La mer 38 : 173–178, 2000
Société franco-japonaise d'océanographie, Tokyo

The Kuroshio east of Taiwan and in the East China Sea in July 1997

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Abstract : On the basis of hydrographic data obtained from two cruises by R/V Xiangyanghong No.14 and R/V Chofu-Maru in July 1997, a modified inverse method, and three dimensional diagnostic, semidiagnostic and prognostic models are applied to examine the Kuroshio east of Taiwan and in the East China Sea. Conclusive remarks on the Kuroshio in July 1997 are as follows: 1) The net northward volume transport (VT) of the Kuroshio through Section K_2 southeast of Taiwan was about 37.5×10^6 m^3/s. It was much smaller than those in early summer of 1985, October 1995 and May–June 1996. 2) There was no branch of the Kuroshio east of Taiwan flowing northeastward to the region east of Ryukyu Islands. 3) There were an anticyclonic eddy east of the Kuroshio and southeward flow east of this anticyclonic eddy. 4) There was an anticycloninc recirculating eddy south of Miyako Island and southeast of Okinawa Isand. 5) The net northward VT of the Kuroshio through Section PN in the East China Sea was about 23.0×10^6 m^3/s.

Key words : *Kuroshio, East of Taiwan, East China Sea, Numerical study, 1997 El-Niño*

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). YUAN *et al.* (1998b) gave a remark in explanation of some studies on the Kuroshio east of Taiwan. The Kuroshio has some important current characteristics in the area east of Taiwan and its adjacent region. For example, YUAN *et al.* (1998a, b) pointed out that there was an eastern branch of the Kuroshio east of Taiwan, flowing northeastward to the region east of Ryukyu Islands and occupying a part of the western boundary current east of Ryukyu Islands in October 1995 and early summer of 1996. However, no branch of the Kuroshio flowed into the region east of Ryukyu Island in early summer of 1985 (YUAN *et al.*, 1996). YUAN *et al.* (1996, 1998a, 1998b) 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, on the basis of hydrographic data obtained in summer of 1997, a modified inverse method, and three dimensional and nonlinear diagnostic, semidiagnostic and prognostic models are applied to examine the Kuroshio east of Taiwan and in the East China Sea during summer of 1997. The current features of the Kuroshio east of Taiwan and in the East China Sea, and those in its adjacent region are also discussed. Furthermore, we make a comparison of results in 1997 with the previous cruises, and a comparison of the computed results with ADCP current data.

2. Numrical Models and Data

The hydrographic data were obtained from two cruises, i. e., a cruise of China–Janpan

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Cooperative Research on the subtopical gyre during July 3–20, 1997 (hereafter called cruise 1) and another cruise during July 16–22, 1997 by R/V Chofu-Maru (hereafter called cruise 2) in the East China Sea (Fig. 1). The modified inverse method proposed by YUAN *et al.* (1992) is applied to calculate the current structure, volume transport (VT) and stream function in the regions east of Taiwan, southeast of the Ryukyu Islands and in the East China Sea (hereafter called computation 1). All of the three dimensional and nonlinear diagnostic, semidiagnostic and prognostic σ-coordinate models (WANG and YUAN, 1997) are used to compute the circulation east of Taiwan and southeast of the Ryukyu Islands (hereafter called computation 2). For computation 1, seven boxes are selected in the regions east of Taiwan and southeast of Ryukyu Islands, and one box in the East China Sea.

3. Major results of computation 1

In this section, major features of the Kuroshio east of Taiwan and in the East China Sea, and distributions of eddies east of Taiwan

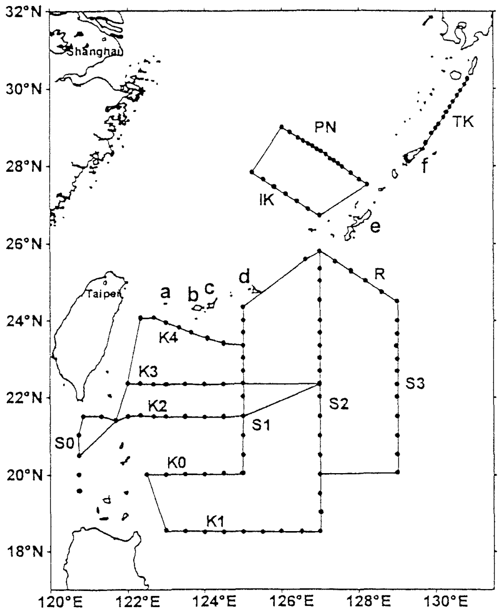

Fig. 1. Location of hydrographic stations and sections, and computation boxes in July 1997 (a : Yonakuni I., b : Iriomote I., c : Ishigaki I., d : Miyako I., e : Okinawa I., f : Amami-Oshima I.)

estimated by computation 1 are discussed. We compare the computed results with the ADCP measurement also.

3.1 The velocity distributions at Sections K_2 and PN

We discuss only the velocity distributions at Section K_2 southeast of Taiwan (Fig. 2) and Section PN in the East China Sea (Fig. 3) due to limitation of pages.

1) Section K_2 southeast of Taiwan

Section K_2 is located southeast of Taiwan (Fig. 1). In Fig. 2, there are two current cores in the Kuroshio. The main branch of the Kuroshio is near the southern tip of Taiwan, i. e., at the computational points 1 and 2. The maximum velocity at Section K_2 is about 112 cm/s at the sea surface of the computational point 2. It is much smaller those in early summer of 1985 (YUAN *et al.*, 1996), October 1995 (YUAN *et al.*, 1998a) and early summer of 1996 (YUAN *et al.*, 1998b). The second core is located at the computational points 4 and 5 with its maximum velocity of about 49 cm/s at the surface of the computational point 4. There are southward flows in the upper 800 m of the computational point 3, in the upper 75 m of the computational point 6, in the lower 50 m of the computational point 7, at the computational points 8 and 9, and below the Kuroshio. The comparison be-

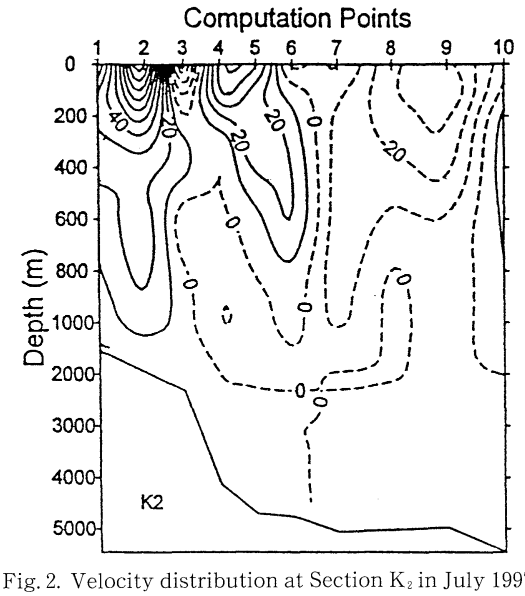

Fig. 2. Velocity distribution at Section K_2 in July 1997 (positive: northward, : unit: cm/s)

tween the current calculated above (Fig. 2) and the ADCP current observed at Section K_2 in July 1997 (Fig. 6) shows that they coincide qualitatively to each other.

2) Section PN in the East China Sea

Section PN is a familiar section in the East China Sea (Fig. 1). Fig. 3 shows the velocity distributions at Section PN in July 1997. In Fig. 3, there are two current cores in the Kuroshio. Its main current core is located near the coutinental slope, the computational points 6 and 7 (Fig. 3), with its maximum velocity of 141 cm/s at the sea surface of the computational point 6. The second core is located at the computational points 9 and 10 with its maximum velocity of 91 cm/s at the 125 m of the computational point 9. There are southward flows in the upper layer of the computational points 11 and 12, and below the Kuroshio. Northward flows also exist below southward flows of the computational points 11 and 12, and the computational points 13 and 14.

3.2. Stream function and volume transport

Fig. 4 and Table 1 show the distribution of stream function and total volume transport in July 1997. In Table 1, the net northward volume transport (VT) of the Kuroshio through Section K_2 is about 37.5×10^6 m^3/s in July 1997. It is much smaller than those in early summer of

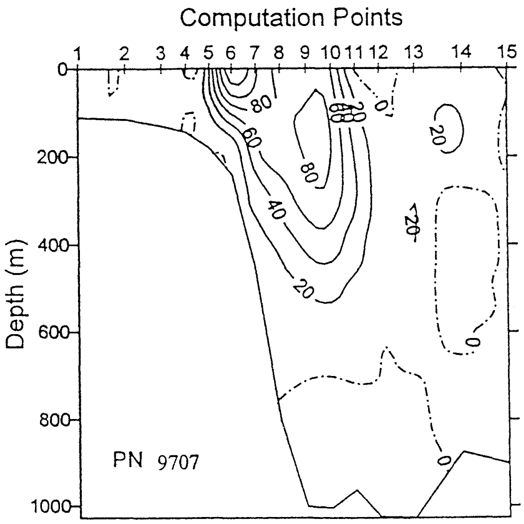

Fig. 3. Velocity distribution at Section PN in July 1997 (positive: northward, unit: cm/s)

1985, October 1995 and May–June 1996 (e.g. YUAN *et al.*, 1998a, 1998b). In Fig. 4, the Kuroshio is located west of 123° E at Section K_2 then flows northward through Section K_4. There is no branch of the Kuroshio east of Taiwan flowing northastward to the region east of Ryukyu Islands. The distributions of stream function, total volume transport, and temperature in Fig. 4 show that: (1) There is an anticyclonic eddy in the east of the Kuroshio, of which center is located at 22°20′ N, 123° E; (2) There is a southward flow, which probably comes from a southwestward flow at the northern part of Section S_3, in the aree east of the adove-mentioned anticyclonic eddy; (3) There is a cold eddy C_1 in the area east of a southward flow, of which center is located at 22° 20′ N, 124° 30′ E. There is also a cold eddy C_2 in a southeastern part of the computed region; (4) There is an anticyclonic eddy in the region south of Miyako and southeast of Okinawa Island. Comparing the computed results in Fig. 4 with the ADCP current averaged in the layer from 25 m to 75 m depths in Fig. 6 in July 1997, we find that they agree qualitatively to each other.

The decrease of the Kuroshio VT through Section K_2 in July 1997 may be due to the following two reasons. (1) The North Equatorial Current (NEC) weakens during El-Niño event suggested by XU *et al.* (1987). They showed that the phase of seasonal variation of the NEC at 130° E and that of the Kuroshio VT were the same phase. As the year 1997 is the strong El-Niño year, the Kuroshio VT at Section K_2 may have decreased with the weakening of NEC. (2) KAGIMOTO and YAMAGATA (1997) pointed out that the role of the anticyclonic eddy activity in the Kuroshio VT along the Nansei Islands. Comparing the strength of the anticyclonic recirculating eddy east of the

Table 1. Volume transport (VT) and position of the Kuroshio at Section K_2 during some cruises

Cruises	VT (10^6 m^3/s)	Its position
Early summer of 1985	45.0	West of 123° E
October 1995	57.8	West of 123° 20′ E
Early summer of 1996	44.6	West of 123° 40′ E
July 1997	37.5	West of 123° E
December 1997	27.6	West of 124° E

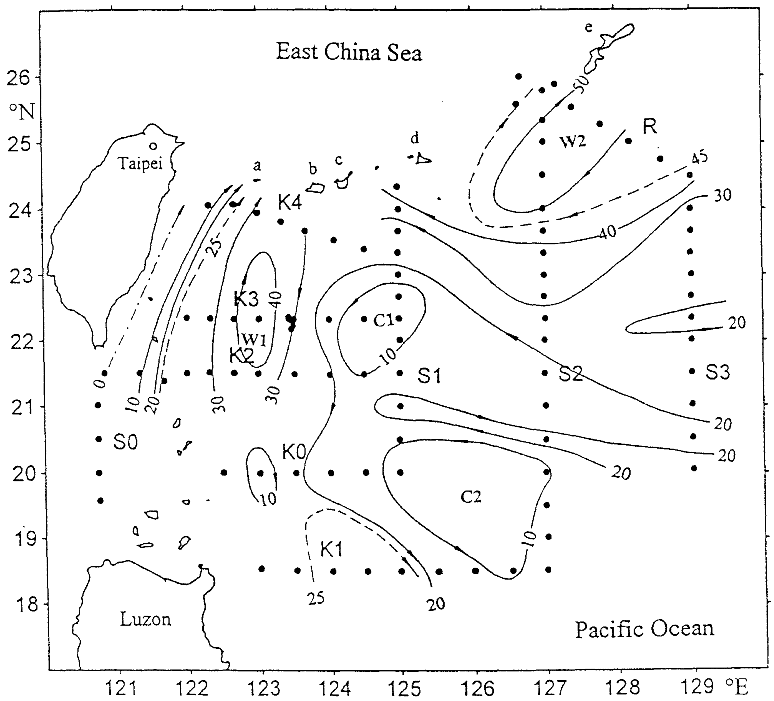

Fig. 4. The distribution of stream function and total volume transport in July 1997 (unit: $10^6\ m^3/s$)

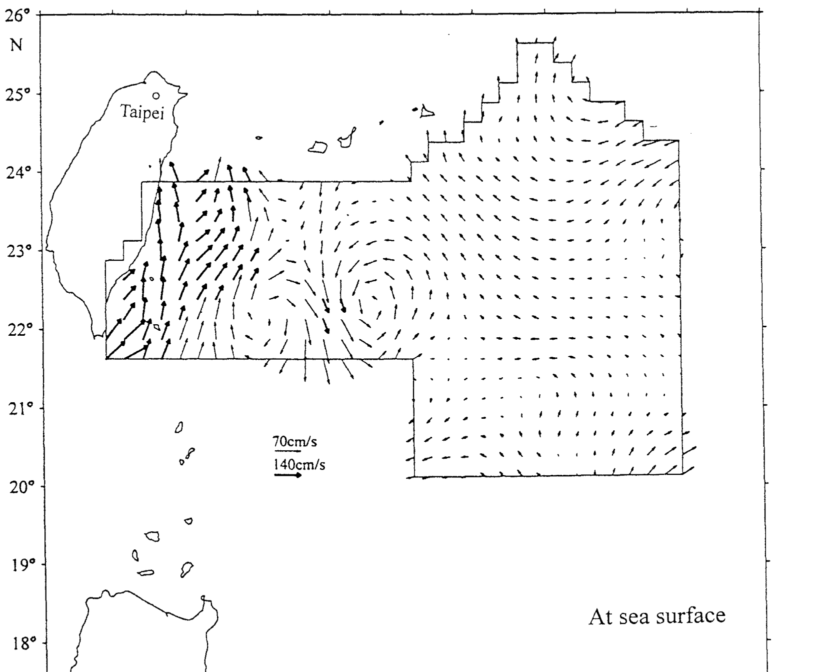

Fig. 5. The horizontal velocity distribution at the sea surface for the diagnostic calculation in July 1997

Ryukyu Islands in July 1997 with that in the other year such as May–June 1996 in YUAN *et al.* (1998b), the decrease of the Kuroshio VT through Section K_2 may be associated with the weakening of the anticyclonic recirculating eddy east of the Ryukyu Islands.

It is warthy to note that the classical Sverdrup relation is not valid in the region of the Kuroshio. However, it is still valid in the broad ocean interior east of the Kuroshio Countercurrent (KAGIMOTO and YAMAGATA, 1997). This means that we can not explain the above seasonal variation of the Kuroshio VT from the classical Sverdrup relation.

In July 1997 the net northward VTs of the Kuroshio through Sections IK and PN in the East China Sea (see Fig. 1) are 26.3×10^6 and 23.0×10^6 m^3/s, respectively, and that through the Tokara strait across Section TK (see Fig. 1) is 23.3×10^6 m^3/s, The average net northward VT of the Kuroshio through Section PN in other cruises are as follow: (1) 28.6×10^6 m^3/s during ten cruises from 1987 to 1990 (YUAN *et al.*, 1994); (2) 28.0×10^6 m^3/s in the four cruises of 1992 (LIU and YUAN, 1999) and 27.1×10^6 m^3/s during the eight cruises of 1993 and 1994 (LIU and YUAN, 1999); (3) 26.7×10^6 m^3/s October 1995 (YUAN *et al.*, 1998a) and 27.2×10^6 m^3/s in early summer of 1996 (YUAN *et al.*, 1998b). This means that VT of the Kuroshio at Section PN was smaller slightly in July 1997 than in other cruises.

4. Major results of computation 2

In this section we first discuss the horizontal velocity distibutions at the sea surface, 200 m, 500 m and 1000 m depths, which are deduced from the diagnostic calculation. Due to the limitation of pages, only the horizontal velocity distribution at the surface (Fig. 5) is shown. The following main results are obtained. (1) The Kuroshio east of Taiwan flows northeastward, and makes a cyclonic meander and truns to flow northward. Its maximum velocity at (or near) the southern boundary is about 147.4, 123.1, 98.5 and 42.8 cm/s at the sea surface, 100

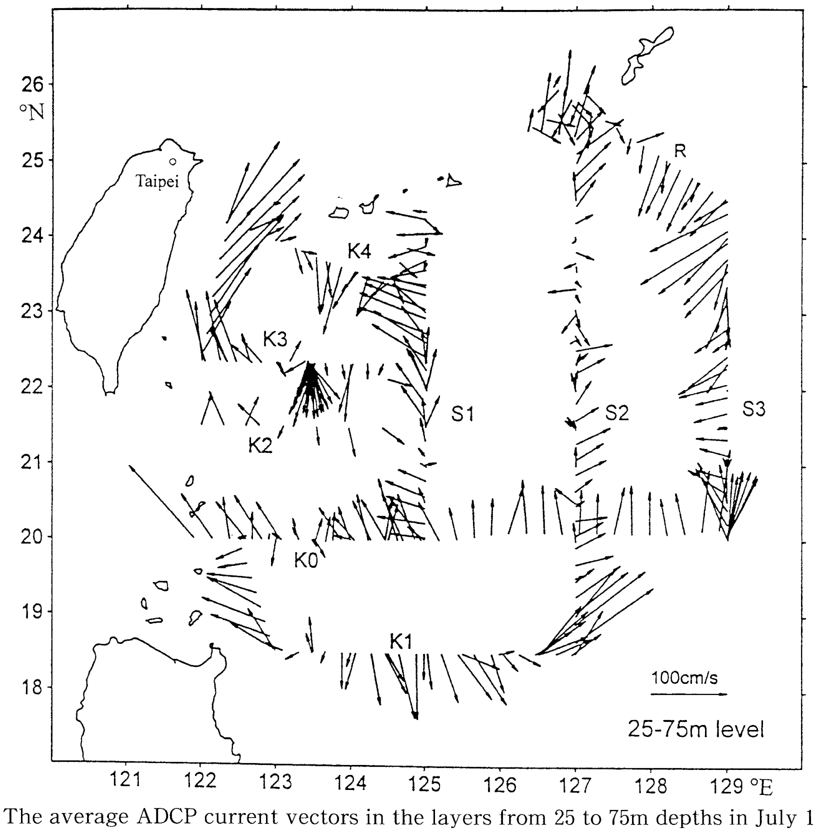

Fig. 6. The average ADCP current vectors in the layers from 25 to 75m depths in July 1997

Table 2. Volume transports (VT) of the Kuroshio through Section PN in the East China Sea during some cruises

Cruises	Average VT of the Kuroshio ($10^6 m^3/s$)
Ten cruises from 1987 to 1990	28.6
Four cruises of 1992	28.0
Eight cruises of 1993 and 1994	27.1
October 1995	26.7
Early summer of 1996	27.2
July 1997	23.0
November 1997	25.9

m, 200 m and 500 m levels, respectively. (2) There is no branch of the Kuroshio flowing northward to the region east of the Ryukyu Islands. (3) As pointed out by the computation 1, there are an anticyclonic eddy (W_1) and a cold eddy (C_1) in the east of the Kuroshio. Their locationas are at 22° 20′ N, 123° 10′ E, respectively. There is a southward flow between the above two eddies of W_1 and C_1. An anticyclonic recirculating eddy appears in the northeastern part of the computational region.

Comparing the results of computation 2 with those of computation 1 and the average ADCP current (Fig. 6), it can be said that the distributions of horizontal velocity deduced from the diagnostic calculation agree quite with the results of computation 1 and the average ADCP current.

Comparing the results of diagnostic calculation with those of semidiagnostic and prognostic calculations, they are coincident qualitatively to each other while there are some differences between them in quantity. For example, the maximum velocities of the Kuroshio east of Taiwan for the semidiagnostic calculation are about 164.9, 147.6, 132.7 and 46.7 cm/s at the sea surface, 100 m, 200 m and 500 m levels, and those for the prognostic calculations are about 164.6, 147.6, 132.3 and 40.0 cm/s at the sea surface, 100 m, 200 m and 500 m levels. This means that the Kuroshio east of Taiwan is strengthened for the semidiagnostic and prognostic calculations. Therefore, we should consider the interaction among the density field, velocity field and bottom topography when the density field and so on have been adjusted.

Acknowledgement

This project was supported by both the National Natural Science Foundation of China under contract No. 49736200 and No. 49776287, and the Major State Basic Research Program, No. G1999043802.

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Received on February 10, 2000
Accepted on October 10, 2000