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Surface Current Fields in the Eastern East China Sea

HEUNG-JAE LIE AND CHEOL-HO CHO
Physical Oceanography Division Korea Ocean Research and Development Institute
P.O. Box 29, Ansan, 425-600 Seoul, Korea

Surface current fields in the eastern East China Sea (ECS) were constructed by analyzing trajectories of 58 satellite-tracked surface drifters released during 1991-1996. Composite trajectories and 20-minute-by-20-minute box-averaged current vectors show that the basic current pattern composes of: the Kuroshio main stream, which turns eastward toward the Tokara Strait; a northward branch current of the Kuroshio on the ECS outer shelf deeper than 100 m; and an anticyclonic circulation in the northern Okinawa Trough west of Kyushu. The northward branch current sharply changes its direction to the northeast when it crosses a line connecting Cheju Island, Korea and Goto Islands, Japan. The basic pattern of current field changes slightly from winter to summer, and the main axis of the Tsushima Current in the Korea Strait is found to shift seasonally. The drifter experiment does not support the claim that the Yellow Sea Warm Current is separated from the northward branch current on the outer shelf southeast of Cheju Island. We suggest that the use of the term 'Tsushima Current' be limited to the northeast channel flow in the Korea Strait. The new term 'Kuroshio Branch Current' is suggested for the northward branch current on the outer shelf south of Cheju-do, which is separated from the Kuroshio.

INTRODUCTION

The circulation in the eastern East China Sea (ECS) may be determined basically by the Kuroshio main stream, a branch current of the Kuroshio west of Kyushu, and the outward extension of fresh coastal water in summer, even though the three are variable in time and space. Schematic flow patterns of the ESC have been suggested, mostly based on hydrographic data (e.g., Uda, 1934; Nitani, 1972; Guan and Mao, 1982; Beardsley *et al.*, 1985; Fang *et al.*, 1991). Some of the patterns are similar, but others are totally different. The differences have been briefly commented on by Lie and Cho (1994). Qiu and Imasato (1990) presented a comprehensive surface current field, using historical Japanese geoelectrokinetograph (GEK) data accumulated over a period of more than three decades. The current field properly represents the main path of Kuroshio along the continental shelf of the ECS and its eastward turning toward the Tokara Strait southwest of Kyushu. However, it does not show the existence of a branch current in the eastern ECS which is separated from the Kuroshio. Recently, Lie and Cho (1994) deployed satellite-tracked drifters west of Kyushu during 1991~1992 and observed a branch current which flowed northward along the western shelf edge of the deep trough west of Kyushu.

Although various circulations have been suggested, there are no comprehensive and reliable current fields for the ECS denoting current direction and speed, because of shortage of direct current measurements. Tracking of cost-effective drifters is one of the best ways to observe ocean current. Therefore, we conducted an extensive drifter experiment in the eastern ECS during the Coastal Ocean Process Experiment of East China Sea (COPEX-ECS) in 1991~1996. In this study, we present the mean surface current field of the eastern ECS, using all drifter data collected through the COPEX-ECS in 1991~1996. Seasonal patterns of the current field are also constructed from the same drifter data file.

DRIFTER EXPERIMENT

Fifty eight satellite-tracked drifters were released at different times during 1991~1996. The number of drifters deployed each year was 3 in 1991, 7 in 1992, 5 in 1993, 13 in 1994, 14 in 1995, and 16 in 1996. Most of the drifters were released on the outer shelf of the eastern ECS deeper than 100 m, and on the

Table 1. Information on satellite-tracked drifter experiments for 1991~1996

Float number	Date Deployed	Releasing Point North Latitude	Releasing Point Float Longitude	Wast depth, m	Center of drogue, m
9728	July 17, 1991	32°	127°	124	15
9729	July 17, 1991	32°	128°	166	15
9727	July 17, 1991	32°	129°	821	15
2031	Apr. 17, 1992	32° 10'	127°	112	15
2032	Apr. 17, 1992	32° 10'	128°	143	15
2033	Apr. 17, 1992	32° 10'	129°	466	15
11010	Nov. 18, 1992	31°	125° 30'	63	15
11013	Nov. 18, 1992	31°	126° 20'	81	15
11012	Nov. 18, 1992	31°	127° 10'	110	15
11011	Nov. 18, 1992	31°	128°	210	15
09729	Dec. 9, 1993	30°	126° 46'	100	15
03157	Dec. 9, 1993	29° 48'	127° 18'	126	45
09731	Dec. 9, 1993	29° 45'	127° 26'	200	15
09728	Dec. 12, 1993	32° 30'	126° 45'	115	15
09727	Dec. 12, 1993	33° 20'	125° 30'	88	15
23019	Aug. 31, 1994	30° 51'	127°	101	30
23024	Aug. 31, 1994	30° 40'	127° 50'	164	30
23020	Sept. 3, 1994	29° 20'	127° 13'	180	50
23017	Sept. 3, 1994	29° 19'	127° 16'	220	50
21581	Sept. 3, 1994	29° 19'	127° 18'	260	15
23016	Sept. 3, 1994	29° 18'	127° 21'	353	50
23022	Sept. 3, 1994	29° 18'	125° 15'	92	15
23025	Sept. 3, 1994	29° 30'	126° 30'	104	15
21582	Sept. 3, 1994	29° 22'	127°	124	30
23018	Sept. 5, 1994	32° 30'	126° 02'	100	15
23023	Sept. 5, 1994	33°	127° 20'	127	15
09761	Oct. 6, 1994	33° 57'	125° 07'	94	50
23021	Oct. 6, 1994	32° 57'	123° 46'	41	15
21584	Apr. 27, 1995	31° 30'	128°	150	15
09728	Apr. 27, 1995	31° 30'	127° 30'	131	15
09730	Apr. 30, 1995	30° 12'	127° 45'	250	50
03156	Apr. 30, 1995	30° 23'	127°	103	15
09731	May 3, 1995	29° 38'	126°	97	15
21581	May 3, 1995	29° 26'	126° 45'	110	15
03157	May 3, 1995	29° 23'	126° 59'	122	50
21579	May 3, 1995	29° 19'	127° 15'	204	15
21582	May 3, 1995	29° 18'	127° 19'	282	15
21580	Sept. 27, 1995	33° 12'	125° 6'	85	15
03548	Dec. 3, 1995	31° 30'	126° 30'	89	15
03580	Dec. 5, 1995	30° 54'	128° 01'	307	50
03531	Dec. 5, 1995	30° 55'	127° 57'	180	15
08041	Dec. 5, 1995	31°	127° 30'	124	50
27262	May 28, 1996	28° 26'	126° 40'	170	50
27263	May 28, 1996	28° 42'	126° 20'	119	50
27264	May 28, 1996	28° 50'	126° 10'	112	15
27265	May 28, 1996	28° 10'	126° 50'	260	15
27266	May 28, 1996	28° 34'	126° 30'	136	15
27267	Oct. 5, 1996	33° 45.14'	126° .13'	87	15
27268	Oct. 5, 1996	33° 44.13'	124° 50.12'	82	15
27269	Oct. 7, 1996	29° 49.61'	123° 40.87'	74	15
27270	Oct. 9, 1996	30° 50.14'	125° 9.78'	58	15
27513	Oct. 9, 1996	30° 30.01'	126° 29.81'	87	50
27271	Oct. 9, 1996	30° 15.00'	127° 29.90'	130	15
27272	Oct. 11, 1996	29° 18.87'	125° 15.12'	90	15
27514	Oct. 11, 1996	29° 15.03'	125° 30.03'	89	50
27274	Oct. 11, 1996	29° 3.98'	126° 14.86'	103	15
27515	Oct. 11, 1996	29° 2.16'	126° 21.64'	110	50
27273	Oct. 12, 1996	33° 51.59'	128° 9.70'	100	15

continental slope. The others were released on the middle shelf 70~100 m deep, and in the northern ECS. Table 1 presents information on the drifter experiment, including date and location of releases,

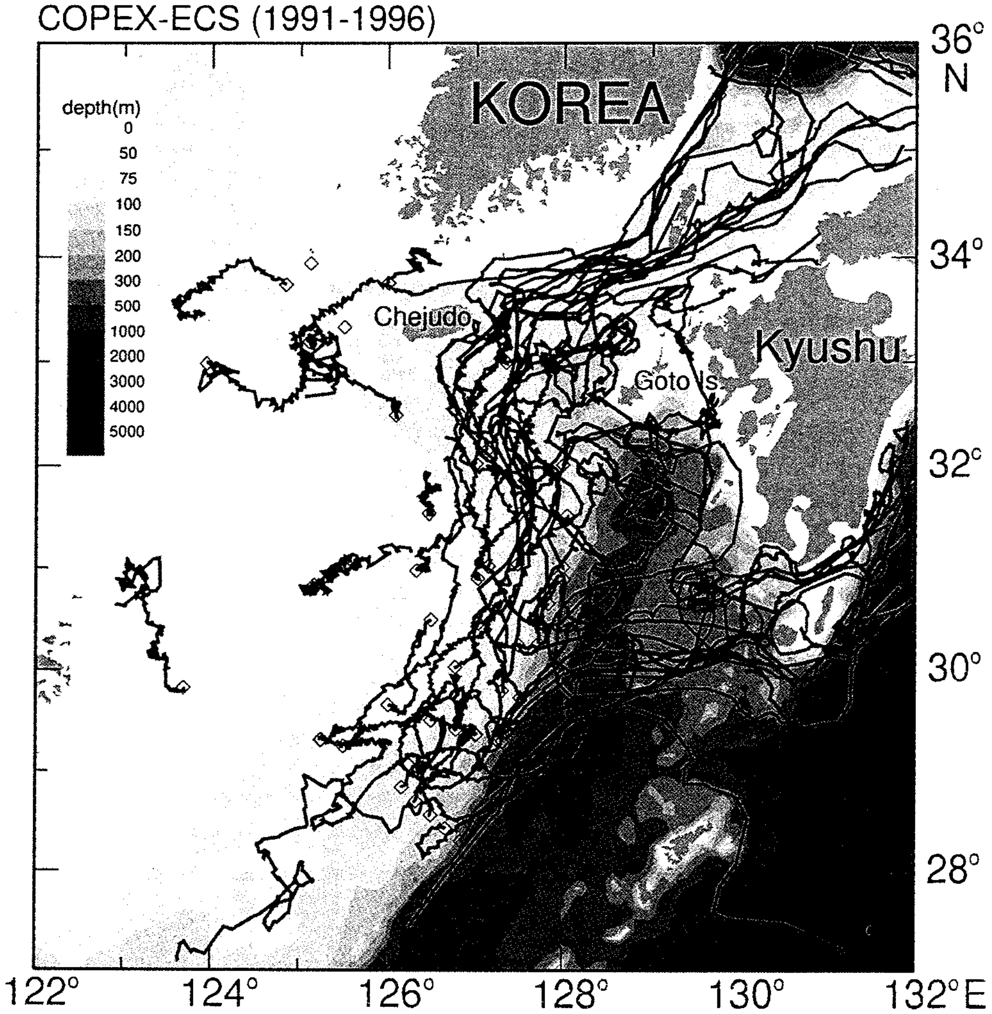

Fig. 1. A composite map of all trajectories of satellite-tracked drifters deployed in the East China Sea by KORDI during 1991~1996. Symbol '◇' denotes release points. Red and blue lines correspond respectively drifters drogued at 15 m and at deeper depths of 30 m and 50 m.

water depth, and drogue depth.

The drifters used for the study were of the World Ocean Circulation Experiment/Surface Velocity Programme (WOCE/SVP) type, equipped with a thermistor for sea surface temperature and holey sock drogue 644 cm in length. Of 58 drifters, 41 sets were drogued at 15 m below sea surface and the others at deeper depths of 30 m or 50 m. Drifters which were released in 1991 and 1992 transmitted positions for 8 hours a day, while drifters released in 1993~1996 were manufactured to transmit positions in dual cycles, for 24 hours a day during the first 30 days after launch, and for 8 hours a day during the remaining lifetime. The reason for the dual transmission cycles was to observe drifter positions more frequently in the study area.

SURFACE CURRENT FIELD

A composite map of all trajectories positioned during 1991~1996 is presented in Fig. 1. Trajectories of the 41 standard drifters with a drogue at 15 m are marked in red, and those of drifters drogued at deeper depths are marked in blue. Trajectories are distributed in a southwest-northeast direction on the continental slope, and in a west-east direction in the deep Okinawa Trough west of the Tokara Strait. This shows that the northeastward-flowing Kuroshio main stream along the continental slope turns eastward toward the Tokara Strait. Trajectories in the northern cul-de-sac of the trough west of Kyushu result from clockwise turning of drifters around the trough (Lie and Cho, 1994). South-north trajectories on the outer shelf deeper than 100 m between Cheju Island and the Kuroshio, and southwest-northeast trajectories in the Korea Strait show the main path of a branch current of the Kuroshio. This branch current will be discussed in detail later. The trajectories on the shelf are clearly indicative of a sharp change in direction of the branch current when it crosses a line connecting Cheju Island, Korea and Goto Islands, Japan (hereafter, this line is called the 'Cheju-do line').

Fig. 2 shows the distribution of data in 20'-by-20' boxes. Numerals on the upper left and lower right sides of each box correspond, respectively, to number of drifters entering the box and the length of position data in days. In an area where strong current exists, the data length is short relative to a large number of drifters, and vice versa. Fig. 3 presents box-averaged current vectors which are estimated from the trajectories in Fig. 1. The Kuroshio main stream is identified by strong current vectors at a speed of about 1 m/s, faster than the estimate based on GEK data (Qiu and Imasato, 1990). The northeast-flowing Kuroshio along the continental slope of the ECS turns eastward toward the Tokara Strait after leaving the slope. The eastward turning of the Kuroshio is clearly seen in the trajectories. In the neighbourhood of the turning point of the Kuroshio, the Kuroshio is separated into the main stream and a branch current (Lie *et al.*, 1995). The branch current at a speed of 10~35 cm/s flows northward both on the outer shelf deeper than 100 m and on the western flank of the trough west of Kyushu. Southwest of the Goto Islands, it splits into a northward-continuing flow and an eastward-turning flow along the shelf edge, as already pointed out by Lie and Cho (1994). The eastward flow turns back to the south along the west coast of Kyushu. Therefore, an anticyclonic circulation is formed in the northern trough. This anticyclonic circulation is also seen on the current field constructed from GEK data (Hsueh *et al.*, 1996). The northward-continuing flow turns sharply to the northeast after passing the Cheju-do line.

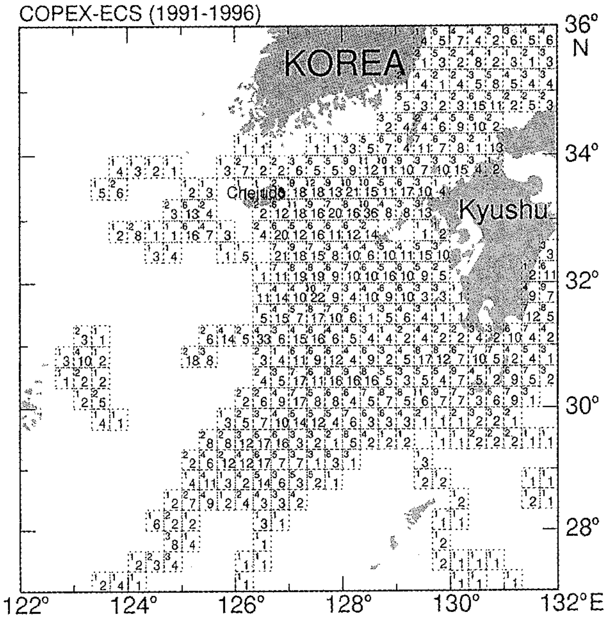

Fig. 2. Data number of drifters deployed during 1991~1996 by KORDI. Numerals on the upper left and lower right corners of each 20-minute-by-20-minute box correspond respectively to number of drifters entering the box and the length of position data in days.

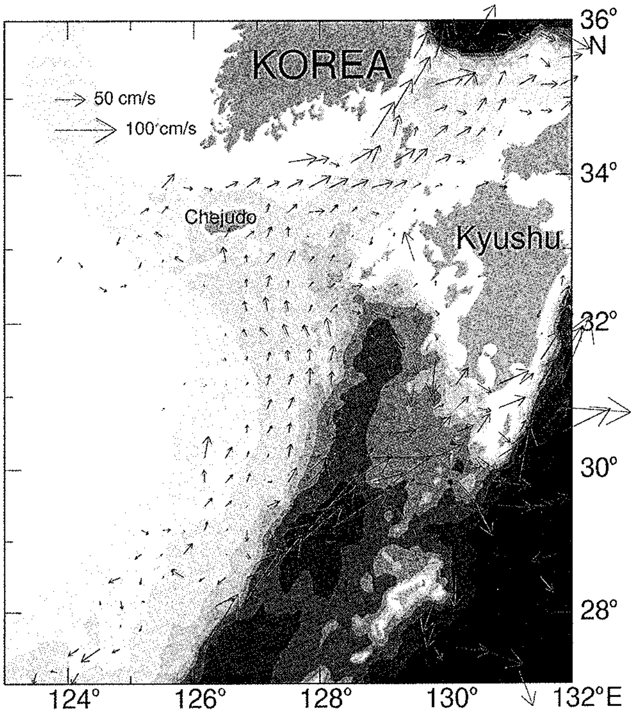

Fig. 3. 20'-by-20' box-averaged surface current vectors derived from the composite map of trajectories in Fig. 1.

The northeast flow maintains its direction almost along isobaths between Cheju Island and Tsushima Island. It is interesting to see the trajectory of a drifter which was deployed southwest of Cheju Island. The drifter turned around Cheju Island and moved into the Korea Strait after passing through the Cheju Strait in autumn. The existence of the eastward channel flow in the Cheju Strait was detected by drifter trajectories in summer (Beardsley *et al.*, 1992) and by moored current data in spring (Chang *et al.*, 1995). The eastward channel

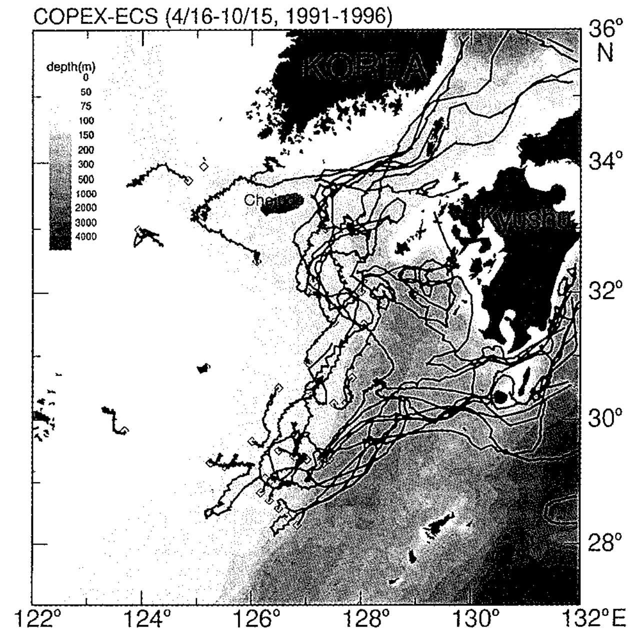

Fig. 4. A composite map of all trajectories of satellite-tracked drifters observed in the warm season (mid-April through mid-October) in the East China Sea by KORDI during 1991~1996. Symbol '◇' denotes release points.

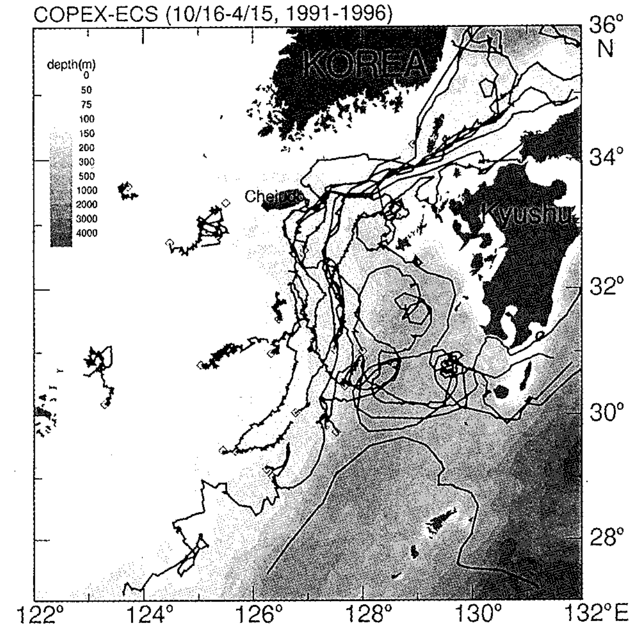

Fig. 5. A composite map of all trajectories of satellite-tracked drifters observed in the cold season (mid-October through mid-April) in the East China Sea by KORDI during 1991~1996. Symbol '◇' denotes release points.

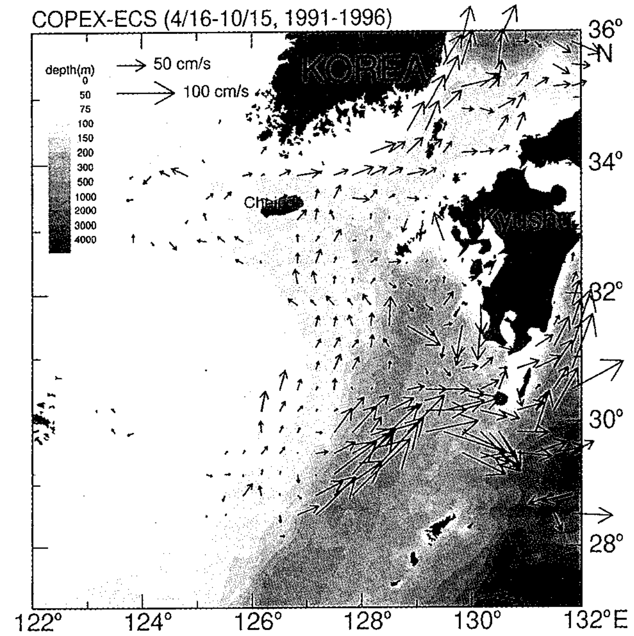

Fig. 6. 20'-by-20' box-averaged surface current vectors for the warm season, derived from the composite map of Fig. 4.

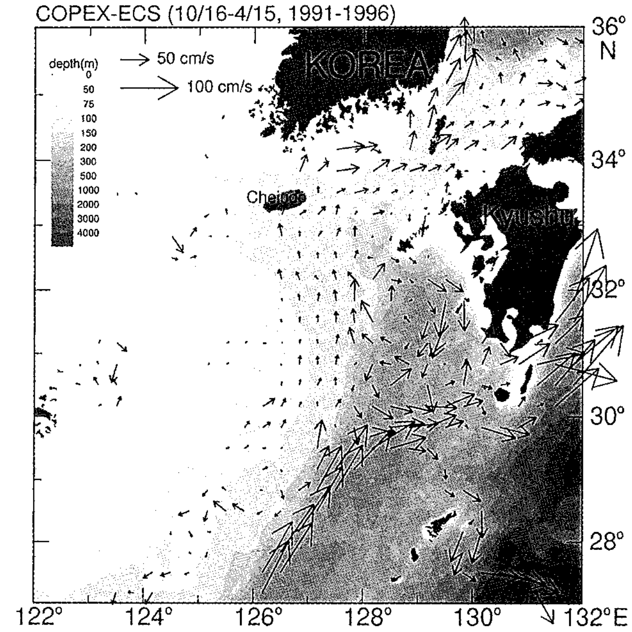

Fig. 7. 20'-by-20' box-averaged surface current vectors for the cold season, derived from the composite map of Fig. 5.

flow eventually joins the northeast extension of the branch current in the eastern part of the Cheju Strait. Consequently, the northeastward flow in the Korea Strait is concluded to consist of the northeast continuation of the branch current and the eastward channel flow passing through the Cheju Strait. The flow in the western channel, with a speed of more than 50 cm/s, is much stronger than that in the eastern channel. The eastward channel flow in the Cheju Strait contributes to an increase in flow speed in the western channel of the Korea Strait.

SEASONAL VARIATION OF SURFACE CURRENTS

The water column on the ECS shelf is strongly stratified in the warm season, but well mixed or weakly stratified in the cold season (e.g., Lie and Cho, 1994). Surface wind fields are also very seasonal: strong northerly wind in the cold season, but weaker southerly wind in the warm season (Lie *et al.*, 1994; Han *et al.*, 1995). Therefore, it is necessary to examine seasonal patterns of the surface current. Trajectories and box-averaged current vectors were mapped for both the warm season (mid-April through mid-October) and the cold season (mid-October through mid-April).

Spaghetti diagrams of trajectories and box-averaged current vectors for the two seasons are presented in Figs. 4-7. The Kuroshio path in the cold season is not clearly seen in Figs. 5 and 7, since only a small number of drifters were deployed across the continental slope. However, WOCE drifter data clearly show the eastward turning of the Kuroshio west of the Tokara Strait (Lie *et al.*, 1995). The flow patterns for the two seasons resemble each other, both showing the eastward Kuroshio west of the Tokara Strait, the northward branch current on the outer shelf west of Kyushu, and the northeast continuation of the branch current in the Korea Strait. However, smaller scale structures are slightly different, especially on the shelf.

Trajectories on the outer shelf in the cold season are relatively straight in the north-south direction, while those in the warm season are bent (Figs. 4 and 5). Furthermore, the northward current in the cold season is weaker than that in the warm season (Figs. 6 and 7). Reasons for the bent trajectories are not clear, although the trajectories are expected to be associated with the meander of the Kuroshio front (e.g., Qiu *et al.*, 1990) and an outward extension of fresh coastal water in summer, mostly the Changjiang diluted water (Lie and Cho, 1994). Drifters which were deployed in the area south of the Cheju-do line, approached closer to the southern Korean coast in the warm season than those deployed in the cold season, but drifters deployed in the cold season shifted toward the northwestern Kyushu coast. In the cold season, a surface-to-bottom thermohaline front runs almost along a line between Cheju Island and the southern tip of Tsushima Island, as pointed out by Lie and Cho (1994). Sea surface temperature estimated from an infrared image of NOAA-14 on February 22, 1997 (Fig. 8) clearly shows the existence of a strong thermal front along the southern Korean coast in winter. Drifters coming up from the south hardly cross the front. On the other hand, in the warm season, the thermohaline front is broken and the water column in the Korea Strait is vertically stratified. The surface layer in the southern Korean coastal area is largely filled in with fresh coastal water. Therefore, drifters which were deployed south of Cheju Island approached a little closer to the Korean coast in the warm season than those deployed in the cold season. This implies a shift of the northeast branch current to the Korean coast in the Korea Strait in the warm season.

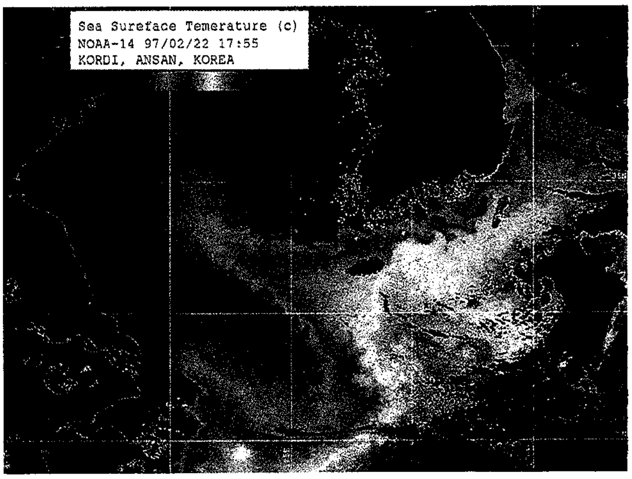

Fig. 8. Sea surface temperature estimated from an infrared image of NOAA-14 on February 22, 1997.

NEW TERMINOLOGY OF KUROSHIO BRANCH CURRENT

The term 'Tsushima Current' (TC) has been confusingly used in three different senses: (1) a branch current of the Kuroshio west of Kyushu (Uda, 1934; Nitani, 1972); (2) a northeastward continuation over the ECS shelf of the outflow through the Taiwan Strait (Beardsley *et al.*, 1985; Fang *et al.*, 1991); and (3) a northeastward channel flow passing through the Korea Strait (e.g., Yi, 1966; Kawabe, 1982). Therefore, the terminology should be more precisely defined to avoid such confusion. We suggest that the use of the term 'TC' be limited to the northeast channel flow in the Korea Strait, since the word 'Tsushima' is the geographical name of the Tsushima Island, located in the Korea Strait. In this sense, 'TC' may designate the channel flow in the Korea Strait which transports two different water masses of saline Kuroshio water and fresher coastal water to the East Sea. Therefore, the northward branch current on the outer shelf south of Cheju Island needs to be newly named to differentiate it from the TC in the Korea Strait. 'Kyushu Warm Current', 'Cheju Warm Current', 'East China Sea Warm Current', and 'Kuroshio Branch Current' may be candidate names for the branch current. Of the four candidates, 'Kuroshio Branch Current' seems to be the most proper name, since it describes the branching of the Kuroshio more explicitly than the other three. It may be objected that the Kuroshio has another branch current northeast of Taiwan. However, the latter has been known to the oceanographic community as the 'Taiwan Warm Current', rather than the 'Kuroshio Branch Current'.

CONCLUSIONS

The surface current fields in the eastern ECS were constructed, based on trajectories of numerous drifters deployed during 1991~1996. They present clearly for the first time the surface current pattern which consists of: (1) the eastward turning of the Kuroshio; (2) a northward branch current on the outer shelf; (3) an anticyclonic circulation in the northern Okinawa Trough west of Kyushu; and (4) a northeastward channel flow in the Korea Strait. The basic pattern changes slightly from the warm season to the cold season.

We suggest that the use of the term 'Tsushima Current' be limited to the northeast channel flow in the Korea Strait. The new term 'Kuroshio Branch Current' is suggested for the northward branch current on the outer shelf south of Cheju-do, since it describes the branching of the Kuroshio more explicitly than the Tsushima Current.

Uda (1934) and Nitani (1972) suggested that the Yellow Sea Warm Current (YSWC) is branched from the northward branch current southeast of Cheju Island. However, the drifter experiment does not indicate its branching there southeast of Cheju Island. The origin and detailed structure of the YSWC should be investigated in future, which will require comprehensive current measurements in the northwestern ECS.

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