al.*, 1993*b*). Previous studies were based on hydrographic, GEK and/or onboard ADCP data which are confined into surface layers. Very few direct current measurements have been done with moored meters in this region. CHAEN *et al.* (1993) made deep and bottom current measurements at three mooring sites southeast of Okinawa from Nov. 1987 to May 1989.

In the framework of a China-Japan cooperative study, long term current measurements with moored current meters were made southeast of Okinawa (TAKANO *et al.*, in preparation). Hydrographic data were obtained during two cruises by the R/V Shijian, one for the deployment of the moorings in Oct. to Nov. 1991 and the other for recovery in Sept. 1992. The current velocity and the volume transport are obtained with the modified inverse method together with the current meter data.

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2. Calculation

Figure 1a shows hydrographic sections in Oct. to Nov. 1991 with mooring stations OA, OB and OC and isobaths, and Fig. 1b hydrographic sections in Sept. 1992. The modified inverse method is applied to boxes (1) to (4). The result for Oct. to Nov. 1991 is presented in another paper (YUAN *et al.*, 1994). The computation points (hereafter abbreviated to Cp) are at the middle of nearby two hydrographic stations. The boundary sections of each computation box are divided into five layers according to $\sigma_{t,p}$ - iso -

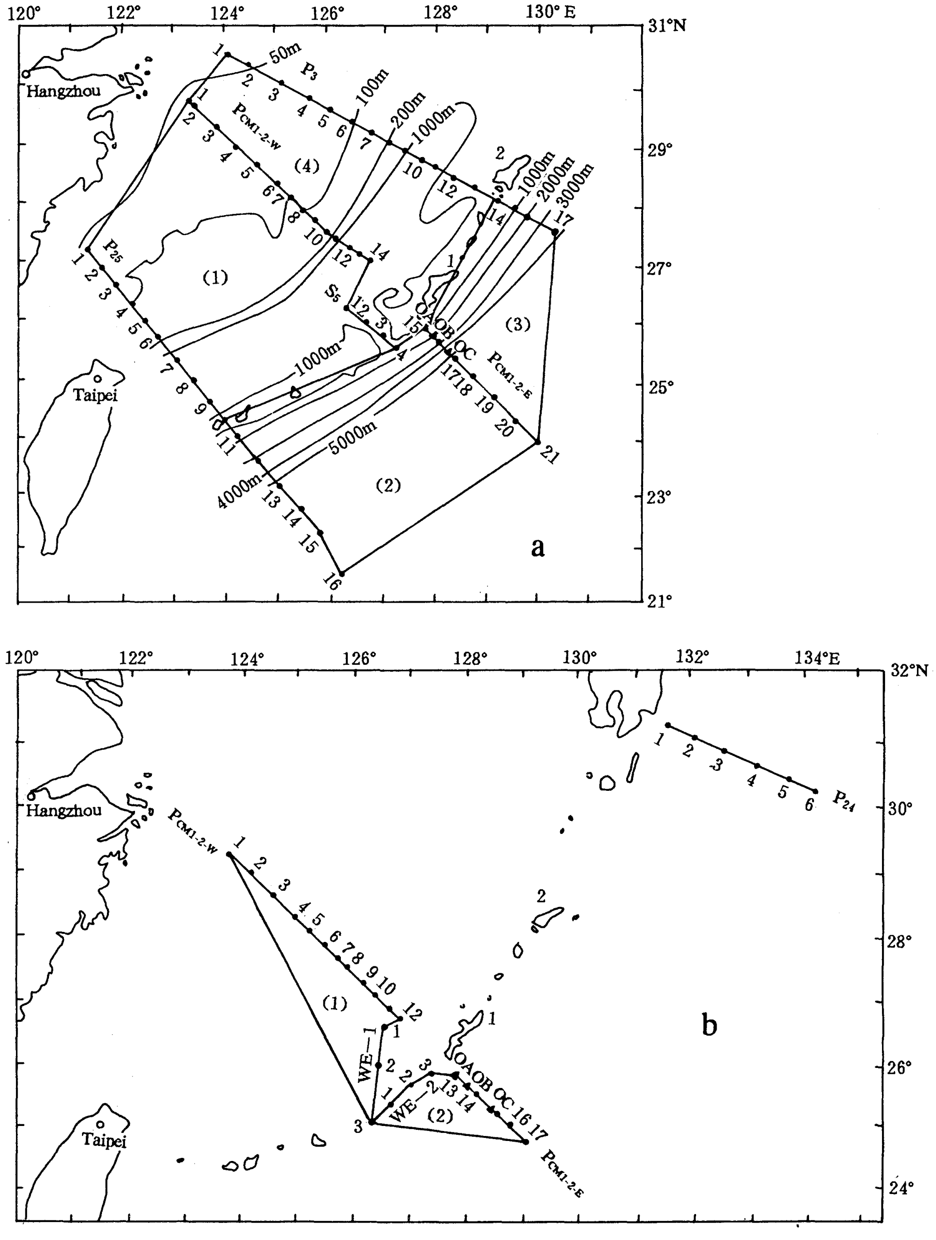

Fig. 1. Locations of hydrographic sections and moorings OA, OB and OC. a: in Oct.–Nov. 1991; b: in Sept. 1992; 1: Okinawa Is.; 2: Amamioshima Is. Isobaths are shown in (a).

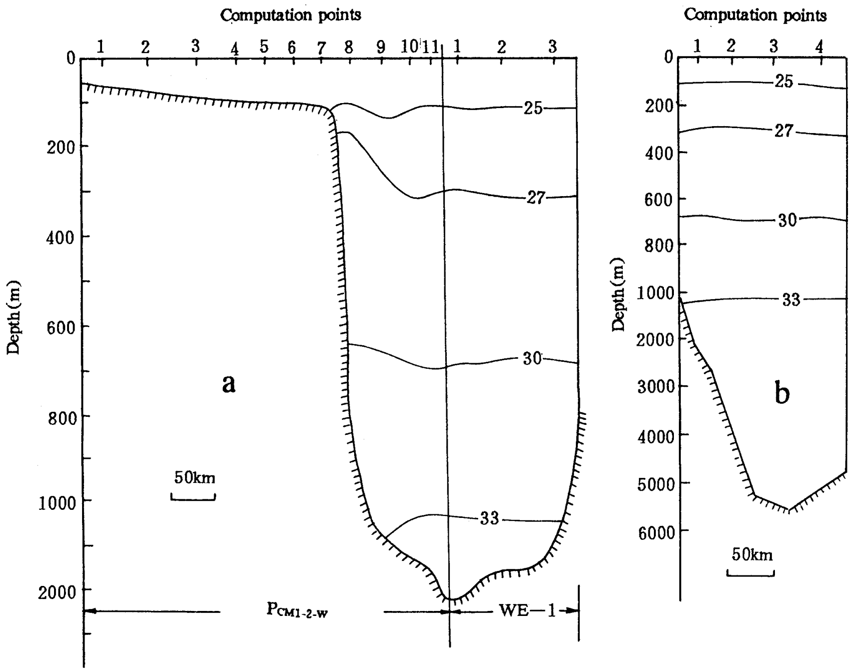

Fig. 2. Isopycnal surfaces in Sept. 1992. a: along PCM 1-2-W and WE-1; b: along PCM 1-2-E.

pycnal values of 25, 27, 30 and 33. At Sections PCM1-2-W and WE-1 in Sept. 1992, depths of $\sigma_{t,p}$ = 25, 27, 30 and 33 lie between 60m and 136m, 177m and 315m, 646m and 696m, 1231m and 1409m, respectively (Fig 2a). At PCM 1-2-E they lie between 102m and 120m, 313m and 328m, 690m and 700m, 1193m and 1206m, respectively (Fig. 2b).

The average wind speed and direction observed aboard the R/V Shijian are 2.3m/s and 335° in Sept. 1992. Because no reliable wind data are available over the whole survey region, this average wind is assumed as the wind forcing which is constant in time and space. The minimum and maximum upward surface heat fluxes are prescribed to be -1.05×10^7J/(m^2 day) and 1.26 $\times 10^7$ J / (m^2day) according to 10-year long climatological data for September (Institute of Oceanography and Geography, 1977). The computation is done in such a way that the calculated surface heat flux comes between these two bounds. The vertical eddy diffusion coefficient is $10^{-2}m^2/s$ for momentum and $10^{-3}m^2/s$ for heat and salinity. The horizontal eddy diffusion is neglected because it is very small with the diffusion coefficient of the order of $10^4m^2/s$ or less. Hydrographic and current meter data in Sept. 1992 are used. The mooring stations OA, OB and OC are located along PCM 1-2-E.

Usable data are obtained at a depth of 1980m at OB, and depths of 2000m and 4500m at OC. The low-passed current velocities averaged over 1 to 6 Sept. 1992 are listed in Table 1. Figures 3a, b, c show progressive vector diagrams for Nov. 1991 to Sept. 1992. The low-passed currents are fairly steady in Sept. 1992.

As shown in Fig. 1, Stn OC is not exactly located on any Cp but Stn OB is on Cp 1 at PCM 1-2-E, so that the average velocity at 1890m depth at OB is used as a known value for the computation. The velocity at 2000m depth of Cp 2 is interpolated from the average velocities at 1890m depth of OB and 2000m depth of OC, and used as a known value.

The depth of the reference level is determined as 2500m with a method by FIADEIRO and VERONIS (1982). It is assumed to be the water depth if the bottom is shallower than 2500m.

Table 1. Low-passed current velocities averaged over 1 to 6 Sept. 1992.

Mooring station	Location	Water depth(m)	meter depth(m)	v* (cm/s)	θ ** (°)	v′ *** (cm/s)
OB	25°48′ N, 128°03′ E	2020	1890	3.6	263	−2.8
OC	25°34′ N, 128°20′ E	4630	2000	3.1	193	−2.7
OC			4500	2.0	200	−1.9

* Speed. ** measured clockwise from the due north.
*** velocity component normal to section PCM 1-2-E. negative: southward.

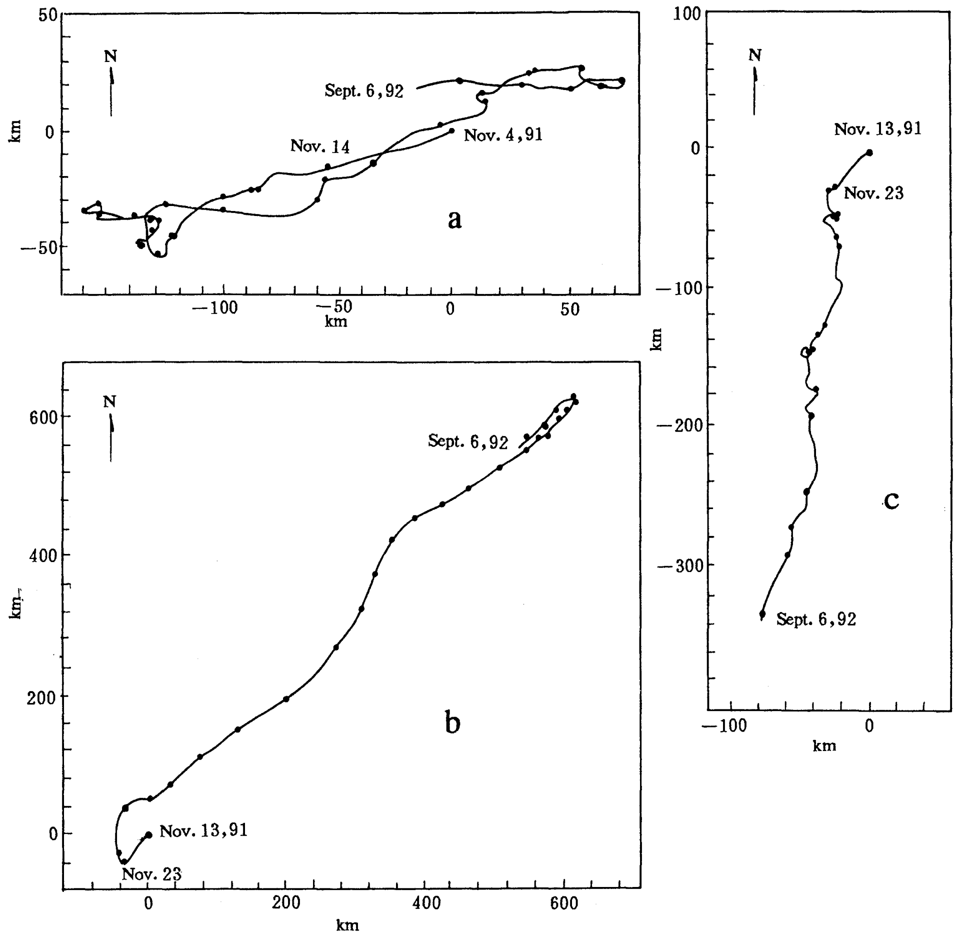

Fig. 3 Progressive vector diagrams of the observed currents. a: 1890m depth at Stn OB; b: 2000m depth at OC; c: 4500m at OC. Time interval between two dots: 10 days.

3. Result in September 1992

(1) *Velocity distribution*

(a) Sections PCM 1-2-W and WE-1

The Kuroshio flows northeastward through PCM 1-2-W. Its core is located above the continental slope (Fig. 4). The velocities are greater than 100cm/s in the upper 200m at Cp 8. The maximum velocity is 172cm/s at 50m depth. There is a weak southward countercurrent in deeper layers below the Kuroshio. There is another southward countercurrent east of the Kuroshio with maximum velocity of 31cm/s at 150m depth at Cp 11.

Section WE-1 is mostly occupied by an almost

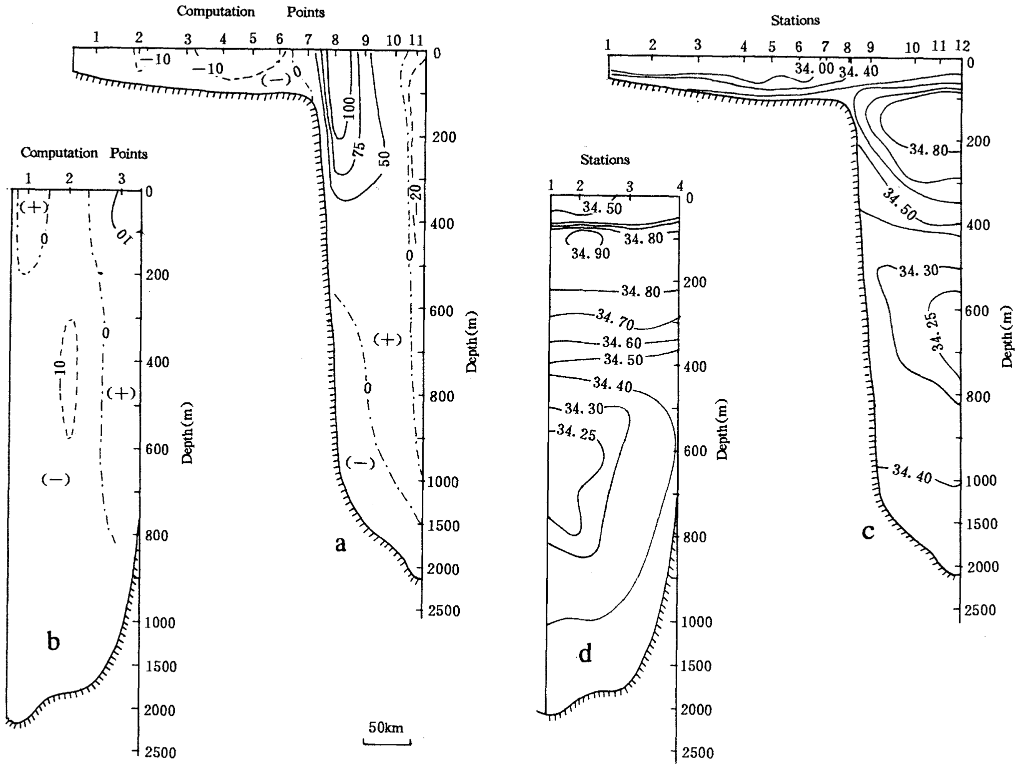

Fig. 4. Velocity (a, b, cm/s) and salinity (c, d, ‰) distribution. a: at PCM 1-2-W (positive: northward); b: at WE-1 (positive: eastward); c: at PCM 1-2-W, d: at WE-1.

westward flow coming into box 1 except in the upper 200m at the northern end (Cp 1) and the upper 800m at the southern end (Cp 3).

Figures 4c, d show the salinity distribution. In the upper 350m there is a salinity maximum tongue (S>34.60‰), which extends to the shelf break. The salinity minimum water (S<34.30 ‰) appears in the mid-layer between 500 and 800m depths as pointed out by YU *et al.*(1994). The flow below 500m depth at WE-1 is mostly westward as mentioned above. Salinity minimum water in the mid-layer flows westward through WE-1 (Figs. 4b, d).

(b) Sections PCM 1-2-E and WE-2

Figure 5b shows that the greater part of PCM 1-2-E is occupied by a northeastward current with two cores, as in Oct.-Nov. 1991 (YUAN *et al.*, 1994). One of the two cores lies between 200m and 700m depths above the maximum slope of the bottom, where the velocity is 23.0 cm/s at 400m depth and 22.6cm/s at 500m depth. The other is located above 200m depth further to the east, where the maximum velocity is 32.5cm/s at the surface. Below the northeastward flowing Ryukyu Current, there is a southwestward flow with the maximum velocity of 5.1cm/s at 2500m depth. This is compatible with the result of the current measurement at OC showing that the average velocity component normal to PCM 1-2-E is 2.7cm/s at 2000m depth and 1.9cm/s at 4500m depth, both southwestward (Table 1). At the eastern part of PCM 1-2-E there is another southward flow between 50m and 750m depths.

In short, these current features are similar to those in Oct.-Nov. 1991 (YUAN *et al.*, 1994).

Section WE-2 crosses a gap of the Ryukyu Ridge between Cp 2 and Cp 3 (Fig.5a). While northward and southward flows alternate in the upper 400m, it is occupied mostly by a northward flow in the mid-layer between 400m and 800m, especially over the Ridge.

Figures 5c, d show the salinity distribution. The salinity maximum (34.50<S<34.93 ‰)

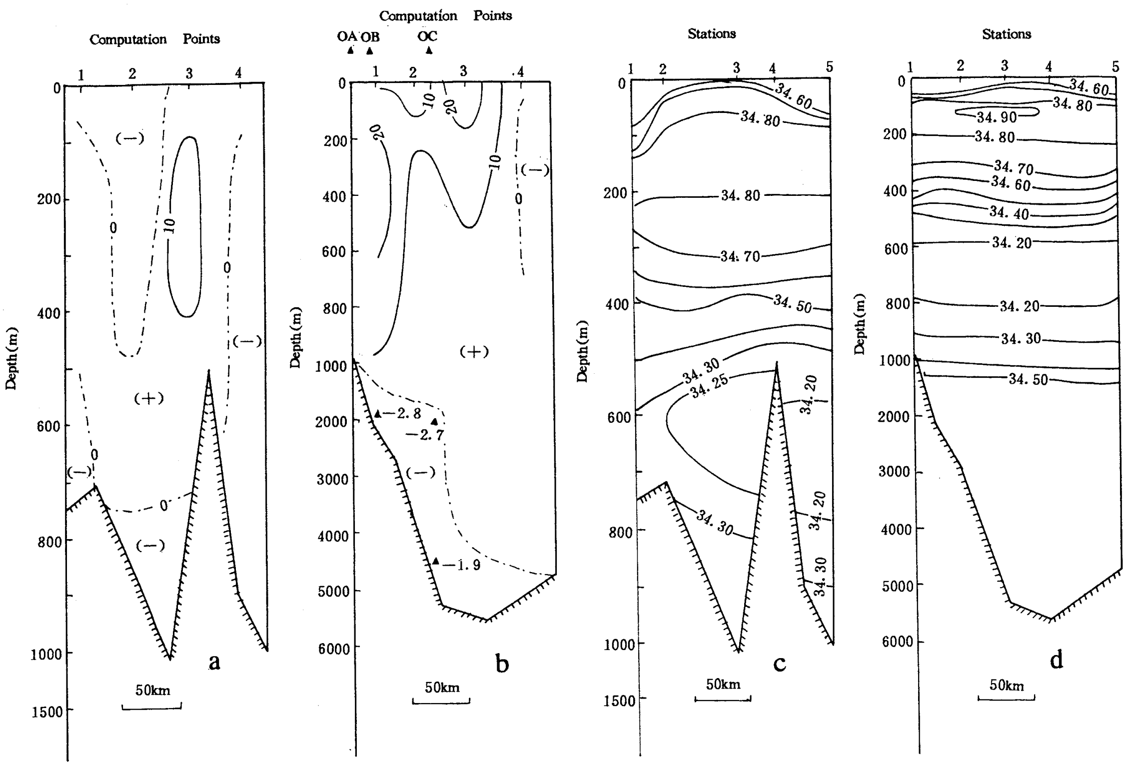

Fig. 5. Velocity (a, b, cm/s) and salinity (c, d, ‰) distribution. a: at WE-2 (positive: northwestward); b: at PCM 1-2-E (positive: northeastward); c: at WE-2; d: at PCM 1-2-E.

water lies in the upper 400m. The salinity minimum (34.14<S<34.50‰) water lying between 400m and 1000m depths extends into the gap at WE-2 with slightly higher minimum value. The salinity is higher than 34.50‰ in the deep layer below 1000m depth. These salinity features were also reported by Yu *et al.*(1993).

An important point follows from the above result: a part of the salinity minimum water in the mid-layer east of the Ryukyu Islands flows northwestward through the gap of the Ryukyu Ridge, then westward through WE-1, probably merging into the Kuroshio afterwards. With a hydrograhic data analysis Yu *et al.*(1994) also pointed out that a part of the salinity minimum water of the Kuroshio in the East China Sea is related to the intrusion of the salinity minimum water east of the Ryukyu Islands through the gap. Here we draw a similar conclusion from the velocity distribution computed with the modified inverse method.

(c) Section P_{24}

Section P_{24} is located southeast of Kyushu (Fig. 1b). Because there are no other sections nearby, the modified inverse method cannot be used. The velocity distribution across the section is obtained as the sum of the surface Ekman drift and the geostrophic current calculated with an assumed reference level 2500m deep. The wind stress is calculated with wind data collected aboard the R/V Shijian at Section P_{24}. Figure 6a shows the most part of the section is occupied by a northward flow with a core above the maximum slope of the bottom. There is a southward flow at its eastern end.

Figure 6b shows the salinity distribution. The salinity maximum (34.50<S<34.93‰) water occupies the most part of P_{24} in the upper 400m. There is the salinity minimum (34.14<S<34.50‰) water in the mid-layer between 400m and 1200m. The salinity is higher than 34.50‰ in the deep layer below 1200m depth. Comparison of Fig. 6b with Figs. 4c and 5d shows that the

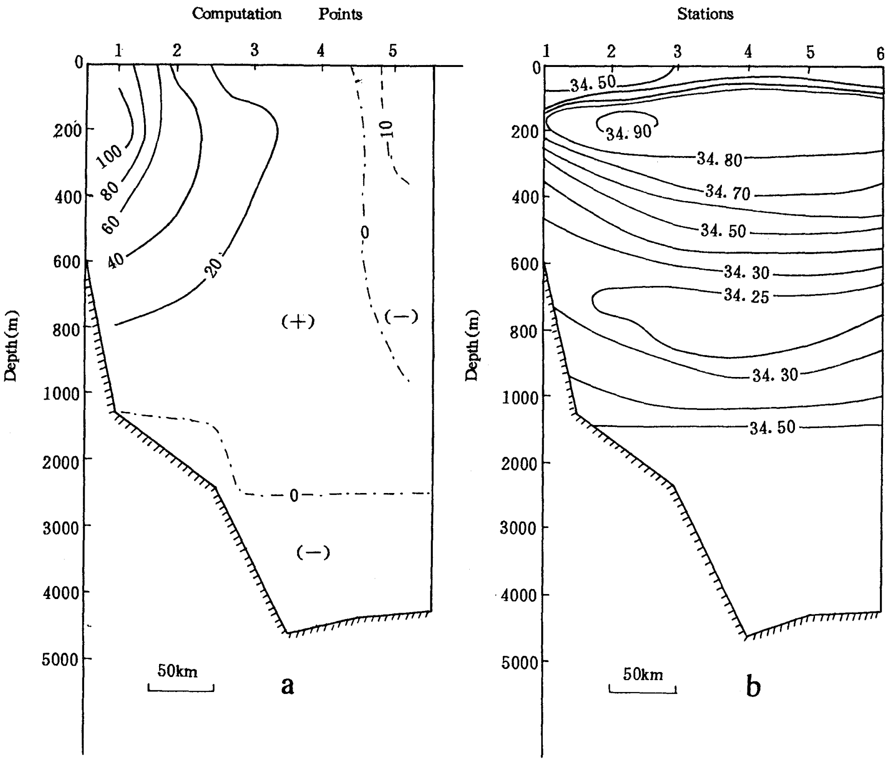

Fig. 6. Velocity (a, cm/s, positive: northeastward) and salinity (b, ‰) at P_{24}.

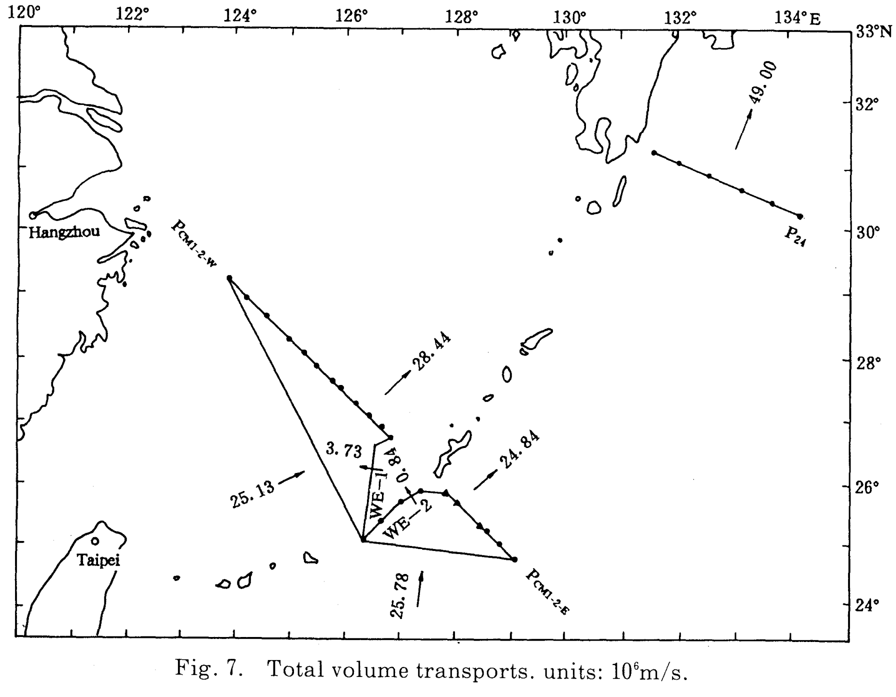

Fig. 7. Total volume transports. units: 10^6m/s.

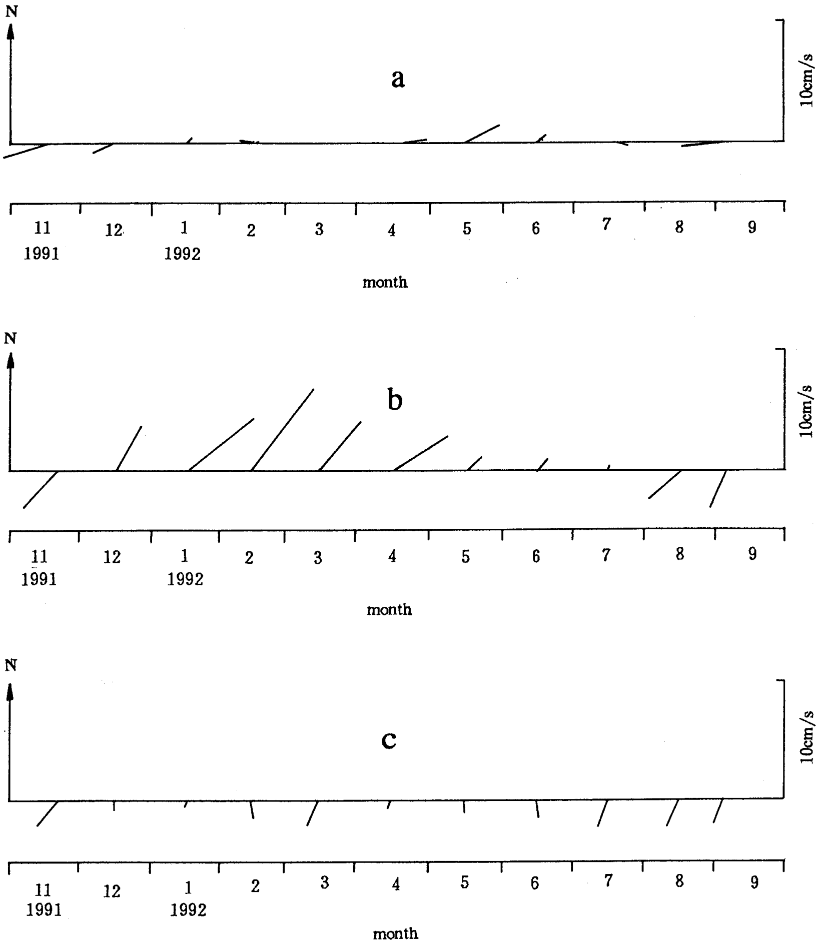

Fig. 8. Monthly averages of the low-passed current velocities. a: at 1890m depth at OB; b: at 2000m depth at OC; c: 4500m depth at OC.

salinity distribution at P_{24} is similar to that at PCM 1-2-E and PCM 1-2-W. However, the salinity minimum water area at P_{24} is much wider than that at PCM 1-2-E and 1-2-W, suggesting that the salinity minimum water in the mid-layer of P_{24} comes from both PCM 1-2-E and 1-2-W. This point will be discussed later with the volume transport.

(2) *Volume transport*

Figure 7 shows the total VT across each section. The total VT of the Kuroshio and Taiwan Warm Current across PCM 1-2-W is 32.1×10^6 m^3/s. The VT of the sothwestward countercurrents below, and east of, the Kuroshio is $3.7 \times 10^6 m^3/s$, so that the net northeastward VT across PCM 1-2-W is $28.4 \times 10^6 m^3/s$. The northeastward VT of the Ryukyu Current, 30.8×10^6 m^3/s, and the southwestward VT, $6.0 \times 10^6 m^3/s$, through PCM 1-2-E make a net northeastward VT of $24.8 \times 10^6 m^3/s$, so that the transport of the Kuroshio is almost equal to that of the western boundary current east of the Ryukyu Islands (hereafter referred to as WBCE). A numerical simulation shows the annual average VT is $22.8 \times 10^6 m^3/s$ to the west of Okinawa and about $30 \times 10^6 m^3/s$ to its east (H. ISHIZAKI, personal communication). The model ocean is driven by an annual average wind stress and seasonally varying surface temperature and salinity. Since the grid size, $1° \times 1°$, is not fine, the coefficient of eddy viscosity is large ($10^4 m^2/s$), which broadens the western boundary current

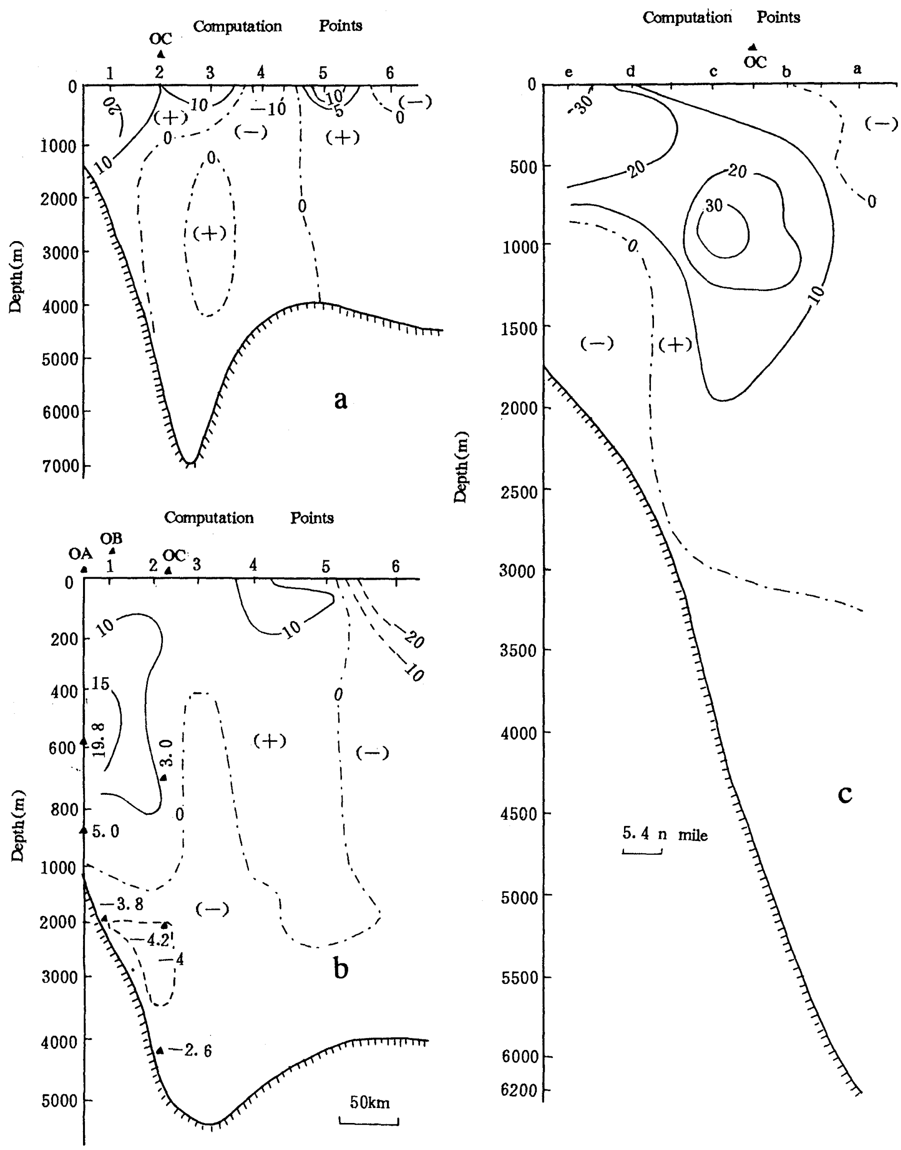

Fig. 9. Velocity distribution at PCM 1-2-E (cm/s, positive: northeastward). a: in Sept. to Oct. 1987 (YUAN *et al.*, 1991a); b: in Oct. to Nov. 1991 (YUAN *et al.*, 1994); c: in April 1988 (YUAN *et al.*, 1993c). Measured velocities are shown beside solid triangles in (b). The horizontal and vertical scales are different from each other.

and turns out that the VT west of Okinawa decreases and the VT of the WBCE increases. Therefore, the observed result appears consistent with the simulated one. The total northwestward VT through WE-2 is $2.9\times10^6 m^3/s$, of which the first layer about 100m thick transports $0.5\times10^6 m^3/s$ and the deeper layer $2.4\times10^6 m^3/s$. This indicates that a significant amount of the salinity minimum water flows from the east of the Ryukyu Islands to the East China Sea through the gap. The total northwestward VT through WE-2 is $0.8\times10^6 m^3/s$.

The total westward and eastward VT through WE-1 are $8.0\times10^6 m^3/s$ and $4.3\times10^6 m^3/s$, resulting in a net westward VT of $3.7\times10^6 m^3/s$.

The total northeastward and southwestward

Table 2. Two core depths (m) and maximum speeds (cm/s).

Cruise	depth	speed	depth	speed
Sept.-Oct. 1987	125～900	20<	0～200	10<
Oct.-Nov. 1991	390～700	15<	0～200	10<
Sept. 1992	200～700	20<	0～200	20<
Apr. 1988	550～1300	30<	0～620	30<

VT through P_{24} are $52.8\times10^6 m^3/s$ and $3.8\times10^6 m^3/s$, resulting in a net northeastward VT of $49.0\times10^6 m^3/s$.

4. Seasonal variability

Figure 8 shows the monthly average of the low-passed currents obtained with the three moored meters. At 2000m depth of OC, the flow is northeastward from Dec. 1991 to June 1992 and southwestward in Dec. 1991, Aug. and Sept. 1992, which suggests a seasonal change in the vertical extent of the WBCE.

The flow at OB is northeastward in May and June 1992 and southwestward in Nov. and Dec. 1991. The flow at 4500m depth of OC is southward for all the months. The maxima of the 10-day and monthly averages are 4.5cm/s and 2.6 cm/s, respectively, which indicated the presence of a fairly steady southward flow under the Ryukyu Current. This is also reported by CHAEN *et al.* (1993). They showed an abyssal boundary current of depths greater than 3000m in the Ryukyu Trench southeast of Okinawa. The observed velocity averaged over Nov. 1987 to April 1989 at 4170m at their Stn RT_3 (25°24′ N, 128°18′ E, water depth: 4570m) located 18.8 km apart from OC was 4.3cm/s and southwestward in agreement with our result.

Features over the whole section PCM 1-2-E common to the three fall cruises in Sept. to Oct. 1987, Oct. to Nov. 1991 and Sept. 1992 are as follows (Figs. 5b, 9a, b). (i) The greater part of the section is occupied by a northward flow with two cores. One is in the mid-layer above the maximum slope of the bottom. The maximum core velocity is about 20cm/s or greater. The other is located above 200m depth further to the east. (ii) There is a southward flow at 2000m depth around OC, which agrees with the direct current measurement.

The spring cruise in April 1988 gives following results (Fig. 9c). (i) The Ryukyu Current has also two cores, of which the locations are variable with time. One is located in the layer from the surface to 620m depth above the maximum slope of the bottom. The maximum velocity is at the surface layer, and an isotach of 20cm/s reaches from the surface to 600m depth, while in fall the maximum velocity is at the mid-layer. The other core is located in the layer from 550m to 1300m furtehr to the east. The core depths and maximum speeds are summarized in Table 2. The cores are deeper and speeds are faster in spring than in fall. (ii) There is a northward flow at 200m depth around OC. The velocities at two Cp nearest to OC (c and d in Fig. 9c) is 9.2cm/s and 3.0cm/s, giving an average of about 6cm/s, which agrees with the monthly average, 5.5cm/s, of the observed velocities at 2000m depth of OC in April 1992.

5. Summary

The modified inverse method is applied to hydrographic data in Sept. 1992 together with moored current meter records from Nov. 1991 to Sept. 1992 for computing the western boundary current east of the Ryukyu Islands and the Kuroshio in the East China Sea.

Following results are obtained.

(1) The WBCE has two cores. One is above the maximum slope of the ocean bottom, and the other is located further to the east.

(2) There is a seasonal change in the vertical extent of the WBCE. It is deeper in winter and spring than in fall.

(3) Under the Ryukyu Current there is a southward abyssal boundary current which is fairly steady for all the months.

(4) The VTs of the Ryukyu Current and deep southward countercurrent through PCM 1-2-E are $30.8\times10^6 m^3/s$ and $6.0\times10^6 m^3/s$, resulting in a net northeastward VT of $24.8\times10^6 m^3/s$.

The total VT of the Kuroshio and Taiwan

Warm Current through PCM 1-2-W is $32.1\times10^6 m^3/s$, and the VT of the southwestward undercurrent is $3.7\times10^6 m^3/s$, so that the net northeastward VT is $28.4\times10^6 m^3/s$.

The northeastward VT through P_{24} is $52.8\times10^6 m^3/s$, and the southwestward VT is $3.8\times10^6 m^3/s$, so that the net northeastward VT is $49.0\times10^6 m^3/s$.

(5) The salinity minimum water in the mid-layer flows northwestward through a gap of the Ryukyu ridge from the east of the Ryukyu Islands to the East China Sea. Its northwestward VT at WE-2 is $2.4\times10^6 m^3/s$. The westward and eastward VT through WE-1 are $8.0\times10^6 m^3/s$ and $4.3\times10^6 m^3/s$, making a net westward VT of $3.7\times10^6 m^3/s$.

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琉球諸島東側の西岸境界流

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要旨：1992年9月の海洋観測データと1991年11月から1992年9月までの流速データに改訂インバース法を使い，琉球諸島東側の西岸境界流と西側の黒潮を計算した。琉球諸島東側の境界流には2つのコアがあり，その深さは季節によって変わる。その下には南西に向かう深層境界流がつねに存在する。沖縄の南東では，北東向きの流量は$30.8\times10^6 m^3/s$であり，南西向きの流量は$6.0\times10^6 m^3/s$なので，正味の北東向き流量は$24.8\times10^6 m^3/s$となる。沖縄の北西では，黒潮と台湾海流の流量の和は$32.1\times10^6 m^3/s$であり，南西向きの反流の流量は$3.7\times10^6 m^3/s$なので，正味の北東向き流量は$28.4\times10^6 m^3/s$となり，南東側の流量よりもすこし大きい。中層を塩分極小水が琉球諸島の東側から琉球海嶺の割れ目を通って北西に流れる。その流量は沖縄の西側で$2.4\times10^6 m^3/s$である。