A Circulation Study of the East Sea Using Satellite-Tracked Drifters
1 : Tsushima Current

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Satellite-tracked drifters deployed in the East Sea since 1991 are used to study the Tsushima Current (TC). It is found that the TC is a steady current with a mean speed of 10 cm/s before it enters the East Sea. Only during the summer, the TC flows along Honshu Island with a mean speed of 30~40 cm/s and then exits through the Tsugaru Strait. In fall and winter, the TC does not follow the coast along Honshu Island but it enters into the interior of the East Sea before it reaches the Tsugaru Strait. The water that passes the West Channel of the Korea Strait mostly comes from the western East China Sea and spreads into the interior of the East Sea. It also forms the large eddies in the southern East Sea. The outflow through the Tsugaru Strait comes from the interior of the East Sea in all seasons except summer. The mean speed of the Tsugaru Strait outflow is about 60 cm/s. The largest current variability is found in the eastern central area of the East Sea, south of sub-polar front.

Key words : tsushima warm current

Introduction

The studies of the East Sea circulation had been based on routine hydrographic surveys or repeated direct current measurements by ship-mounted Acoustic Doppler Current Profiler (ADCP) along selected transects (Nitani, 1972; Katoh, 1994). According to these studies, the Tsushima Current (TC) is a persistent current that flows along Honshu Island and exits through the Tsugaru Strait (Ishii and Michida, 1996). After the TC exits the Korea Strait, it branches itself to the East Korea Warm Current (EKWC) that passes along the eastern Korean coast, and to the main TC that flows along the western Japanese coast as shown in Figure 1. Since most of the current measurements in previous studies are from the Eulerian current measurements (for example, GEK, ship-mounted ADCP and moored current meter),. the synoptic features and time variations of the circulation path, which can be studied mostly by the Lagrangian current measurements, are not well established.

WOCE/SVP (World Ocean Circulation Experiment/ Surface Velocity Program) ARGOS-tracked drifters (Sybrandy et al., 1991) have been used to study the synoptic features of the circulation in the East Sea since 1990. These drifters were first deployed by the Korea Ocean Research and Development Institute (KORDI), subsequently by the Department of Marine Sciences of Pusan National University and by the Japan Hydrographic Office (Ishii and Michida, 1996). During this time, the US (United States of America) Navy also released air-deployed drogueless surface drifters in the East Sea.

The main objective of this study is to analyze 34 drifter tracks (Section 2) and to show circulation patterns of the TC by analyzing individual drifter tracks (Section 3). We present the mean and variability of current from the Korea Strait to the Tsugaru Strait by calculating ensemble averages and variabilities on a $1°\times1°$ geographical grid (Section 4).

Drifter and Data Processing

Water following characteristics and the downwind slip of WOCE/SVP drifters are analyzed by Niiler et al. (1995) and the configuration and schematic diagram of SVP drifter are described by Sybrandy and Niiler (1991) and by Poulain et al. (1996). The transmitter of the WOCE/SVP drifter has duty cycle of 8 hours of transmission time and 16 hours of silent time in a 24 hour period to save the battery and ARGOS service

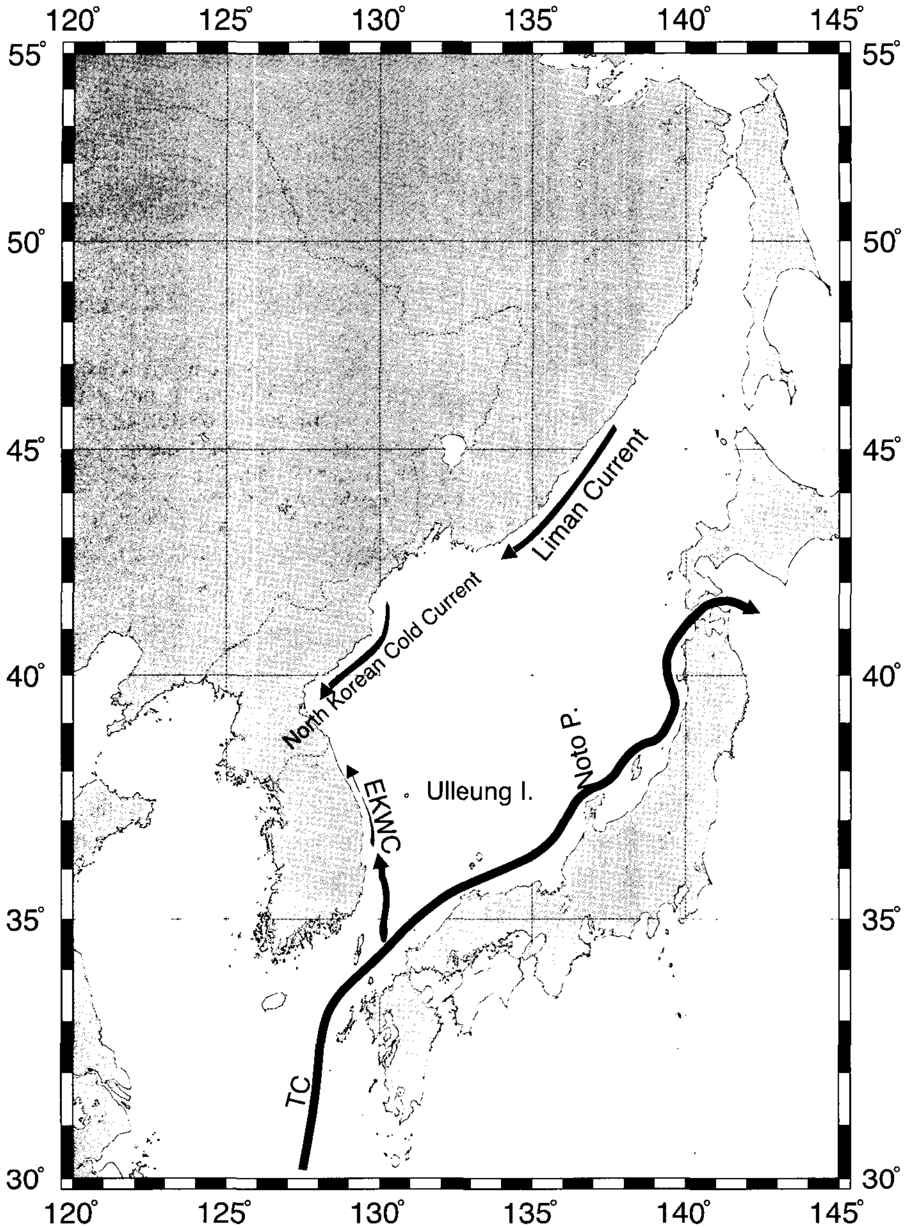

Fig. 1. A surface circulation pattern in the East Sea after Uda (1935).

fee. The SVP drifters have a SST sensor with an accuracy of ± 0.1℃ ranging from −5° to 40℃. They also have surface float submergence sensors to indicate attachment of the drogue.

ARGOS satellites report drifter positions two to three times per day during the 8 hours of transmitter operation. The raw positional data from Service ARGOS are despiked and interpolated to a 2-hour interval using a kriging technique (Hansen and Poulain, 1996). The 2-hour interpolated positions and velocities are averaged daily to eliminate the tidal and inertial currents, which can be as large as the sub-tidal current in the study area.

All drifter tracks used in this study are shown in Figure 2. The US Navy drifter tracks are colored white and the SVP drifter tracks are colored black. A total of 29 WOCE/SVP standard drifters and 5 US Navy surface drifters are used in this study. The water following characteristics of WOCE/SVP drifters differ from the

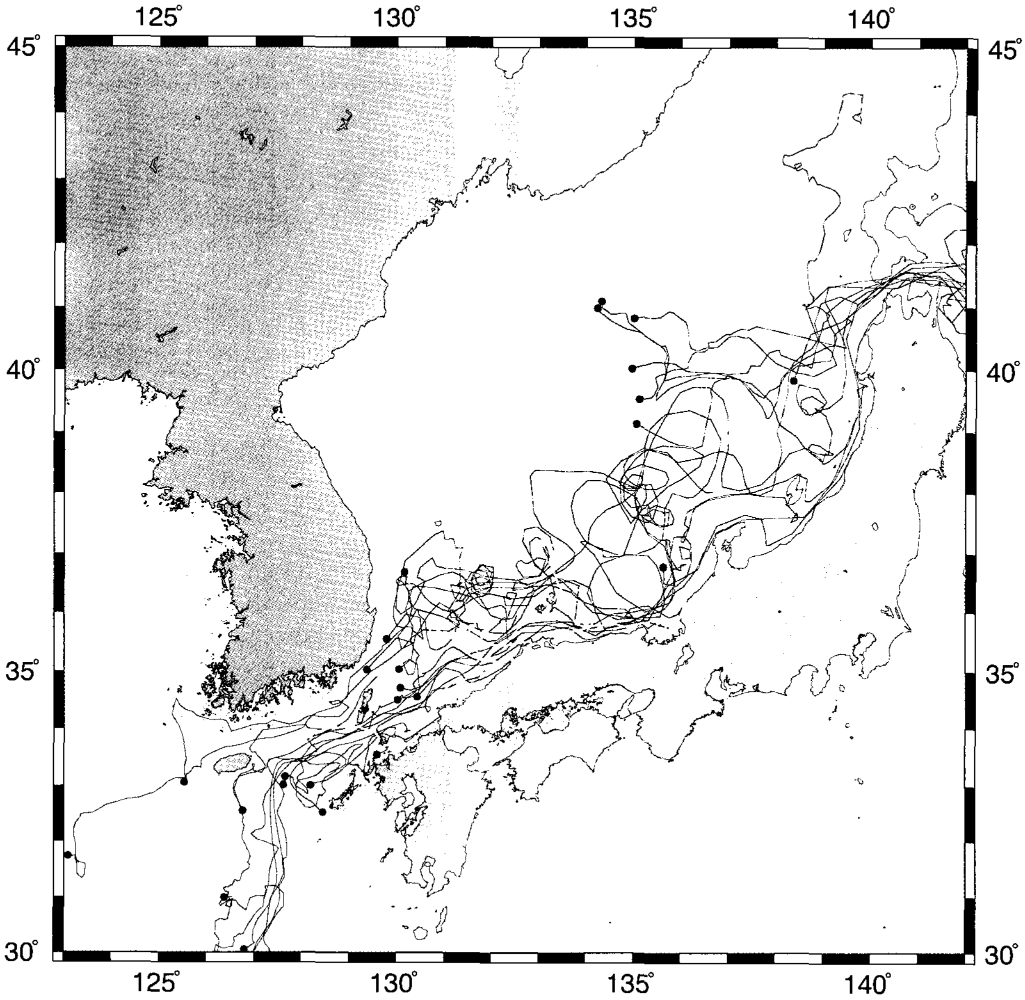

Fig. 2. Trajectories of US Navy (white) drifters and of WOCE/SVP (black) drifters used in this study.

US Navy drifters that are affected by wind, causing them to behave like undrogued SVP drifters. Thus, the wind-correction for US Navy drifters with wind is performed. The correction formula used by Poulain et al. (1996) is

$$U_c = aU_{NAVY} + bW, \quad (1)$$

where U_{NAVY} is the surface velocity measured by the US Navy drifter, U_C is the corrected velocity to 15 m depth and W is the interpolated wind speed at the US NAVY drifter position from the ECMWF (European Center for Medium Range Weather Forcasts) wind field. Complex coefficients a and b are determined from least square regression with pairs of US NAVY and SVP drifters separated by less than 20 km within same day.

Results

1. The TC at the Korea Strait

The Korea Strait has two channels - the East Channel and the West Channel - separated by Tsushima Island which is located at the center of the Korea Strait. Nitani (1972) analyzed the historical hydrographic data of horizontal temperature and salinity and constructed the circulation pattern the East Sea and the East China Sea. According to his circulation pattern, the flow in the East Channel is the TC which is branched off from the Kuroshio and the flow in the West Channel starts from the coastal sea between Korea and Cheju Island. Lie and Cho (1994) deployed several drifters in the shelf area

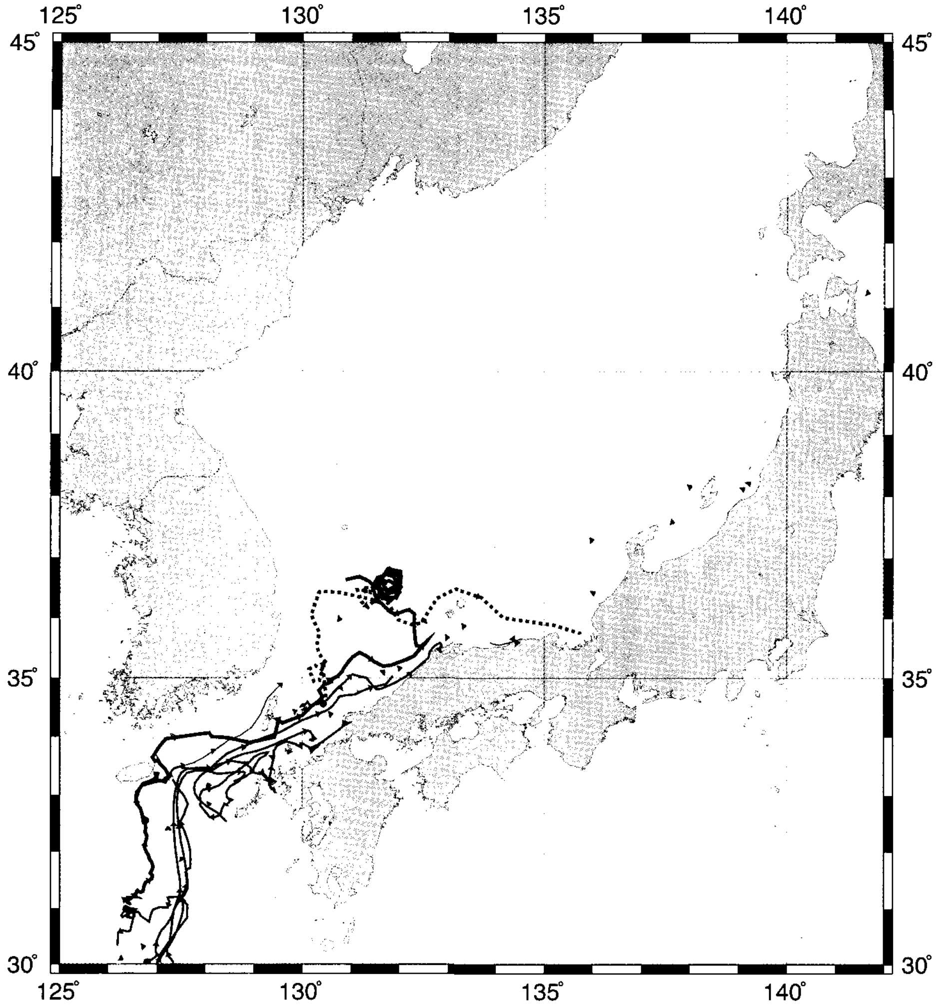

Fig. 3. Selected drifter trajectories that pass the East Channel of the Korea Strait. The tracks are color coded with respect to season: summer (white) and other seasons (black). The black arrow heads are marked at every ten days.

west of Kyushu Island and their drifter tracks showed the main route of a northward branch of the Kuroshio. Figure 3 reproduces their drifter tracks with additional drifters that were released in the East Channel. To show the seasonal changes of the flow, the tracks of summer months between June and August are colored white and that of other months are colored black. Most of the drifters, which were released in the continental shelf area of the eastern East China Sea, pass the East Channel. After they pass the East Channel, they follow the coast of Honshu Island during summer, but they are landed on the coast of Honshu Island during fall and winter. One drifter (dotted black track), which was released in September at the center of the East Channel, enters the southern East Sea and catches a small eddy (about 50 km) that is caught by another drifter (solid black track) in spring.

The drifters that pass the West Channel and that are released on the continental shelf near the eastern coast of South Korea are shown in Figure 4. All drifters enter into the Ulleung Basin or the Yamato Basin. Once they are in the interior of the East Sea, they form large eddies of diameter over 200 km as observed by Lie et al. (1995). One drifter that passes the West Channel in

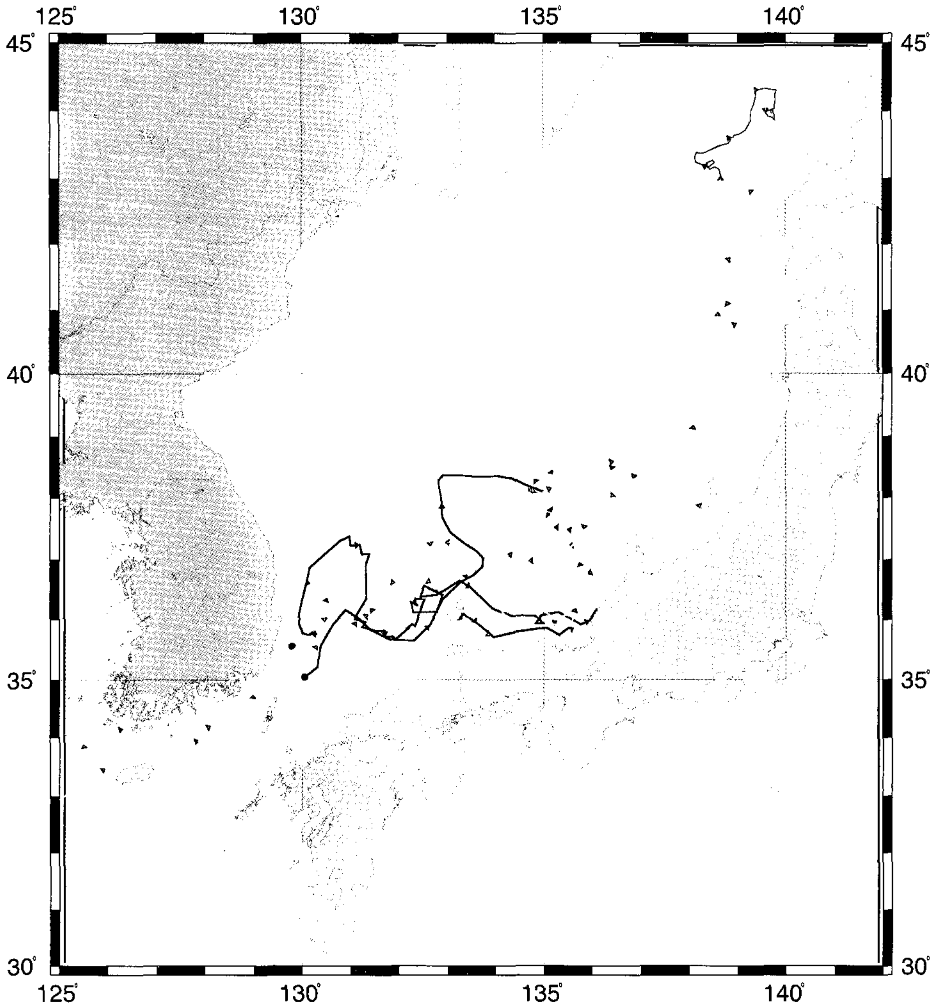

Fig. 4. Selected drifter trajectories that pass the West Channel of the Korea Strait. The tracks are color coded with respect to season: summer (white) and other seasons (black). The black arrow heads are marked at every ten days.

September go far north to the sea near Sapporo Island. Even in summer months, drifters that pass the West Channel do not join in the flow along Honshu Island.

Based on hydrographic data and on the repeated ADCP surveys, Kato (1993) suggested several current paths in the area north of the Korea Strait. All of his circulation patterns have separate paths for the flows in the East Channel and in the West Channel. Our drifter observations do not show the branching of the TC in the southern East Sea that was studied by Kim and Legeckis (1986) using NOAA satellite AVHRR images in the area north of the Korea Strait. Although Kato (1994) suggests five circulation patterns, only one of his pattern (pattern C in Figure 13 of Kato, 1994) is similar to our observations.

Lee et al. (1998) shows that the East China Sea water mixed with the Changjiang River discharge enters through the West Channel in the months between July and September. The fresh water fills the surface layer of most of the southern East Sea. It is possible that this fresh water does not mix well with the warm and salty water from the East Channel in the summer season. This kind of circulation pattern is hard to study without using particle following instruments like a SVP drifter.

2. The TC along Honshu Island

Figure 5 displays the drifter tracks that resemble the historical concept of main branch of the TC. All drifters do not depart from the continental shelf except one that is originated from the fresh water of the western East China Sea. Two drifters pass through the Tsugaru Strait in August. The TC along Honshu Island is strong (30~40 cm/s) compared to the inflow speed of 10 cm/s at the East Channel.

Seven drifters follow the main path of the TC during summer months as shown in Figure 1. The AVHRR SST images in July (Figure 6.a) and in May (Figure 6.b) are presented to show the dramatic seasonal change of surface temperature in the East Sea. The sub-polar front is pushed north up to the area east of Sapporo Island in July and the warm water enters the Korea Strait. This warm surface water occupies entire East Sea. Figure 6.b shows well developed sub-polar front from 38°N near the eastern coast of Korea to the Tsugaru Strait and the spreading of warm water into the interior of the East Sea. This seasonal change of the sub-polar frontal path may force the warm water from the Korea Strait to enter into the interior of the East Sea when the sub-polar front forms in the south of the Tsugaru Strait. Since there are not enough drifter observations for statistically significant analysis of the TC, it is too early to conclude that the historical concept of the TC is valid only during summer.

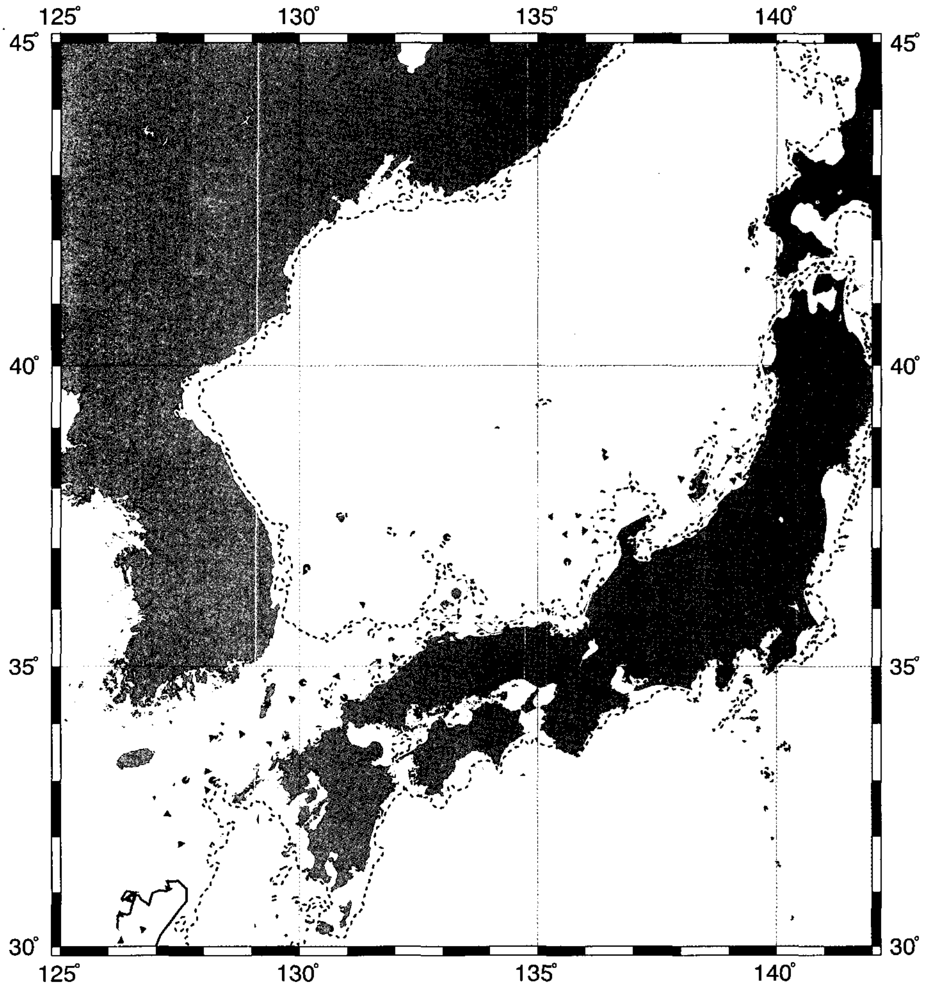

Fig. 5. Selected drifter trajectories that follow the historical TC path. The black arrow heads are marked at every ten days.

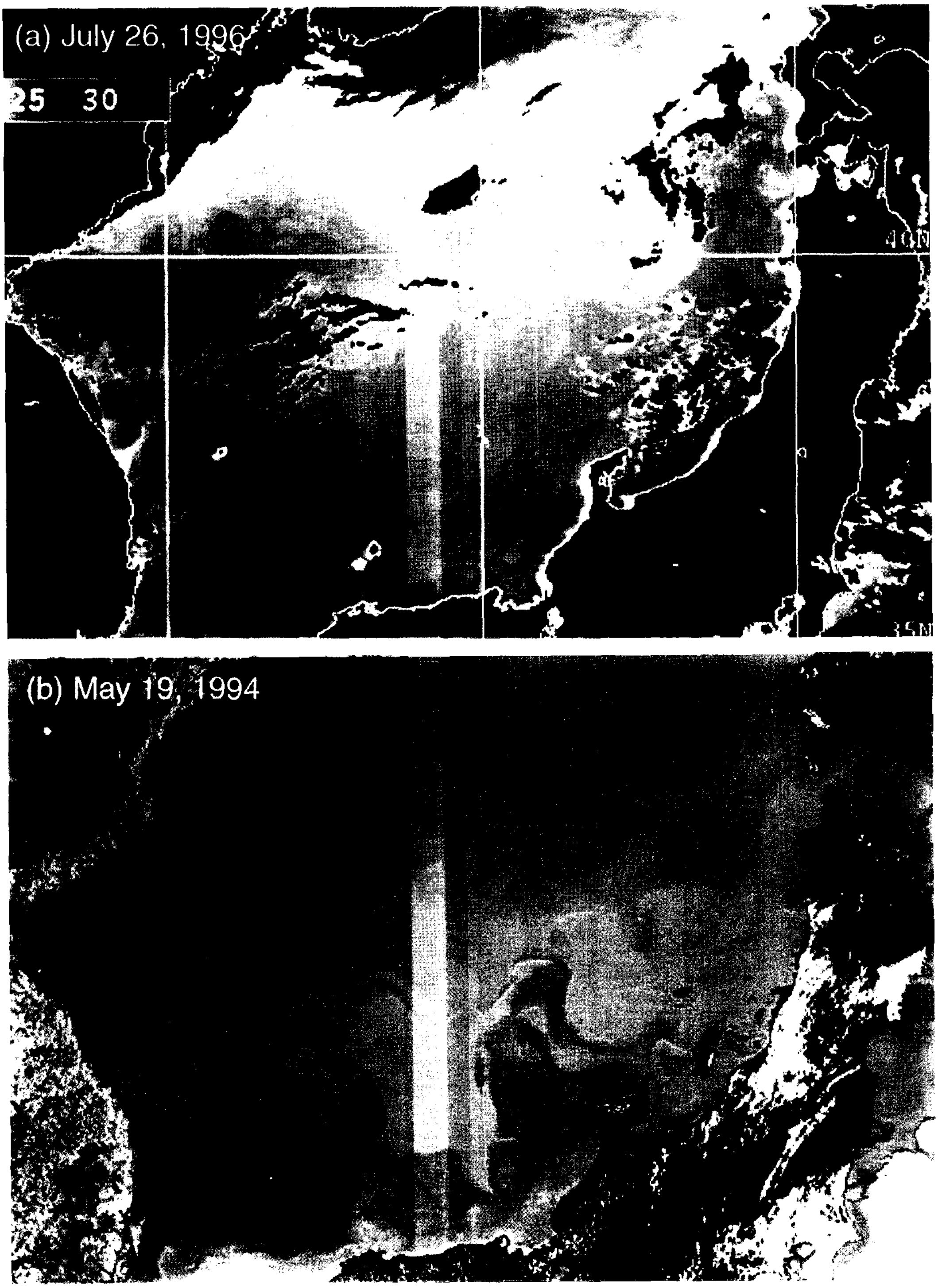

Fig. 6. Satellite AVHRR sea surface temperature images (a) on July 26, 1996 and (b) on October, 1994.

3. Flow at the Tsugaru Strait

Figure 7 shows the drifters that pass through the Tsugaru Strait. All drifters come from the interior of the East Sea and pass the strait in fall or winter. Most of the drifters follow the sub-polar front. One drifter shown in Figure 4 crosses the sub-polar front in fall of

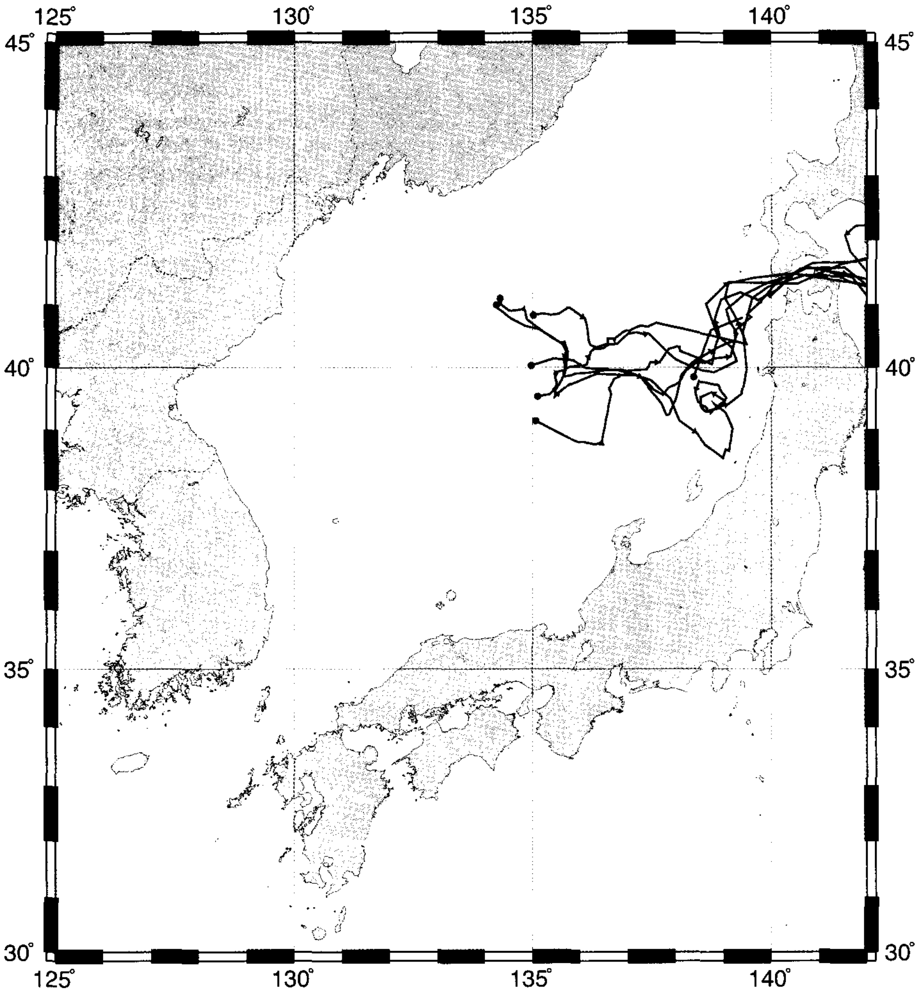

Fig. 7. Selected drifter trajectories that pass the Tsugaru Strait. The tracks are color coded with respect to season: summer (white) and other seasons (black).

1987 and reaches 45°N near Sapporo Island. More studies in this area are needed to determine when and how the water particles cross the sub-polar front. A detailed study of the characteristics of the current along the sub-polar front is in preparation, thus, the description of the circulation along the sub-polar front is deferred to that paper.

Seasonal variation and variability of the current

Figure 8 shows 1°×1° grid average currents in summer (white arrows) and in other seasons (black arrows). The larger seasonal changes are in the continental shelf area west of Honshu Island. The mean current speed during summer near the coast of Honshu Island is about 2~3 times stronger than that of other seasons.

The mean current direction also changes from an along-shore direction during summer to a cross-shore direction during other seasons. The mean current at the Korea Strait is 20 cm/s in the West Channel and 10 cm/s in the East Channel. The seasonal change of the East Channel is small compared to that of the West Channel. Isobe et al. (1994) found a large seasonal change of the volume transport in the Korea Strait based on the ADCP

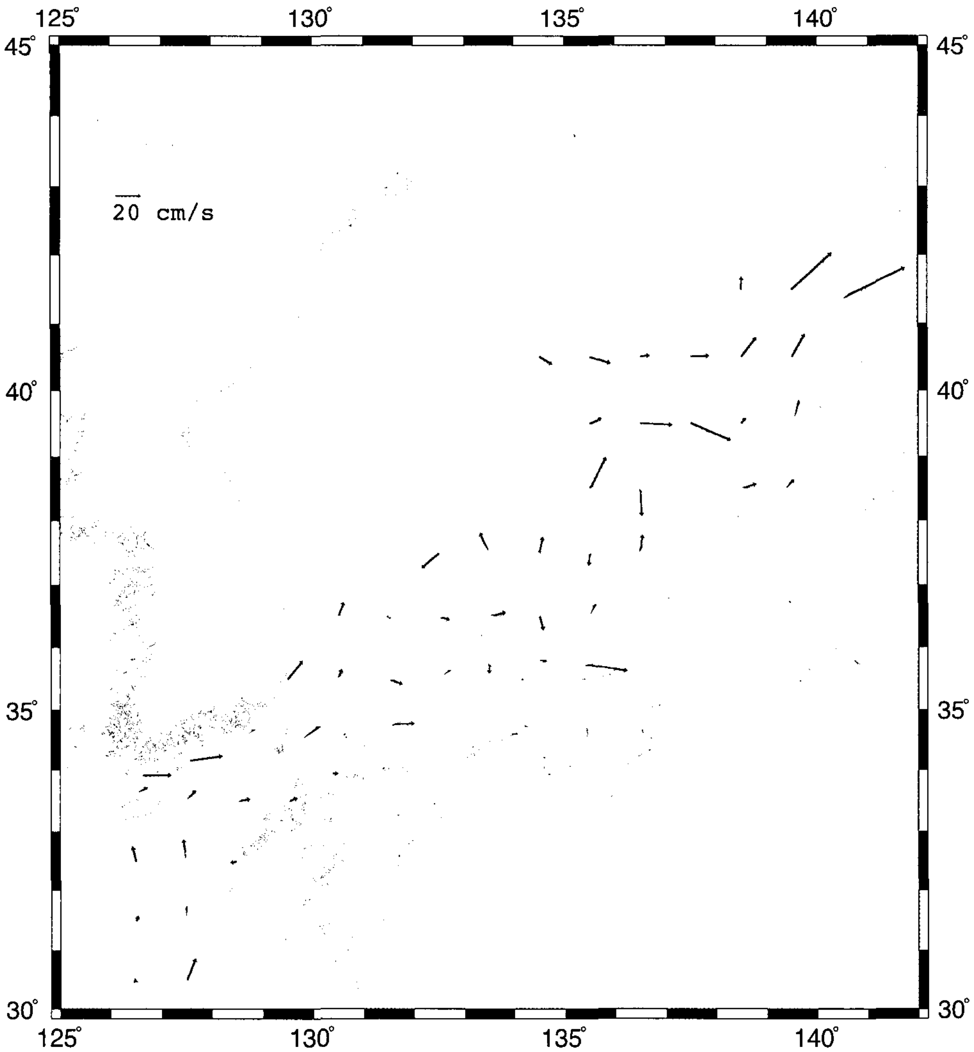

Fig. 8. Mean velocity vectors of summer (white) and of other seasons (black).

measurements but their along-cruise measurements by the ship mounted ADCP may not be the accurate estimate of the mean current because of the strong tidal and inertial current in the area.

The mean current along the sub-polar front is 30~40 cm/s and the mean current at the Tsugaru Strait is over 50 cm/s with seasonal changes of both current speed and current direction. The large seasonal changes also occur in the Yamato Basin and are due to large eddy activities in the area. The large current variability in the Yamato Basin is shown in Figure 9. The mean currents between 36°N and 37°N are small with large variances. The variances along the sub-polar front are also very large due to the seasonal change of the location of the front. One of the most remarkable result here is that the TC is relatively steady before it enters the East Sea; the variability of the TC in the Korea Strait and in the area west of Kyushu Island is very small compared to other seas around Korea.

Discussion and Summary

The calculation of the mean current along the TC path and the analysis of the drifter tracks spur the following questions: If the water of the TC does not mix with the water from the interior of the East Sea during the summer, how does the TC accelerate? Is seasonal

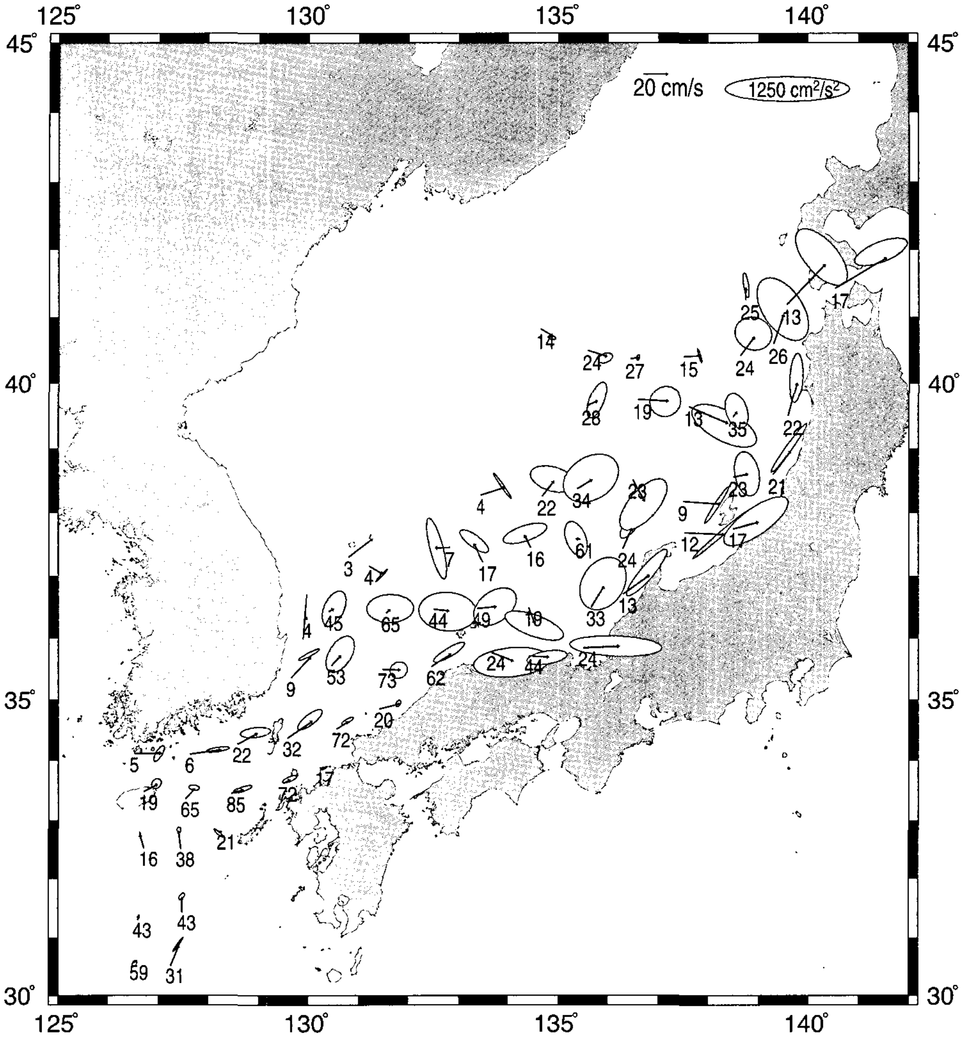

Fig. 9. Mean velocity vectors with principal variance ellipses. The numbers represent the number of daily observations in the 1°×1°grids.

change of wind or position of sub-polar front responsible for these seasonal circulation changes?

The monthly mean Special Sensor Microwave/Imager (SSM/I) winds (Atlas et al., 1996) averaged from 1988 to 1993 in the East Sea are presented in Figure 10. Winds in the East Sea have seasonal changes; strong north-westerly winds during the months between October and March, and weak south-westerly winds during the months between April and August. In September, the winds are transitional from typical summer winds to typical winter winds and they are north-easterly. The strong north-westerly winds during winter may push the coastal waters toward Honshu Island, thus the continuous TC path along Honshu Island may be disrupted.

In summary, the major portion of TC water enters the East Channel and flows along the coast of Honshu Island only during summer when the wind is weak south-westerly. During fall and winter, the TC enters the East Channel, but the strong north-westerly wind disrupt the continuous flow along Honshu Island. The TC in the East Channel is relatively steady all year long with an average speed of 10 cm/s and its variability is very small compared to other seas around Korea. The water that enters through the West Channel flows mostly into the interior of the East Sea and it forms large eddies. The

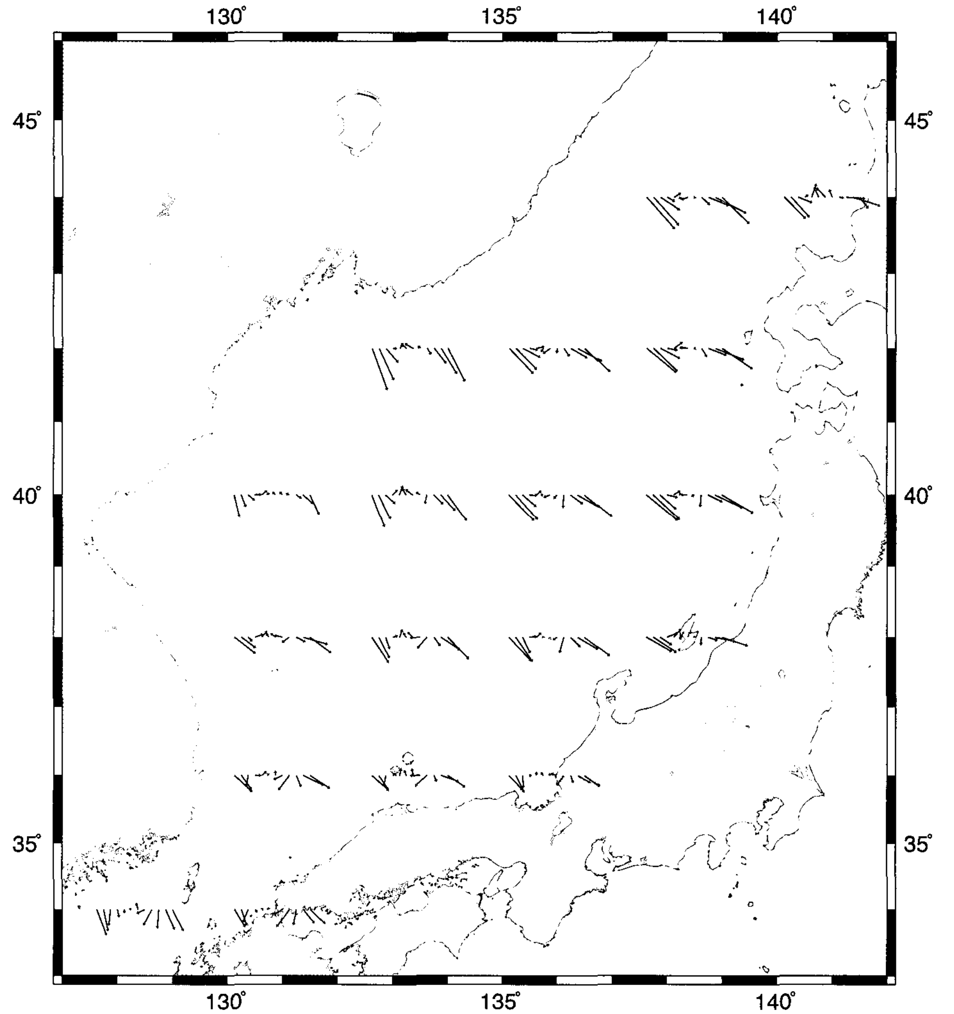

Fig. 10. Monthly mean SSM/I wind vectors in the East Sea averaged from 1988 to 1994.

speed of the flow at the Tsugaru Strait is strong throughout the year and it is about 50 cm/s. Most of the water in the Tsugaru Strait comes from the interior of the East Sea except during summer when the TC passes the strait. Monsoon-type wind plays an important role for the circulation in the East Sea but further study of the wind-current relationship is needed.

The historical view of the TC is challenged here but we lack enough Lagrangian measurements to make a firm conclusion. More drifter deployments in the area are in progress to study the characteristics of the circulation in the East Sea.

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