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An Analysis on Observational Surface and upper layer Current in the Yellow Sea and the East China Sea

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The characteristics of surface circulation in the Yellow Sea and the East China Sea are discussed by analyzing a great deal of current data observed by 142 sets of mooring buoy and 58 sets of drifters trajectories collected in the Yellow Sea and the East China Sea through domestic and abroad measurements. Some major features are demonstrated as bellow: 1) Tsushima Warm Current flows away from the Kuroshio and has multiple sources in warm half year and comes only from Kuroshio surface water in cold half year. 2) Taiwan Warm Current comes mainly from the Taiwan Strait Water in warm half year and comes from the intruded Kuroshio surface water and branches near 27N in cold half year. 3) The Changjiang Diluted Water turns towards Cheju Island in summer and flows southward along the coastal line in winter. 4) The study sea area is an eddy developing area, especially in the southern area of Cheju Island and northern area of Taiwan.

Key words: Surface circulation, the Yellow Sea and the East China Sea

INTRODUCTION

So far many scientists have done a great deal of research work on the characteristics of circulation and current structure. Guan (1994) proposed a complete circulation scheme in the Yellow Sea (YS) and the East China Sea (ECS). Previous studies on current structure and circulation system used to be by means of analyzing thermohaline structure together with a few observational current data or dynamical calculation and inverse method. Such as Hu (1984), Zao (1985) studied on cyclonic eddy in the southwestern area of Cheju Island; Lin (1991), Su (1993) analyzed the current features in the continental shelf of the ECS; Pan *et al.* (1997) explored the formation and evolution of dense water circulation in the middle part of the ECS. Recently, with increasing of observational current data, the studies on circulation in the local area are more popular by analyzing both observational current data and thermohaline structure. Such as, Zao *et al.* (1991), Le *et al.* (1990) and Tang *et al.* (2000) analyzed the circulation in the southern YS (SYS). Guo *et al.* (1998) mentioned the origin of the Taiwan Warm Current (TWC) further. Although some important results have been obtained, the comprehensive analysis of surface circulation in the large sea of the YS and the ECS are still rare. In this paper we collected as more as possible mooring buoy data and satellite-tracked drifter data in the all sea area of the YS and the ECS from domestic and abroad measurements (mooring stations and drifter released positions are shown in Fig. 1 which could help us to understand continental circulation more clearly. The main purposes for this paper are (1) to verify and confirm some previous main conclusions, and (2) to analyze the circulation structure of the YS and the ECS comprehensively and to suggest some new concepts.

DATA

In the past, the residual currents used to be obtained by subtracting tidal current from fixed daily observation at anchored vessel. It is very difficult to present real current condition due to weak residual current and strong tidal current, and influence by other external factors. Since 1980, mooring buoy and satellite-tracked drifter have been used gradually for measuring current with a long time scale. 112 sets of mooring data and 58 sets of drifters data and 30 sets of fixed daily current data are listed in Table 1.

The current fields in the upper and surface layers are

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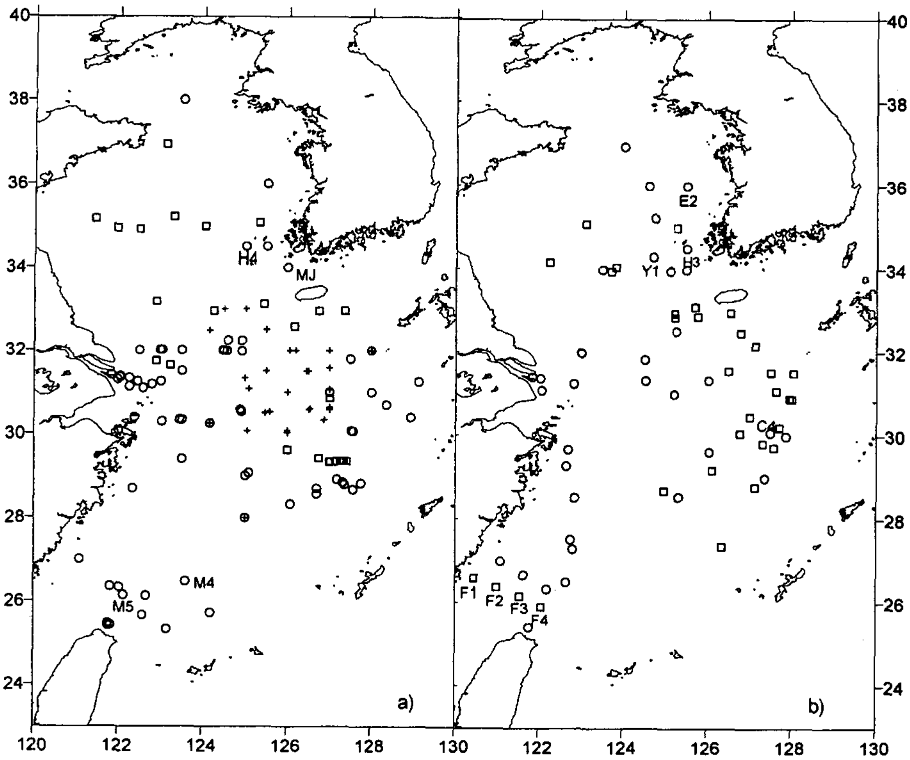

Fig. 1. Mooring stations and released positions of drifters.

Table 1. List of observational current data

Buoy Type	Data source	Oservation time	Number of set
Mooring	FIO[1] and SIO[2] of SOA[3]	1984-1990	25
	Cooperative researches among China, Japan, America and Korea	1986-1996	43
	Oceanology Institute, Academia Sinica	1972-1983	10
	Figures cited from Pan and Huang (1997)	1987-1990	10
	China nearshore investigation	1980, 1989-1991	18
	Literatures from Taiwans scholar	1980-1981	6
Drifter	FIO of SOA	1999-2000	6
	KORDI[4]	1986-1987	2
	References from Korea, America and Japan	1986-1997	50
Daily observation	Chart from *Marine Research* 1979(3)	1970	1
	FIO of SOA	1984, 1986	2
	Provided by Zao (1985)	1972-1983	10
	Figures cited from Zao (1985)	1972-1983	17

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analyzed by using drifter buoy data (15 m or 30 m) in this paper. The observational depth is 5–30 m in shallow sea area and over 100m in deep-sea area, respectively. Based on the hydrographic features of seasonal variation in the study area, all current data used here are divided into two groups: the data for warm half year (from May to October) and for cold half year (from November to April of next year). The positions of mooring station E_2, H_3, Y_2, M_4, M_5 and MJ are shown in Fig. 1. The residual currents of each station are calculated by filtering the time series of current data.

METHOD COMPARISON BETWEEN TWO OBSERVATIONAL CURRENTS

Euler method

The Euler current measured by mooring buoy and fixed daily observations can display better the current variation with time at a certain fixed point. All cur rent can be divided into stable and unstable currents according to different pattern of residual current vectors.

Stable current pattern: The curves on the progressive vector diagram of residual current (residual current means 25 h mean current or low-pass filtered current) are commonly flat with fewer fluctuations and no circle at all. The distributions of current vector show small variation in current direction at the mooring stations. Most of these currents are located at continental shelf edges area between 100–200 m isobath and near the Kuroshio area (moorings are usually set up at left side of the Kuroshio main stream). Mean observed residual current speed is about 20–40 cm/s and 45–88 cm/s in the continental shelf edge and in the left flank of the Kuroshio main stream, respectively.

Unstable current pattern: In the Yellow Sea trough area with the depth of 70–80 m isobath, the southern area of Cheju Island, the left flank of Kuroshio turning point and the northern area of Taiwan Island, the distributions of progressive vector of residual current present meander and circle which means large variation of current direction with time. Such as: buoy C_4 set at 127°30'E, 30°18'N in December of 1987 by FIO, and Y1 at 124°41.5E, 38° 18'N in June of 1986 by America, both of their residual current vectors rotated clockwise more than three times (See Fig. 2a,b). The mean velocities of these residual current were small (0.6–30 cm/s) with a mean velocity of 10.1 cm/s.

Lagranges method

Lagrangian current measured by 58 sets of satellite-tracked drifters can better demonstrate the realistic water transport. This method has become one of the best measurements for observing surface current. The lifetime of drifters were over 10 days and some lasted up to half year except for 9 sets of drifters (less than 10 days). It is shown from drifter trajectories that the drifters turned clockwise around eddy in eddy areas, and drifted flatly away from eddy area.

ANALYSIS OF OBSERVED CURRENT FIELD

Distribution of the current field in warm half year

76 sets of mooring buoys and 27 sets of drifters

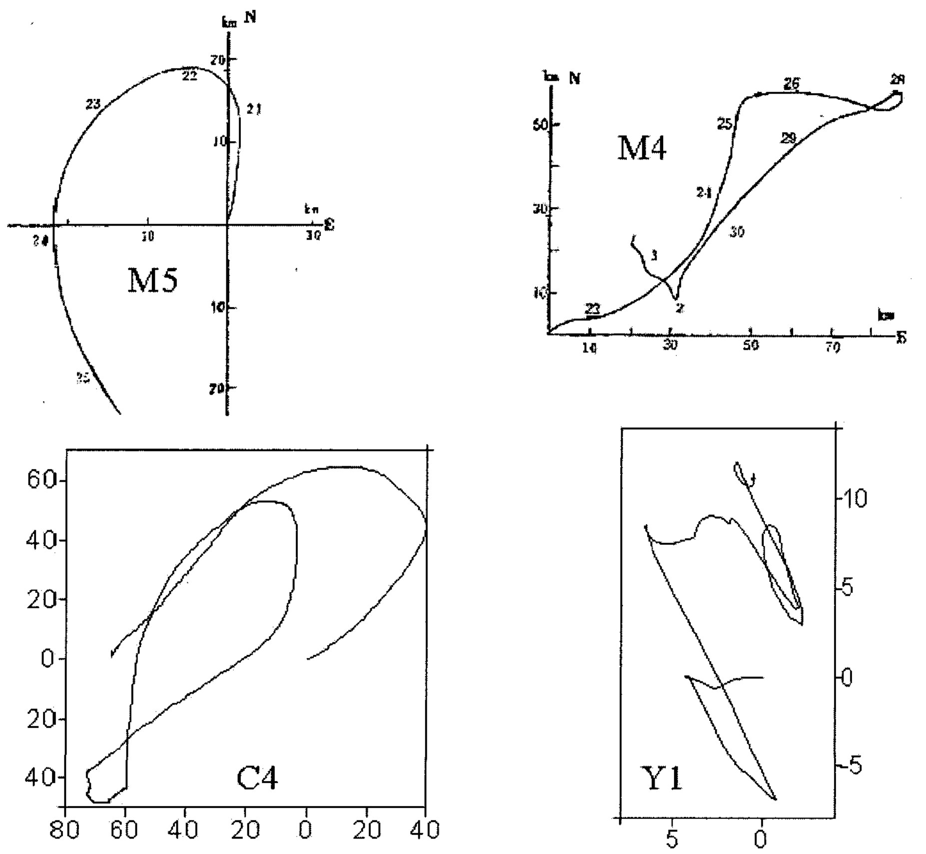

Fig. 2. Progressive vectors of residual current.

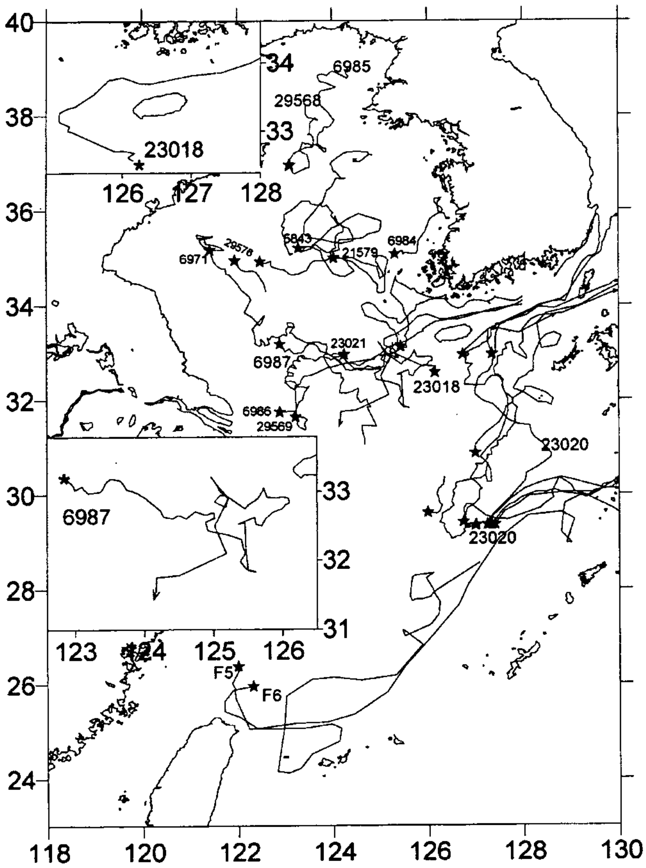

Fig. 3. Trajectories of satellite-tracked drifter.

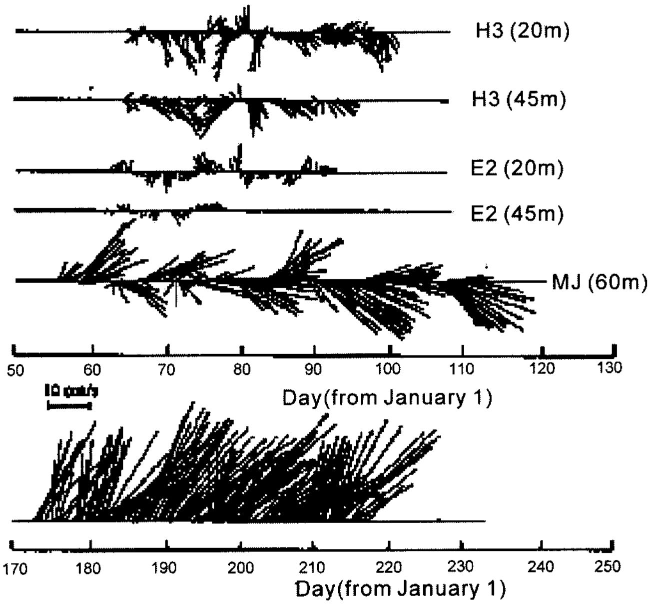

Fig. 4. Current vectors chart.

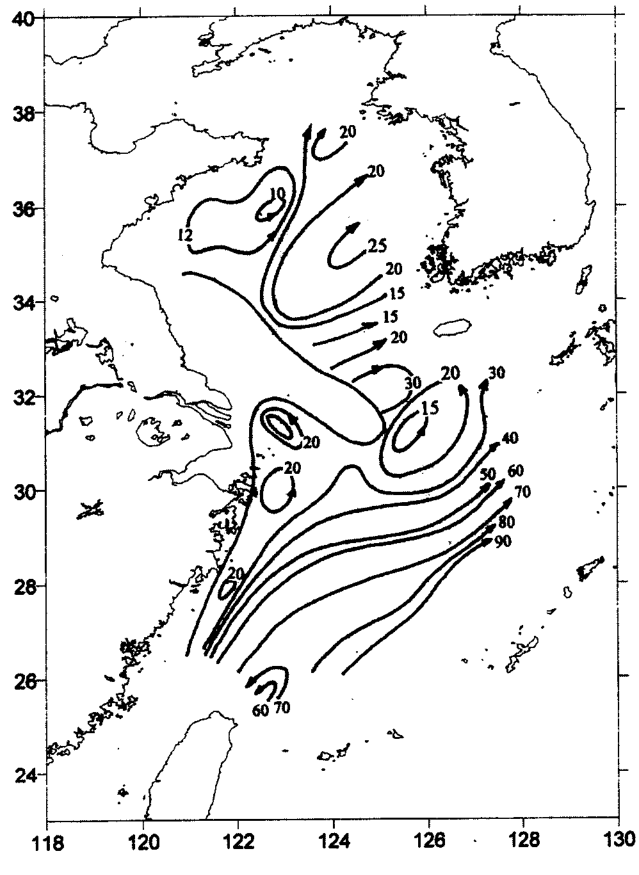
Fig. 5. Distribution of $\sigma_t = 23.5$ isobath.

have been released in the YS and the ECS in warm half year. The releasing positions were set at the SYS, off the Changjiang mouth, Kuroshio sea areas, the Tsushima Warm Current (TSWC) source area and the northern part of Taiwan. The characteristics of current fields in these sea areas are discussed as follows based on the observed current data.

The SYS area: It can be is seen from Fig. 3 those two buoys (No. 6971 and 29576 released at left flank of the SYS) drifted southward; and two buoys (No.23021 and 6987 released at southern part of SYS) drifted eastward. The relatively stable northward currents are measured from the drifter (No.6984) released at western part of Korea and mooring station H4 (See lower plate of Fig. 4). It is suggested that there is a large cyclonic circulation with basin shape in the surface and upper layer of the YS and the ECS in warm half year.

Two drifters were released at middle part of the SYS. The left one (No.5843) ran a cyclonic circle during its lifetime of over 100 days and the right one (No.21579) moved northward along the center of the YS trough after rotating different directions in four times. It is thought that the sea area in the middle part of SYS is referred to as an eddy area besides a large anticyclonic circulation, and there are several small eddies with different rotation directions.

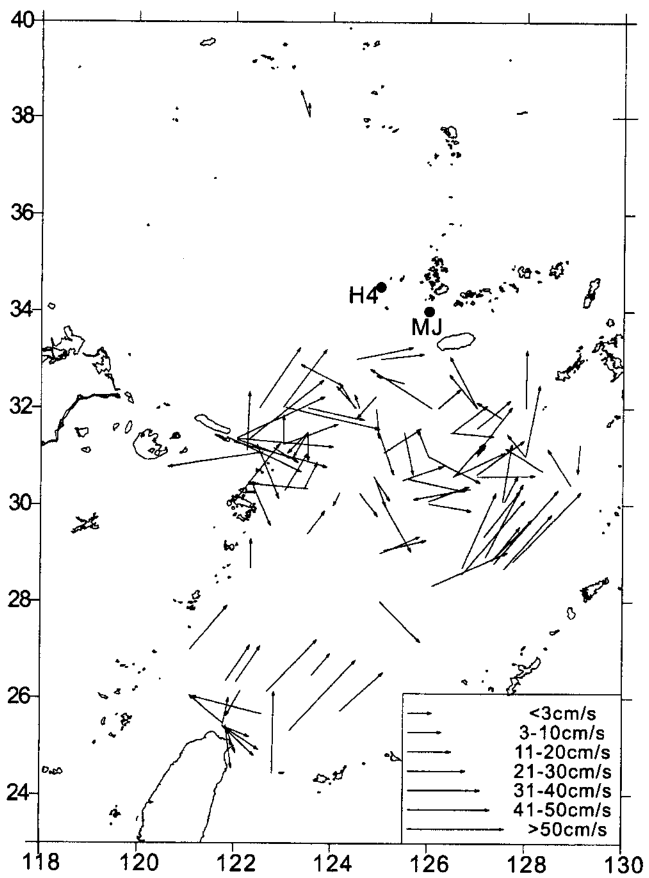

Fig. 6. Distribution of residual current vectors in warm half year.

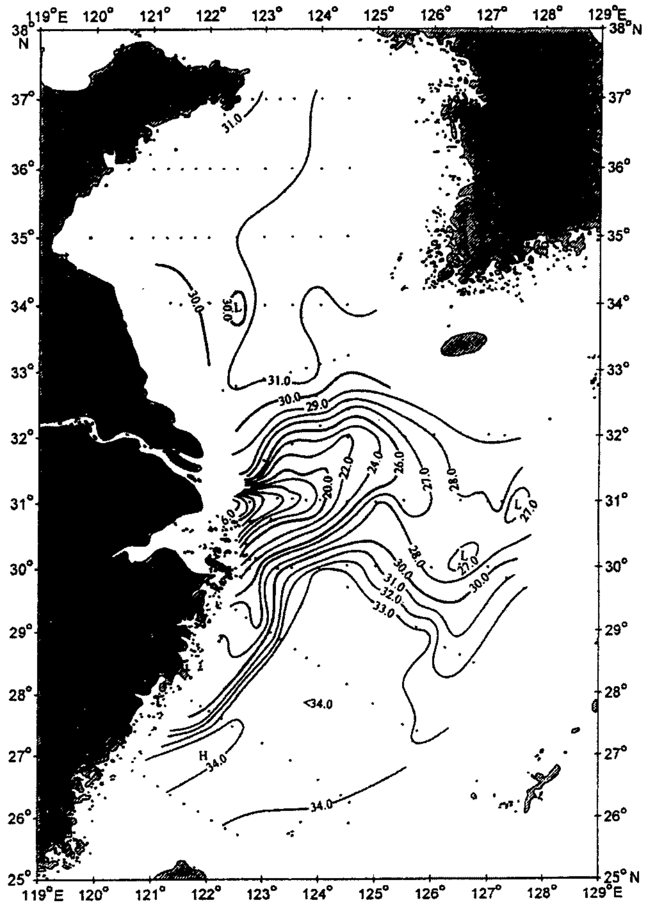

Fig. 7. Distribution of surface salinity in the August of 1998.

The distribution of σ_t = 23.5 isobath (see Fig. 5) can reflect better the current pattern in the SYS. Moreover, It can be seen from two northward drifter trajectories (see No. 29568 and 6985 in Fig. 3) and two northward current vectors (Fig. 6) that there is a northward flow in the northern part of the YS, it can reach 39N to the north.

The Changjiang river mouth sea area: It can be seen from residual current vectors (see Fig. 6) that the residual current off the Changjiang river mouth moves southeastward and northeastward, respectively, the main stream flows directly towards Cheju Island and parts of current reach to the source area of the TSWC. The distribution of residual current was coincident with that of surface salinity tongue during the August of 1998 (see Fig. 7). After circling many times, two drifters (No.29569and 6986) released off the Changjiang mouth and moved northward to Cheju Island with its current speed of 21.2 cm/s, which demonstrated the pathway of the Changjiang Diluted Water (CDW) and the existence of several small eddies in the Changjiang estuary area.

The Kuroshio and source area of the TSWC: The residual current in the left flank of Kuroshio main stream (Fig. 6) moved northeastward with its mean velocity of 63 cm/s, which confirmed that Kuroshio is a stable northward flow. 8 sets of drifters were released at 29N (Fig. 3), four of which moved eastward turning into the Tokara Strait and another four drifters moved northward merging into the TSWC. From above analyses, the decisive evidences can be summarized as follows:

1. It can be seen from drifter trajectories that the Kuroshio in the ECS turns to Tokara Strait at 127°30'E, 29°30'N (turning point of the trajectories). This result is more precise than that analyzed by using temperature and salinity data (turning point at 30°N).
2. Having drifted northeastward for 12 days, Drifter No. 23030 separated from the Kuroshio and inserted into the continental shelf near 31°N and joined into the TSWC at last, which indicated that there is a branch of the Kuroshio indeed supplying water for the TSWC.
3. It is indicated from residual current vectors and

drifter trajectories in the left side of the Kuroshio turning point that the water of TWC (TWCW), northern ECS mixing water and coastal water dominated by the CDW all supported to the TSWC. Therefore, it can be thought that the TSWC has multi-sources in the warm half year. There is a cyclonic eddy in the southern area of Cheju Island with its center located at 126°E, 31°N and a radius of two and half latitudes presented by many observed residual current (Fig. 6). This condition also can be seen from the distribution of $\sigma_t = 23.5$ isobath (see Fig. 5). Moreover, it is clearly shown from two northwestward current vectors southwest of Cheju Island (see Fig. 6), two eastward current vectors west of the Cheju Island and drifter trajectories of No.23018 (see Fig. 3) That there is a current flowing round the Cheju Island, which has referred as "the Cheju Warm Current" (CWC) by Lie (1999) recently.

The Northern Taiwan area: It is shown from northeastward current vectors near-shore (see Fig. 6) that the TWC comes from Taiwan Strait. The TWC flowed northward parallel to Kuroshio after entering into the ECS, and it can reach to the TSWC source area with its mean velocity of 22.5 cm/s. The distribution of southeastward current vectors northeast end of Taiwan and two drifter trajectories (F5 and F6 in Fig. 3) showed the continental shelf water penetrating into the Kuroshio. A cyclonic eddy might form between the continental shelf water and the northward Kuroshio. In addition to, it is also shown from two moorings M4 and M5 (see the position in Fig. 1a) that the flow is very unstable in the northern Taiwan area where unstable eddy developed rapidly.

As mentioned above, the schematic circulation pattern of the YS and the ECS in warm half-year is sown in Fig. 8. Having compared with previous results, the significant features are shown as follows: (1) it is indicated that the TSWC is a current with multi-source structure. The main sources of that are the Kuroshio, the TWC, the CDW and the northern ECS mixing water *et al.* (2) There are some small eddies with different rotating directions in the basin scale anti-clockwise circulation in the SYS. A northward flow may exist in the middle part of the SYS. (3) It is confirm further from above analyses that the CWC pointed by Lie (1999) exists indeed.

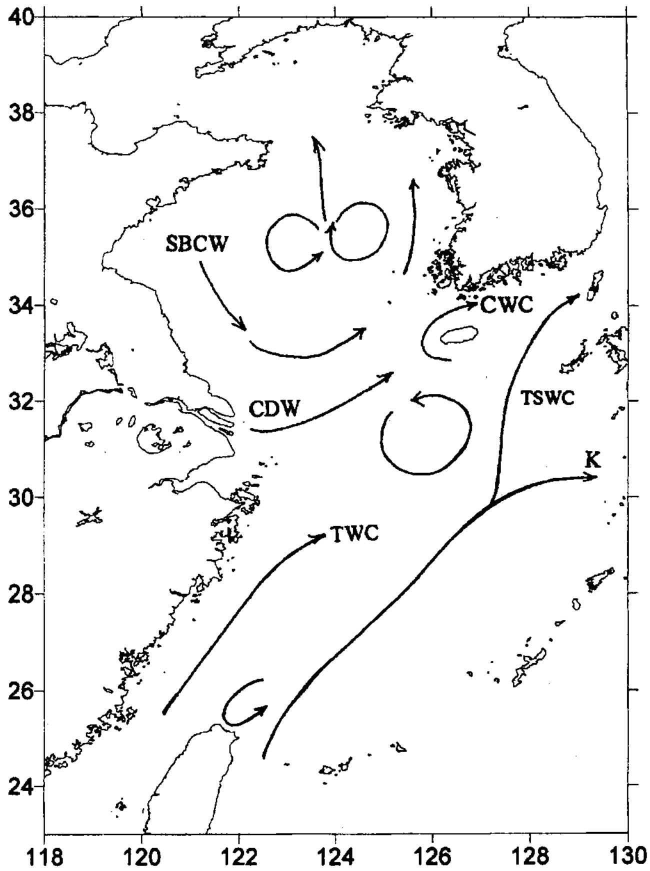

Fig. 8. The schematic surface circulation pattern in the YS and the ECS in warm half-year.

The distribution of current field in cold half year

The 36 sets of mooring buoys and 31 sets of satellite-tracked drifters are used to analyze the variation of current field in cold half-year (from September to April next year).

The SYS sea area: Although the buoy data in cold half year is not as many as that in warm half year and that with short time series, two basic characteristics are reveled as follow:

1. A westward flow was shown by fixed current measurement for three days in mooring M1 (123°30'E, 34°N) in the west flank of the YS trough (see Fig. 9). Drifter No.9602 near mooring M1 ran westward firstly then moved northwestward. Drifter Ck2 rotated clockwise and then ran northward, which confirms the existence of a northward flow in west of the YS trough, and the Yellow Sea Warm Current (YSWC) flowing northward along the west side of the YS trough in wintertime. The flow pathway is consistent with the contours of high temperature and salinity tongue shown in Fig. 2 of Tang *et al.* (2000).

2. Drifter No.9604 west of the SYS moved southward, and drifter 9605 east of the SYS moved southward either, and the southward flows were observed at 20m depth (see Fig. 4) from mooring buoys H3

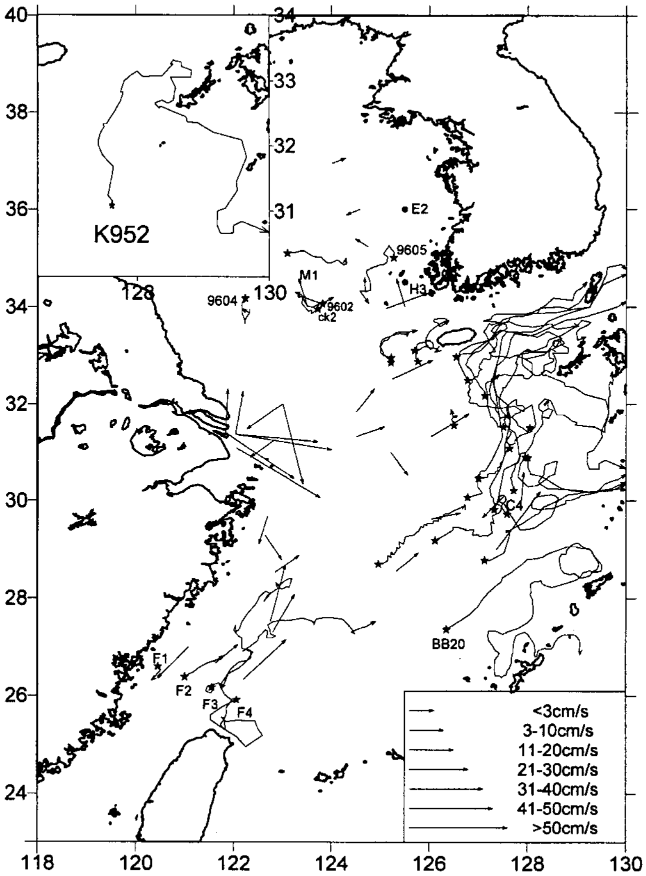

Fig. 9. Distributions of trajectories and residual current vectors in cold half year.

and E2 (see Fig. 1) the southward flows were observed at 20 m depth (see Fig. 4), from which indicated that the circulation in the SYS is composed by the northward YSWC in the middle part of the sea area and the southward coastal current in the both sides of the sea area in cold half year.

Near Changjiang estuary area: The current field near Changjiang estuary area in cold half year is obviously different from that in warm half year: most of residual current vectors off Changjiang estuary show southeastward or southward except for individual northerly, the CDW flowed southward along the coast to form the Ze Jiang coastal current. In northernmost of Taiwan, the southward Ze Jiang coastal current mixed with northward Taiwan Strait Mixing Water and then piled up to form northern Taiwan Strait Mixing Water. Therefore, a large sea area near the southern coastal area of the ECS was full of low salinity water.

Kuroshio and the source of the TWC areas: The drifter trajectories clearly display the Kuroshio pathway (see Fig. 9). That is, the Kuroshio moved northward along the continental shelf slope and then turned to the Tokara Strait. The drifting speed of drifter BB20 reached to 75.2 cm/s in the right side of the Kuroshio main stream. This shows that the Kuroshio is a strong northward stable current, the existence of the Kuroshio counter current was just showed by the pathway of the drifter rotating clockwise one and half circle in the northwestern of Ryukyu Islands and then turning back to southwest. It is clearly indicated from drifter trajectories in the edge of continental shelf that the TSWC was separated directly from the Kuroshio near 30°N with its speed of about 18.1 cm/s and up to 27.6 cm/s after entering Tsushima Strait. It must be point out that among so many drifters, there was not any drifter moving westward towards the YS after separating from the sea area west of Cheju Island. The main reason is that there exists a strong thermocline front in the west flank of Cheju Island. The front blocked the way of westward water. Moreover, it is obviously presented from the rotation of residual current vectors of mooring C4 (see its position in Fig. 1b) in the December of 1987 (see Fig. 2a) that the TWC source area left side of the Kuroshio turning point is also a developing eddy area. It is worth noting that the drifter K952 shown in the up-left corner of Fig. 9 moved northward to 33×N then turned back clockwise and moved southward along west coast of Kyushu, and merged into the Kuroshio south of Japan. This is helpful to form a warm eddy in the southwestern sea area of Kyushu.

Northern sea area of Taiwan: Four sets of satellite tracked-drifters F1, F2, F3 and F4 equipped also a temperature sensor were released in northwestern part of Taiwan in the January of 1999 by FIO, SOA. Drifter F1 near Fujian coast ran southward along the shore. The water temperature measured from the drifter F1 was below 13°C (see Fig. 3b cited from Guo (1998)), which snaps shot a scenario of Fujian-Zhejiang coastal water running southward. Drifter F2 moved northward consistently with its speed of 20–40 cm/s, the drifter trajectories presented pathway of the mixing water having moderate temperature and salinity north of Taiwan Strait running northward.

Drifters F3 and F4 rotated clockwise and then ran to northeast. Drifter F4 rotated largely anti-clockwise in northeast of Taiwan and rotated in the small clockwise and then drifted to northeast, at last, ran to east near 27°15′N. These two paths of drifter interweave each other near 26°30′N and they separated from each other north of 27°N, which reflected a real condition of the TWC branching off north of 27°N: one of branches ran northward along the isobath of 60 m with the speed of 25.5 cm/s, and the another one flowed along the isobath of 90 m and turned to the east to merge into the Kuroshio with the speed of 30 cm/s. It can be seen from measured water temperature that the TWC south of 27°N consists of the northern Taiwan Strait Mixing Water (T=16°C, S=32.9) and the Kuroshio surface water (KSW) intruded from northeast of Taiwan (T>20°C, S=34.5). The measured water temperatures north of 27°N was about 18°C, which means that the northern Taiwan Strait Mixing Water absolutely merged into the KSW coming from northeast of Taiwan. Therefore, the TWC comes mainly from the KSW in cold half-year [see Guo *et al.*(2000)]. Drifter F4 rotated anti-clockwise, it completes an anti-clockwise cycle for about 10 days. It is suggested that there is a stronger cyclonic eddy with the speed of 50–90 cm/s in the northeast of Taiwan, and its existence strengthen the influence of KSW intruding into continental shelf. This concept is different from the concept about internal and external branches of the TWC suggested by Su *et al.* (1987).

Based on above analyses, the schematic surface circulation pattern in study sea area in cold half year can be drawn up (see Fig. 10). The distributions of drifter trajectories have verified the existences of the Kuroshio, the Kuroshio Counter Current, the YSWC and the Min Zhe Coastal Current further.

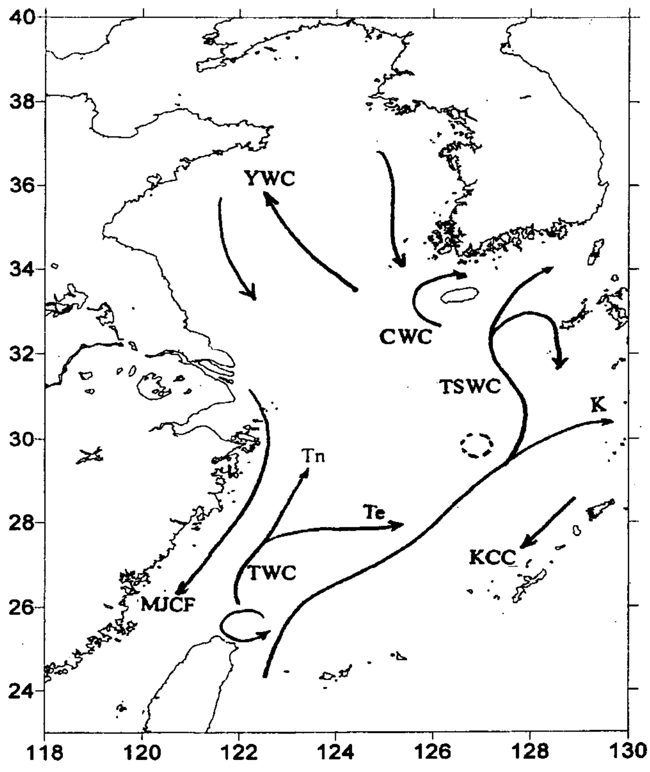

Fig. 10. Schematic surface circulation pattern in the YS and the ECS in cold half year.

The main viewpoints that different from the circulation pattern suggested by Guan (1994) are: (1) It is thought from measured current data that the CWC also exists in cold half year. (2) The TWC is branched in the sea area near 27°N. (3) There is not any branch from the TWC entering the YS in the southwestern area of Cheju Island.

CONCLUSIONS

1. It can be seen from observed current data that the Kuroshio flows northward along the ECS continental shelf (approximately 200–1000 m isobath) all the year round; it turns towards the Tokara Strait at 29°30'N, 127°30'E.

2. The TSWC flows away from the Kuroshio at about 30°N, 127°30'E with the mean speed of 16.9 cm/s, and its speed increases up to 28.4 cm/s after entering Tsushima Strait. It has multiple sources in warm half-year. The main sources of the TSWC comes from a Kuroshio branch, northern East China Sea Mixing Water, the TWC Water and CDW etc., and only the KSW in cold half year. There is not any branch from the TSWC flowing westward into the YS.

3. The TWC mainly comes from the Taiwan Strait Water in warm half year, while it comes from the intruded KSW from continental shelf in winter. During cold half year, the TWC flows away from the Kuroshio in the northern area of 27°N: one of branches flows northward along isobath of 60 m, another one moves eastward along isobath of 90 m merging into the Kuroshio.

4. It is shown from residual current vectors and drifter trajectories that the CDW flows southeastward first, and then turns to northeastward after flowing out of river mouth directly towards Cheju Island in summer, and flows southward along the coastal line in winter.

5. It is proved further from measured current data that "the Cheju Warm Current" defined by Lie flows clockwise around the Cheju Island all the year round.

6. It is indicated from observed current analyses that the study sea area is an eddy developing area, especially in the southern area of Cheju Island and the northern area of Taiwan.

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