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The Kuroshio East of Taiwan and in the East China Sea and the Currents East of Ryukyu Islands during Early Summer of 1996

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Using hydrographic data and moored current meter records and the ADCP observed current data during May–June 1996, a modified inverse method is applied to calculate the Kuroshio east of Taiwan and in the East China Sea and the currents east of Ryukyu Islands. There are three branches of the Kuroshio east of Taiwan. The Kuroshio in the East China Sea comes from the main (first) and second branches of the Kuroshio east of Taiwan. The easternmost (third) branch of the Kuroshio flows northeastward to the region east of Ryukyu Islands. The net northward volume transports of the Kuroshio through Section K_2 southeast of Taiwan and Section PN in the East China Sea are 44.4×10^6 and 27.2×10^6 m^3s^{-1}, respectively. The western boundary current east of Ryukyu Islands comes from the easternmost branch of the Kuroshio east of Taiwan and an anticyclonic recirculating gyre more east, making volume transports of 10 to 15×10^6 m^3s^{-1}. At about 21°N, 127°E southeast of Taiwan, there is a cold eddy which causes branching of the Kuroshio there.

Keywords:
· Kuroshio east of Taiwan,
· three branches,
· Ryukyu Current,
· recirculating gyre,
· modified inverse method,
· velocity measurement.

1. Introduction

The region east of Taiwan is very important for understanding the Kuroshio, the Kuroshio Countercurrent and other subgyres in Western North Pacific because all western ends of the subgyres merge together there, as pointed out by Hasunuma and Yoshida (1978). There have been some studies on the Kuroshio east of Taiwan (Chu, 1974; Guan, 1978, 1985; Liu *et al*., 1986; Yuan ia, 1988; Yuan *et al*., 1996, 1998) and the currents east of Ryukyu Islands (Nitani, 1972; Yuan *et al*., 1990, 1991, 1994, 1995). There are some important current characteristics of the Kuroshio east of Taiwan. For example, (1) Chu (1974) pointed out fluctuations of the Kuroshio Current axis and pattern, and changes of its maximum velocity east of Taiwan on the basis of CSK data obtained during several cruises; (2) part of the Kuroshio made a cyclonic meander on the eastern side of a cold eddy northeast of Lanyu Island during the winter season (Guan, 1985; Yuan and Xia, 1988); (3) Guan (1978) reported the anticyclonic deflection of the Kuroshio across a submarine ridge adjacent to the northern coast of Taiwan; (4) based on a dynamic calculation, Liu *et al*. (1986) pointed out that there is evidence of the band structure southeast of Taiwan; (5) Yuan *et al*. (1996, 1998) showed that there are multi-core structures of the Kuroshio current and several branches of the Kuroshio east of Taiwan. Furthermore, Yuan *et al*. (1998) pointed out that there is an easternmost branch of the Kuroshio east of Taiwan, flowing northeastward to the east of Ryukyu Islands and becoming part of the western boundary current east of Ryukyu Islands during October 1995. However, no branch of the Kuroshio flowed into the region east of Ryukyu Islands during early summer of 1985 (Yuan *et al*., 1996). Yuan *et al*. (1996, 1998) further pointed out that the above Kuroshio current patterns are closely related to the strengths and positions of cyclonic and anticyclonic gyres in the adjacent region.

In this paper, using hydrographic data, moored current meter records and towed-ADCP current data obtained during the early summer of 1996, a modified inverse method is applied to calculate the Kuroshio east of Taiwan and in the East China Sea and the currents east of Ryukyu Islands (Ryukyu Current). The current features of the Kuroshio east of Taiwan and in the East China Sea and the problem of the origin of the western boundary current east of Ryukyu Islands are also discussed. Furthermore, we make a comparison between results obtained during the present and the previous cruises.

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2. Data and Numerical Calculation

The modified inverse method described in Yuan *et al.* (1992) is applied to calculate the current structure and volume transport and the stream function in the computational region (Fig. 1). A brief explanation of this method is presented in the Appendix. The hydrographic data were obtained from two cruises, viz., a cruise of China-Japan Cooperative Research on subtropical gyre during May 10 to June 4, 1996 (hereafter called cruise 1) and a cruise during April 23–May 21, 1996 by the R.V. *Chofu-Maru* (hereafter called cruise 2). There are five boxes in the area east of Taiwan and east of the Ryukyu Islands (hereafter called area 1). There is one box in the East China Sea (hereafter called area 2). The computational points are taken at the mid-points between neighboring hydrographic stations. All boundary sections of the computation boxes are divided into layers according to isopycnal $\sigma_{t,p}$ values of 25, 27, 30 and 33. These isopycnal values correspond to the depths of about 150, 300, 650 and 1200 m. According to the study of Yuan *et al.* (1992), the density convection-diffusion equation is considered for all layers, and the salt convection-diffusion equation for all layers except for the surface layer. One or two boundary sections surrounding individual boxes have no CTD points except edges of the section. We can get only a rough estimation of the volume transport across these boundary sections. It should be noted that most of them are devised to extend in parallel with mean currents.

This calculation uses CTD data at all sections, which form boxes 1, 2, 3, 4 and 5, and the following parameter values are selected. The wind data during the May–June cruise of 1996 were obtained in the area 1 from the observations by R.V. *Xiangyuanhong 14*. The average wind direction and speed were 145° and 7.1 m s^{-1} during this cruise. Because of the lack of accurate wind data, a steady, uniform wind field with above-average values is assumed. According to the study of Yuan *et al.* (1992), the vertical eddy viscosity A_z and the vertical eddy diffusivity K_v are taken to be 100 cm^{2}s^{-1} and 10 cm^{2}s^{-1}. For different values of A_z (50

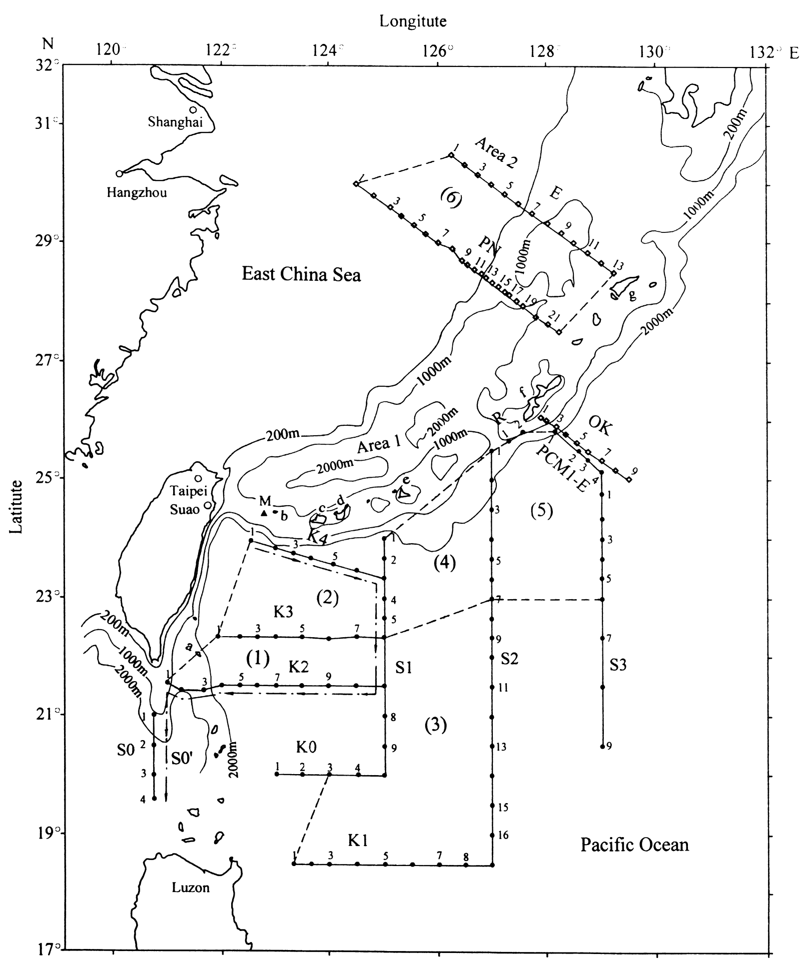

Fig. 1. Location map of hydrographic stations and sections, computation boxes, mooring station M, and ADCP track (—·→). Solid lines are used for the sections with CTD points and dashed lines for those without CTD points. (●: cruise 1, □: cruise 2; a: Lanyu I, b: Yonakuni I, c: Iriomote I, d: Ishigaki I, e: Miyako I, f: Okinawa I, g: Amami-oshima I).

and 100 cm^{2}s^{-1}) and K_v (1 and 10 cm^{2}s^{-1}) calculated velocities and volume transports both change less because the effect of A_z and K_v is mainly confined to the surface and bottom Ekman layers.

For the choice of an optimum reference level, we use the Fiadeiro and Veronis's method (1982). According to their method, an optimum reference level is taken to be the 2000 m level in the area where floor depths are greater than 2000 m, and to be the floor depth where floor depths are less than 2000 m, as in area 1. In area 2, an optimum reference level is taken to be the 800 m level for floor depths greater than 800 m, and to be the floor depth for floor depths less than 800 m.

Direct current measurements by the towed-type ADCP (Kaneko and Koterayama, 1988) were carried out on the observation lines marked in Fig. 1 to compare with results of the inverse and dynamic calculations. The ship speed was about 9 knots (4.5 m s^{-1}). Depth bin and sampling interval were set to 8 m and one minute, respectively. The range of ADCP measurement was accidentally reduced from 300 m to 60 m, due to electric noise introduced by the ship's engine. In addition, velocity measurements often became less accurate because the ship's course deviated appreciably from a straight line. For these reasons, we present only the ADCP data for Section K_4 obtained under the best ship operating conditions.

3. Major Features of the Kuroshio and Currents East of Ryukyu Islands

In this section we present the horizontal distribution of temperature in the whole region of area 1 and the velocity distributions at Sections K_2, K_3, K_4, S_1, PCM1-E, OK, PN and E (see Fig. 1). Major features of the Kuroshio east of Taiwan and in the East China Sea and eddies east of Taiwan are discussed and compared with the results of the measurement and calculation.

3.1 Horizontal distribution of temperature

The horizontal distribution of temperature at 600 m depth is shown with the contour plot in Fig. 2. Masses of warm water exist to the east of Ryukyu Islands and around the region centered in (20°N, 124°E). On the other hand, cold water masses are seen to the east of Taiwan and around (21°N, 127°E). A branch of the Kuroshio Current east of Taiwan is well traced with the isotherms of 7.5 and 8.0°C extending southward from Ishigaki Island.

3.2 Section K_2

Section K_2 is located southeast of Taiwan (Fig. 1). Figure 3 shows the velocity distribution at Section K_2. There are three current cores of the Kuroshio. The first core is near the southern tip of Taiwan, and its maximum velocity is about 196 cm s^{-1} at the surface of computational point 1. At

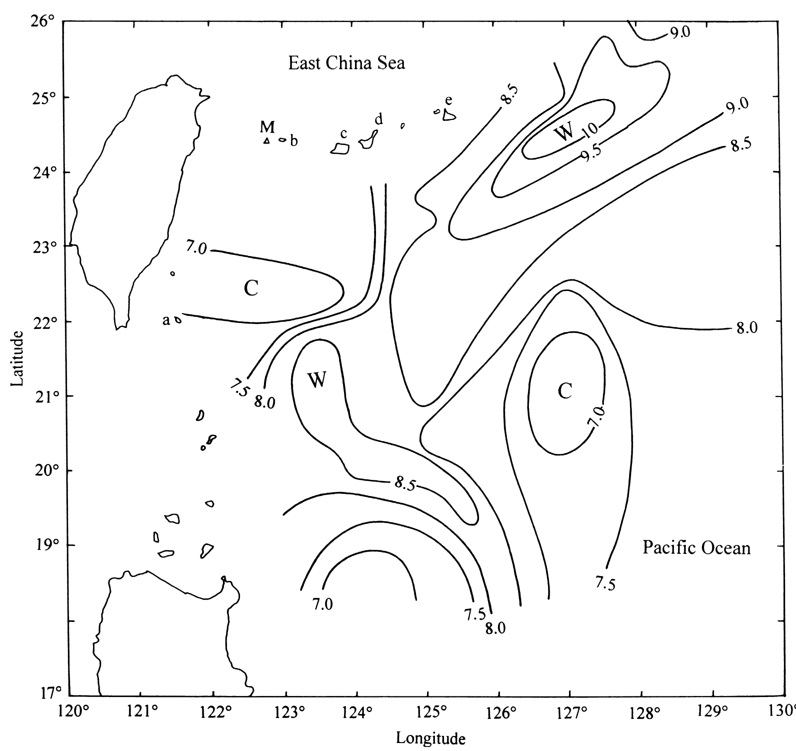

Fig. 2. Horizontal temperature distribution at the 600 m level during May–June of 1996 (unit: °C).

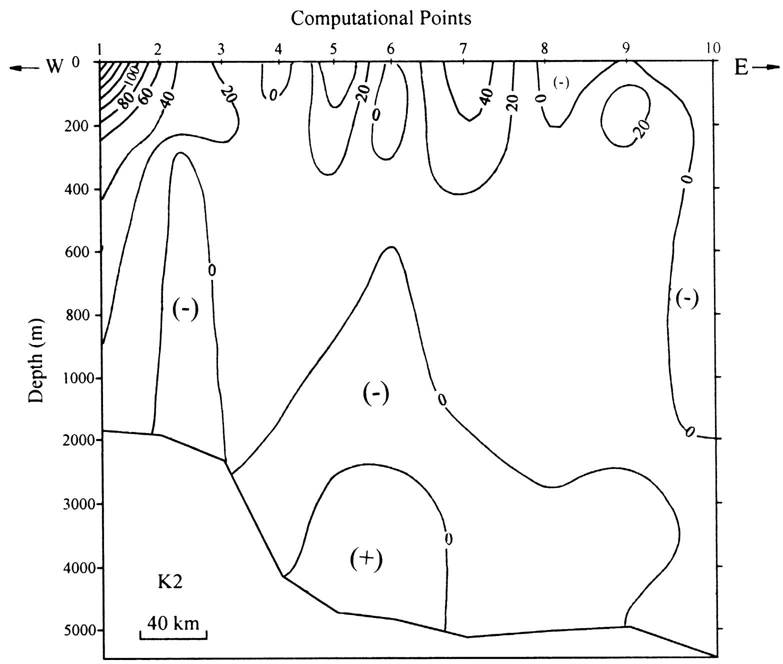

Fig. 3. Velocity distribution at Section K_2 during May–June of 1996 (positive: northward, unit: cm s^{-1}).

computational point 1 the velocity is greater than 100 cm s^{-1} in the upper 150 m. The second core is near computational point 5, and its maximum velocity is about 61 cm s^{-1} at the surface. The third core is near computational point 7 where the isotherms of 7.5 and 8.0°C are located. The maximum velocity of this core is about 58 cm s^{-1} at the surface. There is a weak northward flow at computational point 9, and its core is located at a subsurface layer. There are southward flows in the upper 350 m of computational point 6, in the upper 250 m of computational point 8, the upper 2000 m of computational point 10, and below the Kuroshio.

3.3 Section K_3

Section K_3 is located just north of Section K_2 (Fig. 1). The main branch of the Kuroshio is likely to flow northward through an area west of Section K_3, but other branches of the Kuroshio flow northward through Section K_3 (Figs. 4 and 12, below). Their maximum velocity is about 92 cm s^{-1} at the surface of computational point 6 and placed on the isotherms of 7.5 and 8.0°C (see Fig. 2). At computational points 1 to 4, weak southward and northward flows alternate above a 400 m level. These may both be part of eddies. The horizontal temperature distribution shows that cold water appears below a 500 m level between computational points 1 and 5 (not shown here). Its cold water center is located at the hydrographic station $K_{3,2}$ (22°20′ N, 122°20′ E) at the 600 m level (Fig. 2). The above results provide evidence that other branches of the Kuroshio make a cyclonic rotation east of the cold eddy when they pass through Section K_3. This phenomenon (i.e., the cold eddy and the cyclonic rotation of Kuroshio stream path northeast of Lanyu Island) also appeared during the winter season (Guan, 1985; Yuan and Xia, 1988).

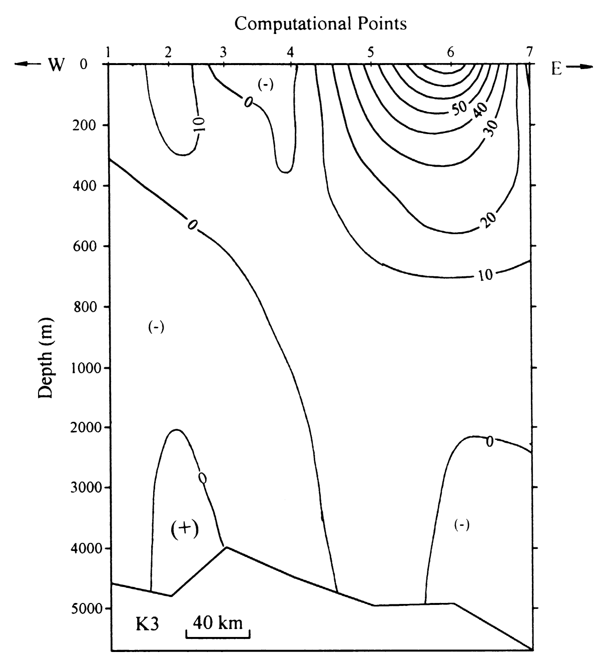

Fig. 4. Velocity distribution at Section K_3 in May 1996 (positive: northward, unit: cm s^{-1}).

Finally, as for northward flows at computational points 6 and 7, both construct part of an anticyclonic recirculating gyre east of Ryukyu Islands (see Figs. 4 and 12, below). Flows passing through an area near computational point 6 are occupied by a branch of the Kuroshio, as mentioned above. Thus the northward flow around computational point 6 is strengthened through a combined effect of the Kuroshio and the recirculation gyre east of it.

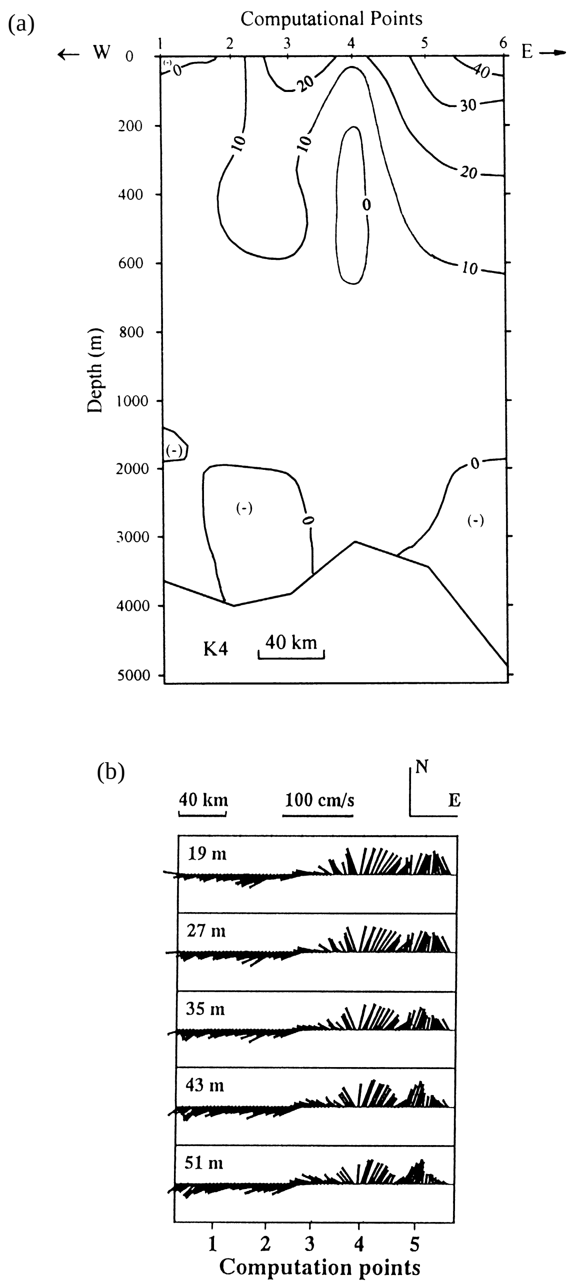

Fig. 5. (a) Velocity distribution at Section K_4 in May 1996 (positive: northward, unit: cm s^{-1}), (b) ADCP observed current vectors at Section K_4 in May 1996.

3.4 *Section K_4 and the mooring station M*

Section K_4 is located east of Suao. As in Section K_3, the main branch of the Kuroshio is likely to flow northward through an area west of Section K_4 (see Fig. 12, below). As mentioned above, other branches of the Kuroshio make a cyclonic rotation east of the cold eddy at Section K_3, and then most of them flow northward through Section K_4 (Figs. 5(a) and 12, below). The Kuroshio across Section K_4 forms two cores at computational points 3 and 6. The velocities at the surface of computational points 3 and 6 are 30 and 48 cm s^{-1}, respectively. Part of the northward flow near computational point 6 is supplied by the anticyclonic recirculating gyre.

We make a comparison between the above calculated current and the ADCP observed surface current at Section K_4 (Figs. 5(a) and (b)). Figures 5(a) and (b) both show that there is a branch of the Kuroshio at the eastern part of Section K_4. The position of this branch is put on the 7.5 and 8.0°C isotherms of Fig. 2. A weak northward flowing core around computational point 3 is also found in the ADCP data.

On the other hand, there are no other branches of the Kuroshio at the western part of Section K_4. The current measurements with moored current meters were carried out at the mooring station M (24°26.18′N, 122°27.27′E, the floor depth is 870 m) southwest of Yonakuni Island (Fig. 1) during May 18–June 1, 1996 (Yuan *et al.*, in preparation). Figure 6 shows the progressive vector diagrams of the observed daily currents. The low-pass filtered currents at 290 m and 594 m depths are both quite steady during the

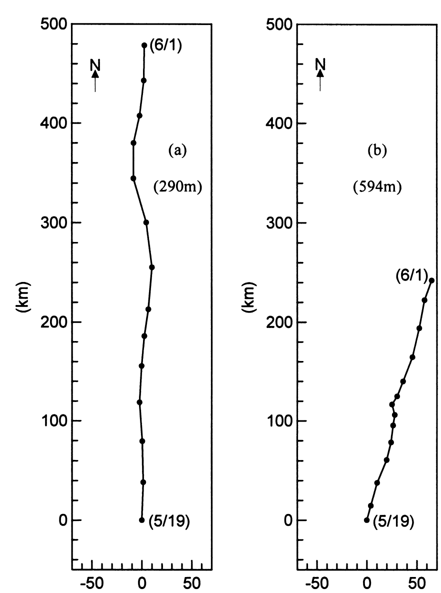

Fig. 6. Progressive vector diagrams of the observed daily currents.(a) 290 m depth; (b) 594 m depth at the mooring station M.

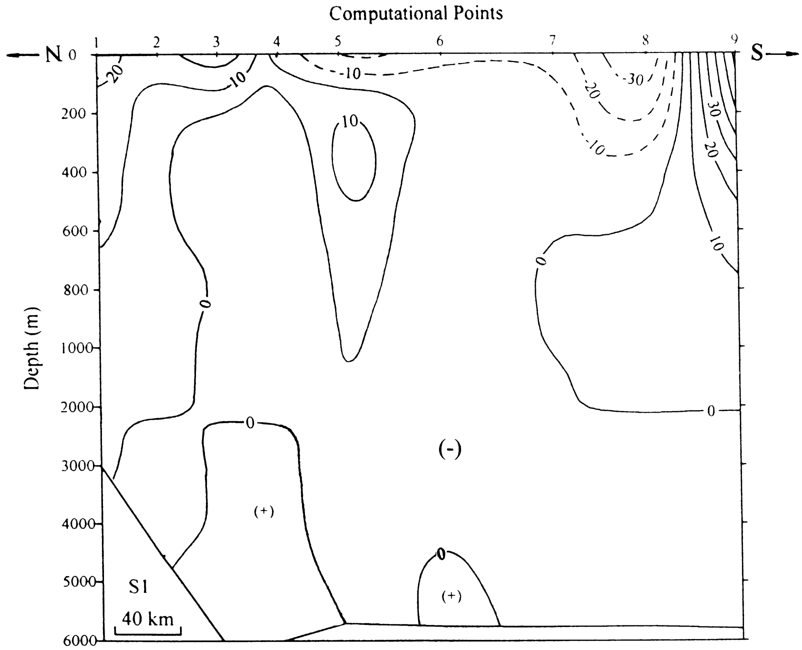

Fig. 7. Velocity distribution at Section S_1 (positive: eastward, unit: cm s^{-1}).

whole period of observation. The average velocities (V, θ) at 290 m and 594 m depths of the station M are, respectively, (42.6 cm s^{-1}, 0.5°) and (22.0 cm s^{-1}, 14.9°) during May 18 to June 1, 1996 (θ is the direction measured clockwise from due north). This result reveals that the Kuroshio surely exists at station M and is not so weak, even at deeper depths.

According to the above results, our speculation is that the main branch of the Kuroshio flows northward through an area west of Section K_4, it rides on a submarine ridge east of Taipei and Suao, it is deflected anticyclonically, as understood from the potential vorticity conservation (e.g., Guan, 1978), and then part of it reaches the mooring station M. It appears that the bathymetric chart around Taipei and Suao also serves to support this speculation (see Fig. 1).

3.5 Section S_1

Section S_1 is located at 125°E (Fig. 1). Figure 7 shows the velocity distribution in Section S_1. In the 500 m layer of Section S_1, eastward flows are dominant at computational points 1–6 and around computational point 9. The former eastward flow is part of an anticyclonic recirculating gyre developing on the southern side of Ryukyu Islands (see Fig. 12, below).

3.6 Sections PCM1-E and OK

Section PCM1-E is located southeast of Okinawa Island. Figure 8 shows that there is a northeastward current between computational points 1 and 2, and its current core is located at the 200 m level with a maximum velocity of 25

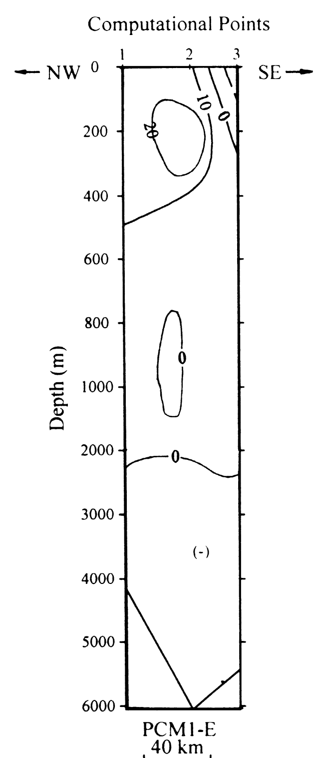

Fig. 8. Velocity distribution at Section PCM1-E (positive: northeastward, unit: cm s^{-1}).

cm s^{-1}. There is a southwestward flow around the computational point 3.

Because the CTD observation at Section OK was made 29 days before the CTD observation at Section PCM1-E, Section OK cannot form a box, so the velocity distribution at Section OK has been calculated by the dynamic method with a reference level of 2000 m. Figure 9 shows the velocity distribution at Section OK. This figure shows that part of the section is occupied by three northeastward flowing areas with cores of different maximum velocity. The first core is between 500 and 700 m levels over the area of maximum slope of the bottom and its maximum speed is 49 cm s^{-1} at the 600 m level. Other cores are at computational points 4 and 8. The above current features southeast of Okinawa Island are similar to those found in previous studies (Yuan *et al.*, 1990, 1991, 1994, 1995).

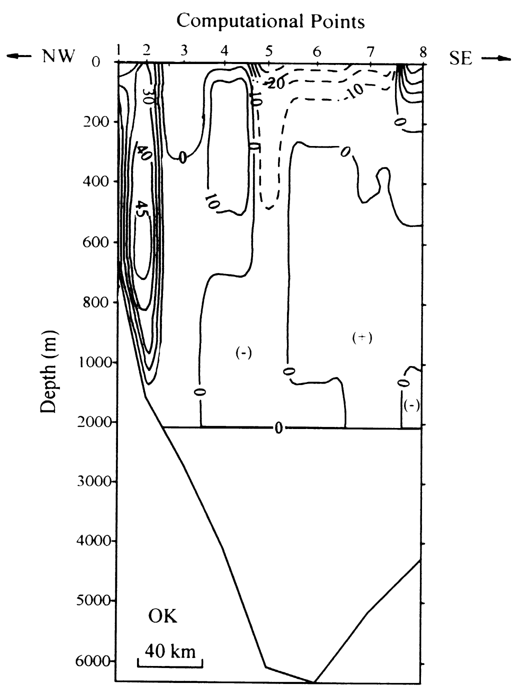

Fig. 9. Velocity distribution at Section OK (positive: northward, unit: cm s^{-1}).

3.7 Sections PN and E in the East China Sea

Section PN is a familiar section in the East China Sea and Section E lies north of Section PN (Fig. 1). Figures 10 and 11 show the velocity distributions at Sections PN and E, respectively. There are a few velocity cores at Section PN. The main Kuroshio current core is located at computational point 14 at the shelf break, and its maximum velocity is about 108 cm s^{-1} at the surface (Fig. 10). At Section E, there is a velocity core, located at computational point 8, and its maximum velocity is about 103 cm s^{-1} at the surface (Fig. 11). There are weak southwestward currents below the Kuroshio across Sections PN and E.

4. Stream Function and Volume Transport

Figure 12 shows the distribution of stream function and total volume transport. The Kuroshio is located west of 123°40′ E at Section K_2, which is almost the same position

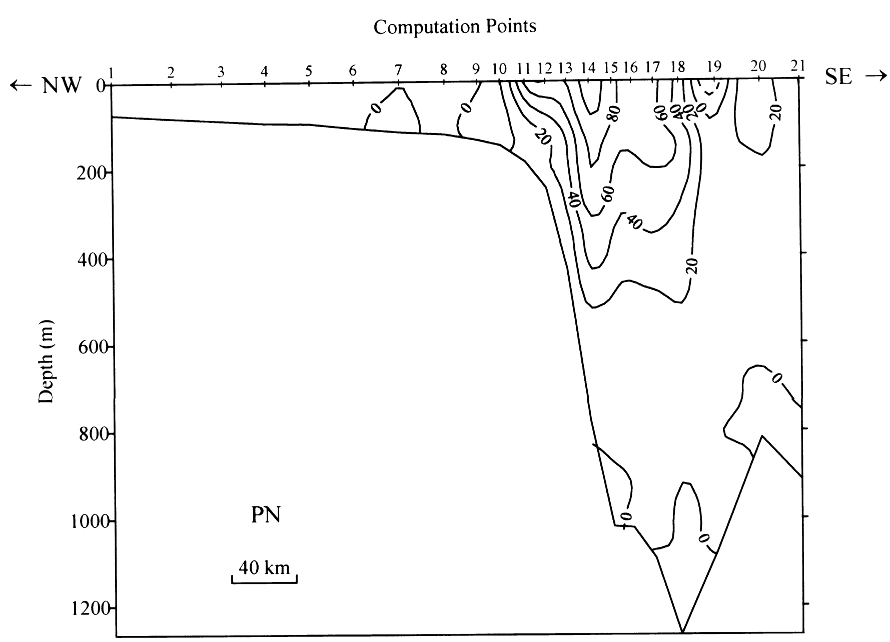

Fig. 10. Velocity distribution at Section PN during April–May of 1996 (positive: northward, unit: cm s^{-1}).

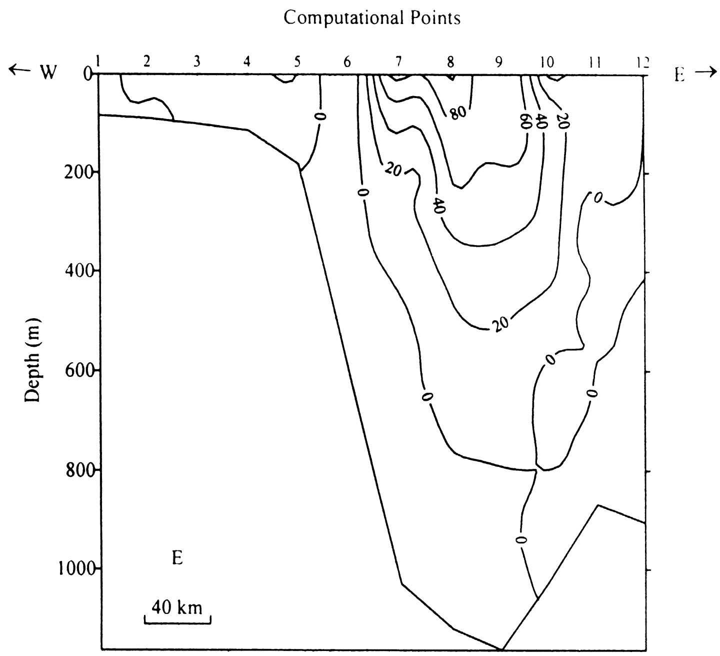

Fig. 11. Velocity distribution at Section E during April–May of 1996 (positive: northward, unit: cm s^{-1}).

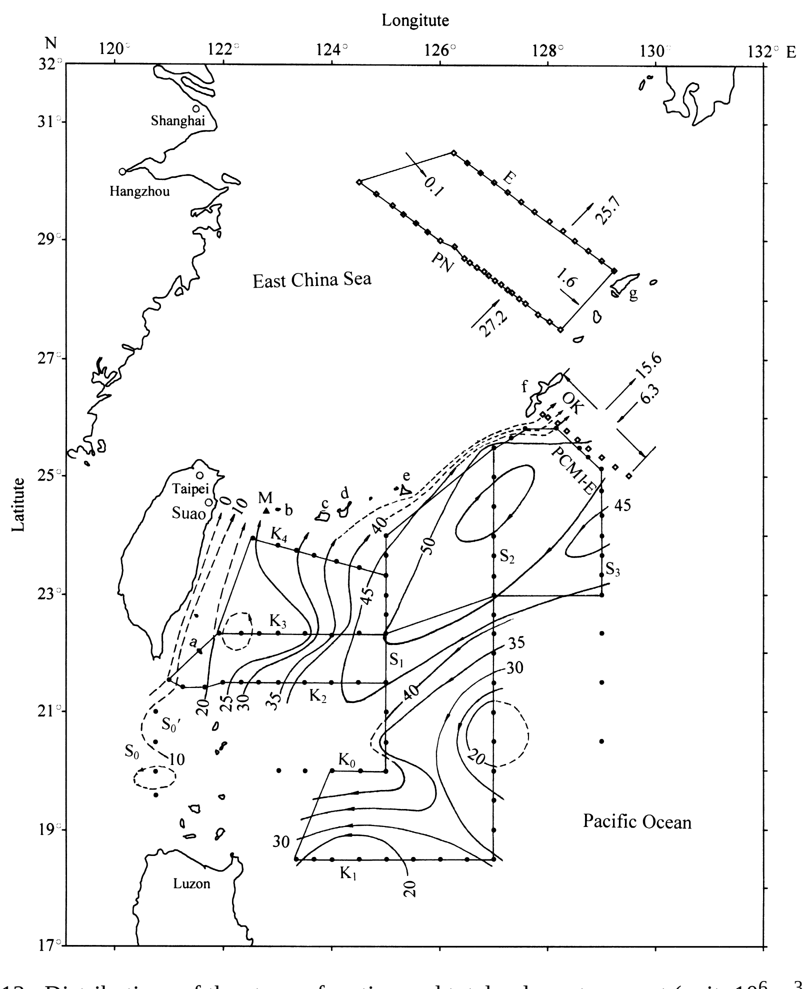

Fig. 12. Distributions of the stream function and total volume transport (unit: 10^6 m^3s^{-1}).

as the Kuroshio during October of 1995 (Yuan *et al*., 1998). The net northward volume transport (VT) of the Kuroshio through Section K_2 is about 44.4×10^6 m^3s^{-1} during early summer of 1996, which is almost the same as the Kuroshio transport at Section K_2, 45.0×10^6 m^3s^{-1}, during early summer of 1985 (Yuan *et al*., 1996). When flowing through Section K_2, the Kuroshio branches into three parts, suggesting that the main branch of the Kuroshio flows northward through an area west of Section K_4, then it rides on a ridge east of Taipei and Suao, it makes an anticyclonic deflection of stream path, and finally it enters the East China Sea through a channel west of Yonakuni Island. As for the second and third branches, we have the following suggestion. The second branch of the Kuroshio makes a cyclonic rotation due to a cold eddy northeast of Lanyu Island, which is very similar to the current pattern obtained by the R.V. *Komahashi* during Feburuaby–March of 1940 (Guan, 1985; Yuan and Xia, 1988), then flows through Section K_4, and finally enters the East China Sea through a channel between Yonakuni and Iriomote Islands. The easternmost (third) branch of the Kuroshio flows through Sections K_3 and K_4, then flows continuously northeastward to a region east of Ryukyu Islands and becomes part of the western boundary current east of Ryukyu Islands. Another origin of the western boundary current east of Ryukyu Islands comes from the anticyclonic recirculating gyre (see Figs. 2 and 12).

To the south of this gyre there is a cold, cyclonic eddy centered around 21°N, 127°E. In comparison with the current patterns during early summer of 1985 (Yuan *et al*., 1996) and during October 1995 (Yuan *et al*., 1998), there are the following three different points: (1) A cold, cyclonic eddy lies at different positions for these three cruises, although it has not been identified as the same one. It lay near Section PCM1-E during early summer of 1985. It moved westward and lay south of Iriomote and Ishigaki Islands during October 1995. However, it moved southward and its center was located at about 21°N, 127°E during early summer of 1996; (2) An anticyclonic recirculating gyre lies at different positions for these three cruises, although it has not been identified as the same one. It was located east of the above cold, cyclonic eddy during early summer of 1985, and it moved southwestward during October 1995. It further extended westward and reached the eastern parts of Sections K_2, K_3 and K_4 during early summer of 1996; (3) There was no branch of the Kuroshio to flow into the region east of Ryukyu Islands during early summer of 1985. This feature differs from the patterns of circulation during October 1995 and early summer of 1996.

Section PCM1-E is a short section of the May–June of 1996 cruise. The northeastward and southwestward volume transports at Section PCM1-E are about 10.0×10^6 and 2.6×10^6 m^3s^{-1}, respectively. The northeastward and southwestward volume transports through Section OK are about 15.6×10^6 m^3s^{-1} and 6.3×10^6 m^3s^{-1} (a reference level of 2000 m), respectively. Section PCM1-E also constructs part of the fifth computational box (see Fig. 1). The volume transport line of 45×10^6 m^3s^{-1} passes the computational point 1 of section PCM1-E, located in almost the same place as the computational point 3 of section OK. There is a northeastward volume transport of about 10×10^6 m^3s^{-1} between computational points 1 and 3 of Section OK. This means that the northeastward volume transport of 5–10 $\times$ 10^6 m^3s^{-1} east of Ryukyu Islands comes from the third branch of Kuroshio east of Taiwan. The remaining northeastward volume transport across Section OK is from the anticyclonic recirculation gyre south of Ryukyu Islands.

The northward VT of the Kuroshio through Section PN in the East China Sea is about 27.2×10^6 m^3s^{-1} during early summer of 1996. The VT is in good agreement with the results of direct velocity observation obtained by the towed ADCPs at Section F about 100 km southwest of Section PN (Kaneko *et al*., 1990, 1993).

5. Summary

The modified inverse method has been applied to hydrographic data gathered in early summer of 1996 for calculating the Kuroshio east of Taiwan and in the East China Sea and the currents east of Ryukyu Islands. In combination with the moored current meter records and the towed ADCP current data during May–June 1996, the following results have been obtained, including the reasonable speculations in (5) and (6).

(1) The net northward VT of the Kuroshio at Section K_2 southeast of Taiwan is about 44.4×10^6 m^3s^{-1} during early summer of 1996, which is almost the same VT as the Kuroshio at Section K_2, 45.0×10^6 m^3s^{-1}, during early summer of 1985 (Yuan *et al*., 1996), but is less than the VT at Section K_2 during October 1995 (Yuan *et al*., 1998).

(2) The northeastward VTs at Sections PCM1-E and OK southeast of Okinawa Island are about 10.0×10^6 and 15.6×10^6 m^3s^{-1}, respectively.

(3) The northward VT of the Kuroshio through Section PN is about 27.0×10^6 m^3s^{-1}.

(4) There is an anticyclonic recirculating gyres east of Ryukyu Islands and a cold eddy centered at about 21°N, 127°E.

(5) There are three branches of the Kuroshio east of Taiwan. The main branch of the Kuroshio rides on the ridge east of Taipei and Suao, forms an anticyclonic deflection, and then enters the East China Sea through the channel west of Yonakuni Island. The second branch of the Kuroshio makes a cyclonic rotation east of the cold eddy northeast of Lanyu Island, and then enters the East China Sea through the channel between Yonakuni and Iriomote Islands. This means that the Kuroshio in the East China Sea comes from the above two branches of the Kuroshio east of Taiwan. The easternmost (third) branch of the Kuroshio flows northeastward to the region east of Ryukyu Islands.

(6) The western boundary current east of Ryukyu Islands comes from the easternmost branch of the Kuroshio east of Taiwan and the anticyclonic recirculating gyre south of Ryukyu Islands during early summer of 1996. The anticyclonic recirculating gyre during early summer of 1996 is extended more westward than those during early summer of 1985 and October of 1995.

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Appendix

In the modified inverse method proposed by Yuan *et al.* (1992), the following three assumptions are applied:

(1) The vertical friction term in the momentum conservation equation is significant in the surface and bottom Ekman layers where the geostrophic balance is not satisfied. Then, the total velocity v may be divided into three parts as

$$v = v_\tau + v_G + v_B. \tag{A1}$$

The v_τ is the velocity component of the surface Ekman layer subject to the wind stress τ and v_G is the geostrophic velocity, i.e.,

$$v_G = b_0 - \frac{g}{f\rho_0}\int_Z^{z_0} \frac{\partial \rho}{\partial x} dz \tag{A2}$$

where b_0 is the value of v_G at the reference level z_0. The v_B is the bottom Ekman layer velocity component.

(2) All convection terms and the vertical diffusion term are considered in the mass and momentum conservation equations, but the horizontal diffusion terms are neglected.

(3) When the heat flux q_e at the sea surface is unknown, the following constraints are imposed, i.e.,

$$q_{e,1} \le q_e \le q_{e,2} \tag{A3}$$

where $q_{e,1}$ and $q_{e,2}$ are, respectively, the minimum and maximum monthly average values in the survey area. We take the values of $q_{e,1}$ and $q_{e,2}$ as given by the Institute of Oceanography and Geography of Academia Sinica in 1977. Positive values of q_e indicate heat transfer from the ocean to atmosphere, and negative values of q_e give the heat transfer in the reverse direction.

Under the inequalities (A3), this is a mathematical problem for quadratic programming.

References

Chu, T. (1974): The fluctuations of the Kuroshio Current in the eastern sea area of Taiwan. *Acta Oceanogr. Taiwanica*, **4**, 1–12.

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. (1978): The topographic effects of Taiwan Islands, China and adjacent bottom relief on the path of the Kuroshio. *Studia Marina Sinica*, **14**, 1–21.

Guan, B. (1985): The path of the Kuroshio deep current east of Taiwan. *Oceanologia et Limnologia Sinica*, **16**(4), 253–260.

Hasunuma, K. and K. Yoshida (1978): Splitting of the Subtropical Gyre in the Western North Pacific. *J. Oceanogr. Soc. Japan*, **34**, 160–172.

Kaneko, A. and W. Koterrayama (1988): ADCP measurements from a towed fish. *EOS*, **69**, 643–644.

Kaneko, A., W. Koterayama, H. Honji, S, Mizuno, K. Kawatate and R. L. Gordon (1990): Cross-stream survey of the upper 400 m of the Kuroshio by an ADCP on a towed fish. *Deep-Sea Res*., **37**, 875–889.

Kaneko, A., N. Gohda, W. Koterayama, M. Nakamura, S. Mizuno and H. Furukawa (1993): Towed ADCP fish with depth and roll controllable wings and its application to the Kuroshio observation. *J. Oceanogr*., **49**, 383–395.

Liu, C., S.-G., Liau, S.-C. Pai and K.-K. Liu (1986): Water masses in the Western Philippine Sea-Physical aspects. *Acta Oceanogr. Taiwanica*, **17**, 1–17.

Nitani, H. (1972): Beginning of the Kuroshio. p. 129–163. In: *Kuroshio*, ed. by H. Stommel and K. Yoshida, Univ. Washington Press.

Yuan, Y. and S. Y. Xia (1988): Three dimensional diagnostic calculation of the Kuroshio current east of Taiwan. *Acta Oceanologica Sinica*, **10**(1), 1–9.

Yuan, Y., M. Endoh and H. Ishizaki (1990): The study of the Kuroshio in the East China Sea and the currents east of the Ryukyu Islands. *Proc. China-Japan Kuroshio Study Symposium*, Tokyo, 39–57.

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. p. 305–319. In: *Oceanography of Asian Marginal Seas*, ed. by K. Takano, Elsevier.

Yuan, Y., J. Su and Z. Pan (1992): Volume and heat transports of the Kuroshio in the East China Sea in 1989. *La mer*, **20**, 251–262.

Yuan, Y., K. Takano, Z. Pan, J. Su, K. Kawatate, S. Imawaki, H. Yu, H. Chen, H. Ichikawa and S. Umatani (1994): The Kuroshio in the East China Sea and the currents east of Ryukyu Islands during autumn 1991. *La mer*, **32**, 235–244.

Yuan, Y., J. Su, Z. Pan, H. Cheng, H. Ichikawa, S. Imawaki, K. Kawatate, K. Takano and S. Umatani (1995): The western boundary current east of the Ryukyu Islands. *La mer*, **33**, 1–11.

Yuan, Y., C. Liu, Z. Pan and S. Zheng (1996): Circulation east of Taiwan and in the East China Sea and east of Ryukyu Islands during early summer 1985. *Acta Oceanologica Sinica*, **15**, 423–435.

Yuan, Y., Y. Liu, C. Liu and J. Su (1998): The Kuroshio east of Taiwan and the currents east of the Ryukyu Islands during October of 1995. *Acta Oceanologica Sinica*, **17**, 1–13.