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Lagrangian flow observations in the East China, Yellow and Japan Seas

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Abstract: Satellite-tracked drifters with drogues centered at 10 and 40 m were deployed in the Yellow and East China Seas in January and July 1986. Two drifters launched in January returned useful data for about 60 days. Both drifters exhibited weak mean velocities of 2–3 cm/s but larger subtidal variability (eddy kinetic energy 31–35 cm^2/s^2). All ten drifters launched in July returned useful data for at least 90 days. The resulting trajectories of five drifters deployed in the Yellow Sea describe a weak basin-scale cyclonic gyre in the surface waters of the Yellow Sea in late summer. The center of the gyre was located near 35.6°N, 123.8°E, and the mean velocities along the Korean and Chinese coasts varied from 2 to 6 cm/s. Within the Yellow Sea, the distribution of eddy kinetic energy was relatively uniform spatially at 30–50 cm^2/s^2 except with an increase to about 80 cm^2/s^2 near the Korean coast and higher near the southeast entrance of the Yellow Sea.

Drifter trajectories in the East China Sea describe a strong inflow of Kuroshio and shelf water in late summer into the Korea Strait through both western and eastern channels. While two drifters continued to move slowly southeastward along the Chinese coast, no drifters entered the Yellow Sea, suggesting that the Yellow Sea Warm Current may not be a coherent and continuous current in summer. The mean eddy kinetic energy in the East China Sea was 112±43 cm^2/s^2. Three drifters entered the Japan Sea and followed quite different paths, suggesting that the Tsushima Current may not simply split into several semi-permanent branches as it leaves the Korea Strait. One drifter entered a cyclonic mesoscale eddy near 37°N, 133°E and made three complete loops with a mean speed and radius of 26 ±14 cm/s and 35±14 km before exiting. The mean eddy kinetic energy in the Japan Sea west of 138°E was 415±91 cm^2/s^2. One drifter was deployed in the Ohsumi branch of the Kuroshio and carried eastward in the Kuroshio and Kuroshio Extension to about 160°E before drifting to the south in the recirculation. While in the Kuroshio and Kuroshio Extension, the drifter had a mean and eddy kinetic energy of 0.29 and 0.38 m^2/s^2.

1. Introduction

It is generally believed from the early work of UDA (1934) and others that some warm water from the Kuroshio flows northward across the East China Sea continental shelf and into the Japan and Yellow Seas via two branches, the Tsushima Current and the Yellow Sea Warm Current, respectively (Fig.1). The Tsushima Current has an annual mean geostrophic transport of about 1.3 Sv (YI, 1966), and carries Kuroshio water of high temperature and high salinity through the Korea Strait into the Japan Sea where it strongly influences water structure within this semi-enclosed basin (SVERDRUP *et al.*, 1942: page 734; MORIYASU, 1972; KOLPACK, 1982). The Tsushima Current has a minimum geostrophic transport of about 0.5 Sv in January to May increasing rapidly to a summer-fall maximum of about 2.2 Sv in July to November. Much less is known about the path, magnitude and seasonal variation of the Yellow Sea Warm Current, although its transport is thought to be less than that of the Tsushima Current. The

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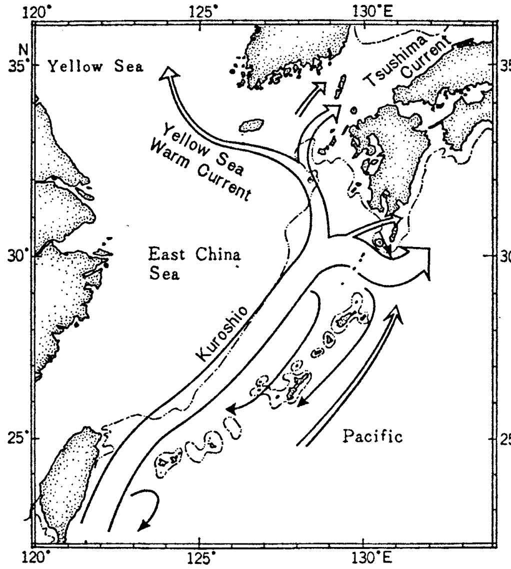

Fig. 1. Schematic representation of the current system in the East China Sea. From Nitani (1972).

Yellow Sea Warm Current is generally thought to flow northward up the deep central channel toward the Gulf of Bohai, with some flow turning westward and feeding a large basin-wide cyclonic gyre in the Yellow Sea.

While there has been little disagreement on this general description of the branching of the Kuroshio in the East China Sea, recent observations question the historical ideas about the path and strength of the Yellow Sea Warm Current in the Yellow Sea, the formation region of the Tsushima Current in the eastern East China Sea, and the subsequent path of the Tsushima Current in the Japan Sea. As part of a cooperative US – Korea – China research program, satellite-tracked drifters were deployed in the East China and Yellow Seas in January and July 1986. The resulting drifter trajectories provide the first long quasi-Lagrangian current measurements in this region, which in turn provide insight into the questions raised about the Yellow Sea Warm Current and Tsushima Current. This paper presents a simple description of the drifter trajectories and some initial conclusions, which are summarized in the discussion, based primarily on this small but unique data set. The drifters were deployed during regional hydrographic surveys so that the initial water masses into which drifters were deployed have been identified by standard and cluster analysis of the temperature-salinity data. Detailed descriptions of the hydrographic data and the results of moored current meter and shipboard acoustic Doppler current meter measurements made in the 1986 cooperative experiment are presented elsewhere by Kim *et al.* (1991), Chen *et al.* (1992, 1993), Hsueh and Pang (1988), Hsueh (1989), and Candela *et al.* (1992), respectively.

2. The Drifter Experiment

Between January 8–February 2, 1986, we deployed one Technocean Associates Tristar (Niiler *et al.*, 1987) and seven ORE (Ocean Research Equipment, Inc.) satellite-tracked drifting buoys in the Yellow and East China Seas from the R/V Thompson during a regional scale CTD/ADCP survey. Six additional ORE drifters were deployed from the Korean R/V Pusan 801 and the Chinese R/V Venus 2 during mooring recovery cruises in April. These were prototype drifters consisting of a surface drifter housing an ARGOS platform transmitter and a Tristar drogue centered at 10 m depth. The ORE drifter and drogue design was patterned after the Tristar. All these drifters had a drag ratio of the drogue to all other components of the drifter of about 28, so that the downwind slip velocities estimated from field tests were about 2.5 and 4.3 cm/s at wind speeds of 10 and 20 m/s, respectively (P. Richardson, personal communication). Data return from the drifters was extremely poor, with only two ORE drifters deployed in January returning useful data for up to about 60 days (Table 1).

Between July 6–18, we deployed ten Draper Laboratory satellite-tracked Low-Cost Drifters (LCDs) in the Yellow and East China Seas during a regional CTD survey aboard the R/V Washington. These ARGOS-tracked drifters featured a surface float attached to a holey sock drogue centered at either 10 or 40 m depth (Dahlen, 1985). The 10 m LCDs had a drag ratio of 36, giving an estimated downwind slip velocity of about 2.2 and 3.8 cm/s for wind speeds of 10 and 20 m/s, while the 40 m LCDs had a drag ratio of only about 18, giving an estimated downwind slip velocity of about 4.0 and

Table 1. Summary of satellite-track drifters deployed in Yellow and East China Seas during 1986. The two winter drifters were ORE drifters with Tristar drogues, while the summer drifters were made by Draper Laboratory with holey-sock drogues. Listed are the drifter identification number (ID), drogue depth, area deployed, and the initial location, start time, and length of the low-passed drifter position time series.

Drifter ID	Drogue Depth (m)	Area Deployed	Latitude (°N)	Longitude (°E)	Start Date (yd)	Record Length (days)
Winter						
6970	10	C Yellow Sea	34.91	124.62	22	43
6975	10	Cheju Island	32.94	125.74	26	56
Summer						
5843	10	C Yellow Sea	35.13	123.29	194	114
6971	10	W Yellow Sea	35.18	121.50	193	280
6974	10	Kuroshio	30.32	129.62	202	180
6978	10	Cheju Island	33.12	125.47	197	15
6983	10	Tsushima Strait	32.69	128.04	199	49
6984	10	E Yellow Sea	35.06	125.47	194	25
6985	10	NC Yellow Sea	36.84	123.15	190	112
6986	10	Yangtze River	31.70	123.03	198	148
6987	10	NC East China Sea	33.01	123.01	196	88
6988	10	Cheju Island	33.05	125.52	197	188

6.0 cm/s, respectively (P. RICHARDSON, personal communication). All LCDs returned useful data for over 90 days, some much longer (Table 1). For both January and July deployments, each drifter obtained about 4–6 fixes per day on average with a nominal accuracy per fix of about 300 m.

The drifter raw position data were first linearly interpolated to a uniform 6-hour time series of latitude and longitude. Then these series were low-pass filtered with a parabolic-linear filter with a 33-hour half-amplitude period (FLAGG *et al.*, 1976) to eliminate tidal and inertial motions. Drifter velocities were then computed by simple backward difference. To examine the influence of wind on the low-passed drifter velocities, values of the 10 m wind at the drifter positions were extracted by linear interpolation in time and space from the ECMWF/WCRP Level III-A global atmospheric surface data set, which has a 12-hour, 2.5° resolution. The drifter wind time series were then converted into wind stress time series using the neutral drag law of LARGE and POND (1981). Time is expressed here in GMT year days (yd) for 1986 to simplify comparison between drifters. Drifter deployment areas and initial position, start time and record length of the low-passed drifter position time series are summarized in

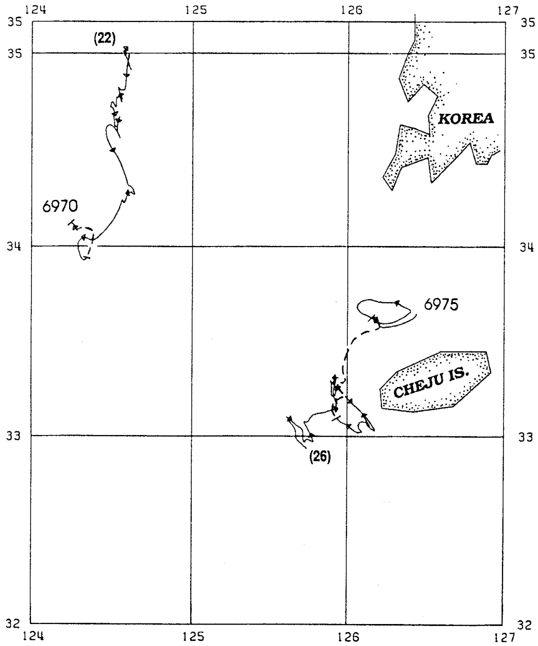

Fig. 2. Drifter trajectories from winter 1986 deployment. Starting date of trajectory in year-day is shown in parenthesis at beginning of each trajectory. Arrows showing direction of motion are placed along each trajectory every five days from yd 1. The drifter trajectory during the spring transition (yd 62–70) is indicated by the dashed path.

Table 2. Statistics for drifters 6970 and 6975 for a 39-day common period starting on yd 26.75. The mean (m), standard deviation (sd), standard error (se), minimum (min) and maximum (max) values and decorrelation time scales are listed for drifter east (U), north (V), and speed (S) in cm/s and wind stress east (E) and north (N) components in dyne/cm². The decorrelation time scale t_{dc} is one-half the zero crossing estimated from the auto-correlation function, and the standard error is the standard deviation divided by the square root of the record length divided by the decorrelation time scale following Kundu and Allen (1976). The initial drifter position, start time in yd and length of averaging period in days is listed at the top for each drifter.

	m	sd	se	min	max	t_{dc}
6970: 35.00° N, 124.60° E, yd 26.75, 39 d						
U	−1.0	3.9	0.6	−12.8	7.6	1
V	−2.8	6.8	1.1	−15.4	19.0	1
S	7.1	4.5	−	0.8	19.8	−
E	.25	.34	.07	− 6.5	1.55	1.5
N	−.58	.53	.10	−2.28	.47	1.5
6975: 32.94° N, 125.74° E, yd 26.75, 39 d						
U	0.6	5.4	.9	−11.7	15.5	1
V	1.1	6.4	1.0	−14.9	12.9	1
S	7.4	4.1	−	0	21.2	−
E	.29	.36	.07	− .94	1.61	1.5
N	−.60	.45	.10	−1.69	.43	1.5

Table 1.

3. Results

A. Winter 1986 deployment

Two drifters (6970 and 6975) deployed in mid-to-late January 1986 returned useful velocity data. Drifter 6970 was launched into Yellow Sea Cold Water (group 3 in Figures 3 and 5 of KIM *et al.*, 1991) near the central Yellow Sea (water depth 94 m) and generally moved toward the south and southwest with a mean velocity of about 3 cm/s during the interval yd 22–66 (Fig. 2). Drifter 6975 was launched southwest of Cheju into a mixture of shelf and Kuroshio water called East China Sea Water (group 4)(water depth 91 m) and moved north and northeastward with a mean velocity of about 2 cm/s during the interval yd 27–83. Both drifters exhibited significant subtidal variability, with mean and maximum speeds of 7–8 and 19–22 c m/s (eddy kinetic energy 31–35 cm²/s²). Winds during this late winter period between launch and early March were predominately oriented toward the southeast with mean and maximum wind speeds of about 6 and 12 m/s, respectively. During yd 62–70 (March 3–11), a large-scale "spring transition" occurred in the wind field over the Yellow Sea, with winds generally

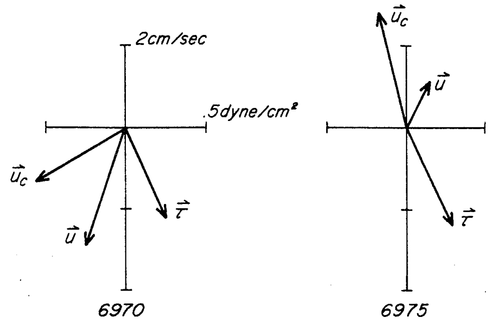

Fig. 3. Mean drifter velocity and wind stress for 6970 and 6975 during common time yd 27–66. Also shown is drifter velocity corrected for windage.

weakening and becoming more variable in direction. HSUEH (1988) shows that accompanying this spring transition is a reversal of the north-south surface pressure gradient in the Yellow Sea from a mean setup toward the south (driven by the predominant southeastward winds) to a mean northward setup. During the later half of this transition (yd 66–70), 6975 moved swiftly northward with mean and maximum speeds of 14 and 23 cm/s, respectively, moving a net distance of about 40 km.

To allow comparison over a common time period, statistics for 6970 and 6975 were computed over the 39-day interval yd 27–66 (Table 2).

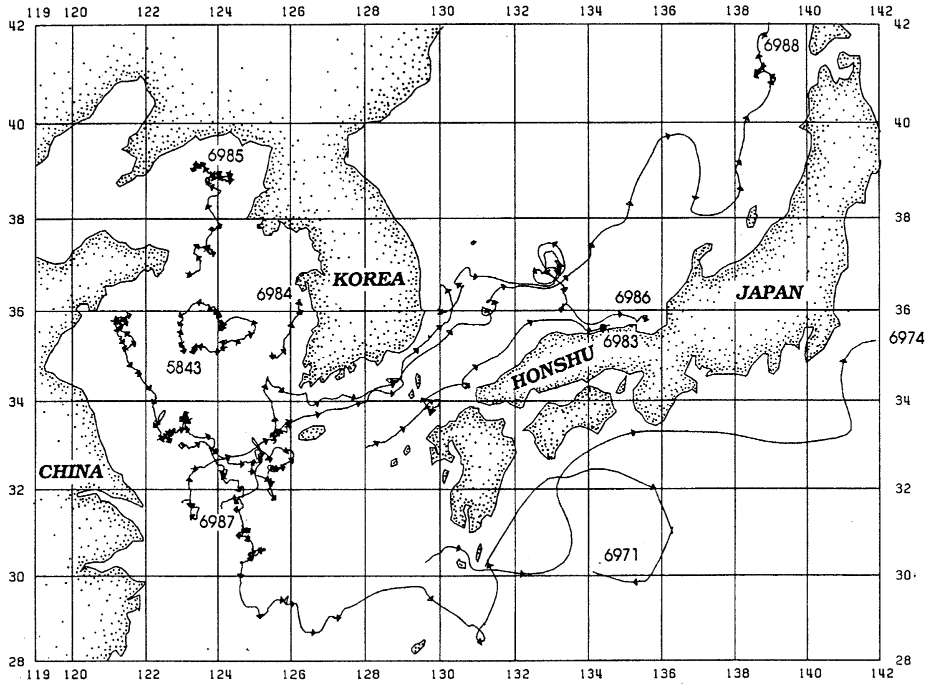

Fig. 4. Drifter trajectories from summer 1986 deployment. The drifter identification number is printed at end of trajectory. Arrows showing direction of motion are placed along each trajectory every five days from yd 1. All drifter trajectories start within a 12-day period (yd 190–202).

This common period ends during the beginning of the spring transition, so the statistics represent late winter conditions. Fig. 3 illustrates the mean drifter velocity and wind stress components: 6970 moved at about a 45° angle to the right of the wind stress while 6975 clearly moved to the left and against the mean wind stress. Also plotted in Fig. 3 are the mean drifter velocities "corrected" for downwind slippage using the drifter drag ratio and empirical slippage curves supplied by RICHARDSON (personal communication). While the uncertainty in this correction may be large, the resulting mean velocity of 6970 is closer to 90° to the right of the wind stress in the correct sense for a surface mixed layer while 6975 moved more directly against the mean wind stress. CTD data collected at deployment showed that the surface mixed layer in late winter was significantly deeper than the drogues which were centered at 10 m. Complex vector correlations computed between drifter velocities and wind stresses indicate that while both drifters essentially experienced the same wind field during the common time period, 6970 and 6975 velocity fluctuations were not correlated in time, and only 6970 exhibited partial wind-driving. Perhaps more importantly, Fig. 3 illustrates the need for higher drag ratios to reduce the relative effects of windage in future drifter experiments in this region.

B. Summer 1986 deployment

Ten drifters were deployed in mid-July 1986 and all returned useful data (Table 1, Fig. 4). Five drifters (5843, 6971, 6984, 6985, and 6987) were deployed with drogues centered at 10 m in the Yellow Sea; with the exception of 6984, which became stuck (perhaps caught in fishing gear) off Korea after about 30 days, the remaining four drifters returned low-pass data for periods ranging from 88 to 280 days. Four drifters (6978, 6983, 6986, and 6988) were deployed in the East China Sea. Drifters 6978 and 6988 were set as a pair with drogues centered at 40 and 10 m, respectively, to examine vertical shear near Cheju Island; 6978 was recovered about 17 days after launch by a fisherman from Cheju. Drifter

Table 3. Statistics for drifters deployed in July, 1986. The mean (m), atandard deviation (sd), standard error (se), minimum (min) and maximum (max) values and decorrelation time scales are listed for drifter east (U), north (V), and speed (S) in cm/s and wind stress east (E) and north (N) components in dyne/cm^2. The decorrelation time scale (t_{dc}) is one-half the zero crossing estimated from the auto-correlation function, and the standard error is the standard deviation divided by the square root of the record length divided by the decorrelation time scale following Kundu and Allen (1976). The initial drifter position, start time in yd and length of averaging period in days is listed at the top for each drifter.

	m	sd	se	min	max	t_{dc}
5843 : 35.13°N, 123.29°E, yd194.0(July 13), 19d						
U	4.5	5.1	…	−4.6	17.2	…
V	.2	4.6	…	−10.3	12.9	…
S	7.2	3.9	…	0	18.1	…
E	0.03	0.11	…	−.28	.40	…
N	0.07	0.21	…	−.60	.81	…
35.16°N, 124.12°E, yd213(August 1), 31d						
U	−.1	10.7	3.3	−45.5	19.3	3
V	2.1	6.7	1.2	−31.4	11.3	1
S	9.5	8.6	…	.7	48.4	…
E	.11	1.05	.19	−3.13	9.03	1
N	−.39	.93	.20	−5.64	.90	1.5
35.65°N, 124.07°E, yd244(September 1), 30d						
U	−1.0	3.8	0.7	−12.1	7.9	1
V	1.8	4.9	0.9	−13.4	15.4	1
S	5.5	3.4	…	.4	15.6	…
E	.02	.17	.03	−.68	.60	1
N	−.21	.27	.05	−1.27	.54	1
36.06°N, 123.78°E, yd274(October 1), 31d						
U	−2.4	5.9	1.1	−16.6	10.5	1
V	−3.6	6.1	1.1	−22.1	7.2	1
S	8.1	5.0	…	1.0	23.1	…
E	.05	.22	.04	−.71	.82	1
N	−.30	.49	.09	−2.29	.57	1
35.18°N, 123.05°E, yd305(November 1), 3d						
U	1.3	2.7	…	−2.9	5.9	…
V	−4.6	9.2	…	−19.0	11.3	…
S	9.1	5.2	…	2.1	19.3	…
E	.10	.16	…	−.08	.40	…
N	−.20	.41	…	−.93	.35	…
6971 : 35.18°N, 121.50°E, yd193.5(July 12), 19.5d						
U	−.8	6.0	…	−14.3	10.1	…
V	4.4	2.4	…	−.5	13.4	…
S	7.0	3.5	…	0	18.5	…
E	.01	.09	…	−.37	.19	…
N	.07	.17	…	−.40	.51	…
35.85°N, 121.34°E, yd213(August 1), 31d						
U	−.2	5.9	1.1	−22.1	11.7	1
V	−1.7	4.9	0.9	−18.0	6.2	1
S	6.4	4.5	…	0	23.3	…
E	.04	.39	.07	−1.20	3.24	1
N	−.31	.86	.16	−4.88	.51	1
35.44°N, 121.29°E, yd244(September 1), 30d						
U	3.4	4.5	0.8	−9.8	13.2	1
V	−7.0	4.3	0.8	−18.5	2.6	1
S	9.0	4.4	…	1.4	21.4	…
E	−.02	.14	.02	−.43	.42	1
N	−.16	.24	.04	−.90	.51	1
33.79°N, 122.24°E, yd274(October 1), 31d						
U	1.6	6.2	1.1	−21.9	15.4	1
V	−2.1	11.0	2.0	−26.3	22.7	1
S	10.8	7.1	…	.7	29.2	…
E	.00	.34	.06	−1.18	1.09	1
N	−.28	.41	.07	−1.35	.53	1
33.32°N, 122.68°E, yd305(November 1), 30d						
U	1.6	5.4	1.0	−11.6	14.2	1
V	1.5	7.5	1.4	−18.0	17.5	1
S	8.4	4.4	…	.7	19.0	…
E	−.05	.29	.05	−.90	.65	1
N	−.50	.66	.12	−3.09	.77	1
6971 : 33.67°N, 123.13°E, yd335(December 1), 31d						
U	5.0	8.9	1.6	−9.1	34.5	1
V	−6.8	10.4	1.9	−36.0	16.0	1
S	13.7	8.4	…	2.1	36.1	…
E	.25	.56	.10	−.54	2.37	1
N	−.54	.71	.13	−2.39	1.09	1
32.01°N, 124.57°E, yd366(January 1), 31d						
U	.9	7.6	1.4	−17.6	17.0	1
V	−4.7	10.2	1.8	−39.1	14.4	1
S	11.7	7.0	…	1.0	40.6	…
E	.13	.60	.11	−.86	2.66	1
N	−.71	.83	.15	−3.14	0.93	1
30.88°N, 124.83°E, yd397(February 1), 28d						
U	0.8	11.8	2.2	−24.9	37.7	1.5
V	−7.2	14.2	2.7	−53.0	11.8	1
S	15.9	11.9	…	.9	55.7	…
E	.28	.65	.12	−.86	3.44	1
N	−.71	1.13	.21	−4.10	1.60	1
29.28°N, 125.04°E, yd425(March 1), 31d						
U	22.0	25.3	4.5	−32.6	123.4	1.5
V	−3.4	22.8	4.1	−49.9	48.5	1
S	33.0	23.7	…	2.1	124.3	…
E	.18	0.46	.08	−1.20	2.52	1
N	−.42	.66	.12	−2.76	1.16	1
28.46°N, 131.08°E, yd456(April 1), 17.75d						
U	17.7	70.0	…	−86.5	198.0	…
V	11.6	84.1	…	−185.8	314.0	…
S	83.1	73.6	…	6.4	371.2	…
E	−.19	.44	…	−1.25	.77	…
N	−.11	.32	…	−.75	.63	…

	m	sd	se	min	max	t_{dc}
6974 : 30.32°N, 129.62°E, yd202(July 21), 11d						
U	37.9	38.4	…	−34.8	138.2	…
V	10.5	40.5	…	−42.7	129.2	…
S	53.4	42.1	…	0	139.3	…
E	.04	.40	…	−.77	1.06	…
N	−.14	.09	…	−.31	.15	…
31.23°N, 133.45°E, yd213(August 1), 31d						
U	83.4	60.5	15.4	−54.5	217.8	2
V	9.6	60.4	13.3	−110.0	193.1	1.5
S	108.5	50.4	…	13.5	217.8	…
E	−.19	.57	.10	−2.02	2.44	1
N	−.28	.50	.14	−2.20	0.50	2
33.31°N, 157.93°E, yd244(September 1), 30d						
U	5.5	29.1	8.4	−27.6	131.7	2.5
V	−13.2	29.4	8.5	−96.8	35.2	2.5
S	33.1	28.4	…	.96	136.3	…
E	−.07	.44	.06	−1.59	.69	1
N	−.03	.33	.05	−1.13	.71	1
30.12°N, 159.20°E, yd274(October 1), 31d						
U	8.1	14.0	4.0	−25.4	39.0	2.5
V	4.2	12.1	3.4	−22.1	26.8	2.5
S	17.5	10.8	…	1.1	39.7	…
E	−.02	.34	.05	−1.26	1.09	1
N	−.16	.45	.06	−2.63	.76	1
31.13°N, 161.54°E, yd305(November 1), 30d						
U	9.3	8.8	2.5	−11.9	26.8	2.5
V	6.6	6.8	2.0	−10.8	22.1	2.5
S	14.6	6.3	…	1.8	27.0	…
E	.06	.33	.05	−.58	1.28	1
N	−.10	.25	.04	−.78	.98	1
6974 : 32.68°N, 164.13°E, yd335(December 1), 31d						
U	4.4	8.8	2.5	−15.0	22.7	2.5
V	−11.6	8.8	2.5	−29.4	6.7	2.5
S	15.8	7.7	…	1.1	31.8	…
E	.30	.40	.07	−.31	1.72	1
N	−.08	.43	.08	−1.25	2.12	1
29.87°N, 165.36°E, yd366(January 1), 15.75d						
U	4.2	6.6	…	−10.3	18.3	…
V	−4.3	3.5	…	−12.9	2.6	…
S	7.9	5.4	…	2.1	20.8	…
E	.44	.58	…	−.50	3.50	…
N	−.11	.37	…	−1.26	.75	…
6978 : 33.12°N, 125.47°E, yd197.5(July 16), 14.75d						
U	4.1	4.3	…	−4.3	14.2	…
V	4.0	3.3	…	−4.1	9.8	…
S	7.3	3.0	…	0	14.2	…
E	.10	.15	…	−.14	.55	…
N	.05	.17	…	−.29	.49	…
6983 : 32.96°N, 128.04°E, yd199.25(July 18), 13.5d						
U	10.7	10.2	…	−15.8	26.9	…
V	5.6	10.5	…	−19.6	27.3	…
S	17.4	7.3	…	0	36.0	…
E	.08	.18	…	−.27	.69	…
N	−.00	.19	…	−.78	.70	…

	m	sd	se	min	max	t_{dc}
34.01°N, 129.55°E, yd226(August 14), 22d						
U	22.7	20.0	…	−10.6	67.6	…
V	9.4	16.1	…	−27.3	65.9	…
S	29.4	19.8	…	2.2	82.4	…
E	−.09	.36	…	−1.39	.72	…
N	.02	.48	…	−.70	2.14	…
6984 : 35.06°N, 125.47°E, yd194.5(July 13), 18.5d						
U	4.4	7.2	…	−14.6	21.3	…
V	8.2	8.8	…	−8.8	26.3	…
S	12.3	7.9	…	0	29.1	…
E	.06	.10	…	−.27	.34	…
N	.06	.14	…	−.29	.46	…
36.25°N, 126.26°E, yd213(August 1), 6.75d						
U	.4	5.7	…	−9.1	13.8	…
V	−5.3	9.4	…	−21.1	12.4	…
S	10.9	5.2	…	1.3	21.1	…
E	.05	.15	…	−0.07	.59	…
N	−.18	.25	…	−1.00	.10	…
6985 : 36.84°N, 123.15°E, yd190.25(July 9), 22.75d						
U	3.2	5.7	…	−16.0	15.7	…
V	2.5	6.5	…	−8.2	17.0	…
S	8.4	4.4	…	0	18.4	…
E	.03	.11	…	−.37	.35	…
N	.04	.20	…	−.44	.75	…
37.28°N, 123.88°E, yd213(August 1), 31d						
U	−.6	7.7	1.4	−18.9	18.9	1
V	6.4	7.1	1.3	−11.8	25.2	1
S	10.8	5.8	…	.7	25.5	…
E	.09	.43	.08	−1.34	3.31	1
N	−.27	.84	.15	−7.53	0.55	1
38.83°N, 123.67°E, yd244(September 1), 30d						
U	.8	5.8	1.0	−8.0	16.4	1
V	.6	5.3	1.0	−9.3	15.4	1
S	7.0	3.8	…	1.2	16.4	…
E	.01	.09	.02	−.33	.26	1
N	−.08	.15	.03	−.72	.19	1
6985 : 38.95°N, 123.90°E, yd274(October 1), 28.75d						
U	−2.0	3.5	…	−9.2	6.8	…
V	.5	3.9	…	−9.3	7.7	…
S	5.1	2.3	…	.5	12.2	…
E	.01	.08	…	−.33	.16	…
N	−.17	.28	…	−1.37	.33	…
6986 : 31.70°N, 123.03°E, 198.25yd(July 17), 14.75d						
U	1.7	9.5	…	−11.4	28.5	…
V	−.2	11.1	…	−17.5	27.3	…
S	12.9	6.8	…	0	29.2	…
E	−.02	.18	…	−.32	.71	…
N	.21	.23	…	−.19	.83	…
31.68°N, 123.26°E, yd213(August 1), 31d						
U	7.7	12.5	2.3	−27.3	35.1	1
V	11.2	10.8	2.7	−24.2	35.0	2
S	19.8	8.1	…	4.4	42.4	…
E	−.01	.80	.13	−2.96	6.08	1
N	−.21	.42	.08	−1.66	.79	1

	m	sd	se	min	max	t_{dc}
	34.36°N, 125.50°E, yd244(September 1), 30d					
U	14.9	15.2	3.4	−50.5	42.6	1.5
V	4.6	12.9	2.4	−35.0	27.3	1
S	23.4	9.6	…	3.7	50.5	…
E	−.08	.26	.05	−.92	.81	1
N	−.15	.23	.04	−.95	.61	1
	35.46°N, 129.71°E, yd274(October 1), 31d					
U	9.8	21.8	4.8	−30.4	66.6	1.5
V	5.9	19.8	3.6	−43.2	56.1	1.0
S	27.0	16.2	…	3.9	67.5	…
E	.05	.26	.04	−.59	.76	1
N	−.15	.30	.06	−1.80	.62	1
6986 :	36.88°N, 132.67°E, yd305(November 1), 30d					
U	2.1	16.7	3.7	−33.1	45.8	1.5
V	−3.3	21.1	4.7	−55.1	37.1	1.5
S	24.2	12.4	…	3.5	65.9	…
E	.22	.48	.09	−1.30	1.63	1
N	−.10	.29	.05	−1.05	.53	1
	36.08°N, 133.29°E, yd335(December 1), 11.75d					
U	19.8	23.3	…	−12.5	70.5	…
V	−3.5	17.8	…	−45.8	34.5	…
S	28.0	21.7	…	0	71.0	…
E	.21	.30	…	−.26	1.10	…
N	−.03	.25	…	−.66	.64	…
6987 :	33.01°N, 123.01°E, yd196(July 15), 17d					
U	11.7	7.1	…	−3.9	28.5	…
V	−2.8	7.9	…	−20.6	15.4	…
S	14.4	7.0	…	0	32.4	…
E	.01	.14	…	−.29	.55	…
N	.10	.22	…	−.58	.65	…
	32.63°N, 124.87°E, yd213(August 1), 31d					
U	2.7	10.3	1.9	−25.3	37.3	1
V	−.3	13.6	2.4	−17.5	70.5	1
S	12.3	12.0	…	1.0	71.8	…
E	−.20	1.19	.21	−5.92	2.46	1
N	−.36	.82	.15	−4.54	1.60	1
	32.56°N, 125.60°E, yd244(September 1), 30d					
U	−2.4	10.6	1.9	−29.0	14.7	1
V	2.7	10.8	2.0	−30.4	29.3	1
S	12.7	9.0	…	1.3	35.3	…
E	−.03	.25	.04	−.82	1.32	1
N	−.30	.36	.06	−1.70	.30	1
6987 :	33.18°N, 124.94°E, yd274(October 1), 9.75d					
U	−9.3	19.4	…	−53.8	19.9	…
V	−20.9	12.6	…	−40.7	.5	…

	m	sd	se	min	max	t_{dc}
S	30.1	12.1	…	6.4	59.2	…
E	.10	.34	…	−.35	1.16	…
N	−.36	.30	…	−1.35	0.04	…
6988 :	33.05°N, 125.52°E, yd197(July 16), 16d					
U	10.3	8.4	…	−6.5	24.4	…
V	6.1	4.1	…	−4.1	14.4	…
S	13.8	6.1	…	0	24.7	…
E	.09	.15	…	−.15	.56	…
N	.06	.16	…	−.28	.46	…
	33.82°N, 127.08°E, yd213(August 1), 31d					
U	18.9	16.9	3.7	−26.6	64.9	1.5
V	11.0	15.1	3.8	−19.6	53.1	2
S	28.4	13.6	…	2.4	83.2	…
E	.00	.39	.07	−1.76	1.39	1
N	.08	.46	.08	−.88	2.47	1
	36.49°N, 132.65°E, yd244(September 1), 30d					
U	18.3	16.2	3.6	−18.2	50.3	1.5
V	10.6	28.4	7.3	−75.7	64.9	2
S	36.2	14.2	…	8.1	75.7	…
E	.07	.46	.09	−.55	2.45	1
N	−.05	.38	.07	−.86	3.14	1
6988 :	39.00°N, 138.02°E, yd274(October 1), 31d					
U	2.3	8.3	1.5	−19.0	24.7	1
V	8.7	10.7	1.9	−12.9	35.0	1
S	13.4	9.2	…	.5	35.0	…
E	.15	.43	.08	−1.20	1.08	1
N	−.14	.51	.09	−3.08	1.01	1
	41.09°N, 138.77°E, yd305(November 1), 30d					
U	−.1	7.5	1.4	−14.0	19.9	1
V	8.1	9.8	1.8	−13.9	35.5	1
S	12.9	7.1	…	1.6	35.5	…
E	.76	.75	.13	−.29	3.64	1
N	−.25	.64	.11	−2.48	1.07	1
	42.99°N, 138.71°E, yd335(December 1), 31d					
U	2.1	9.9	1.8	−14.2	38.1	1
V	5.4	7.4	1.3	−10.3	20.6	1
S	11.6	7.3	…	1.2	41.0	…
E	.59	.70	.13	−.54	3.46	1
N	−.54	.78	.14	−5.17	.99	1
	44.31°N, 139.41°E, yd366(January 1), 19.25d					
U	1.5	6.6	…	−15.2	18.4	…
V	−2.5	7.1	…	−19.6	19.0	…
S	8.7	5.0	…	1.5	19.7	…
E	.71	.80	…	−.75	2.67	…
N	−.59	.70	…	−2.56	1.11	…

6983 went ashore in the lee of Iki Island in the eastern channel of the Korea Strait at 33.7° N, 129.8° E about 18 days after launch, was redeployed about 10 days later nearby to the north at 34° N, 129.6° E, and went ashore on Honshu near 35.6° N, 134.3° E about 22 days after re-launch. Drifters 6986 and 6988 returned low-pass data for 148 and 188 days, respectively. The tenth drifter (6974) was deployed in the core of the Kuroshio with a drogue at 40 m and returned low-pass data for 180 days.

To facilitate comparison over common time periods, statistics of drifter velocity and wind stress computed by calendar month are given in

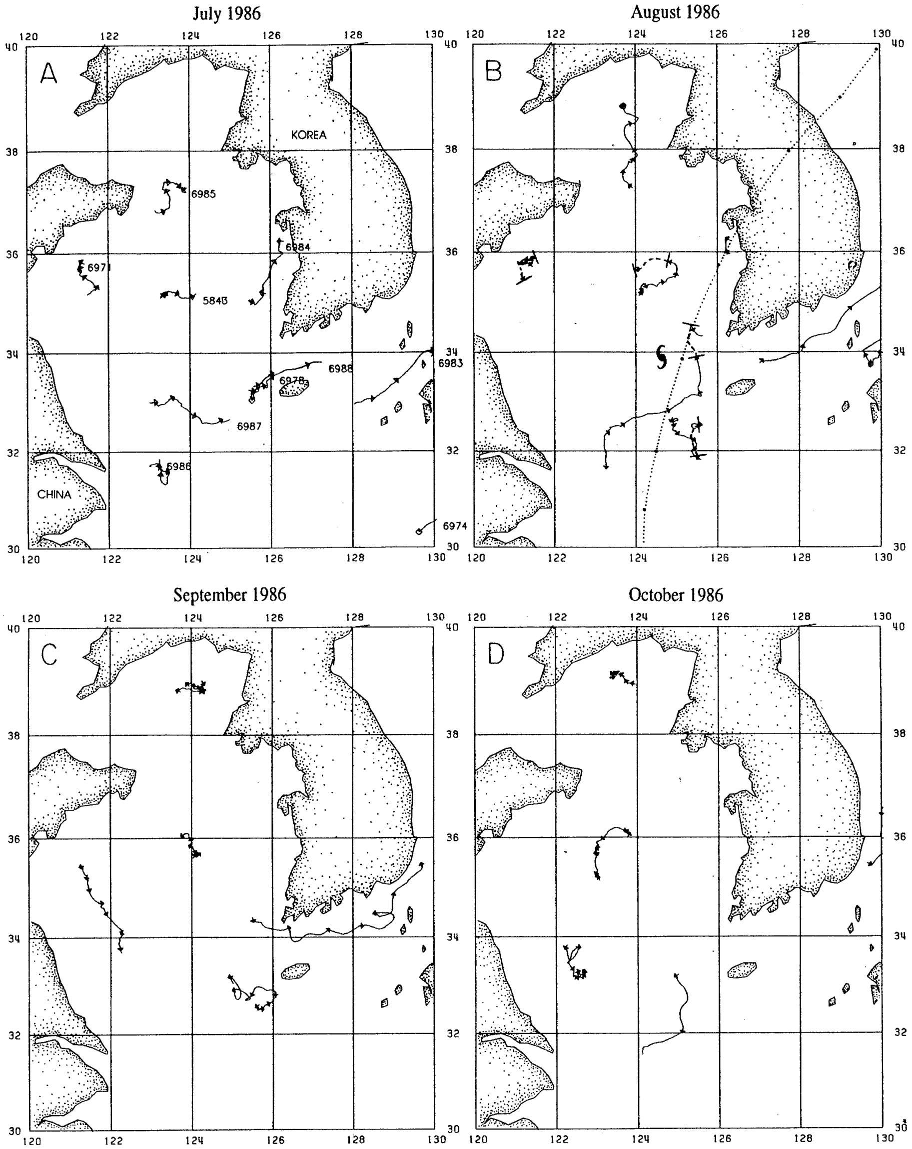

Fig. 5. Drifter trajectories in Yellow and East China Sea for July (A), August (B), September (C), and October (D). Drifter number is printed at the end of each trajectory in panel A. Arrows are placed along each trajectory every five days from first day in each month. The path of typhoon Vera during August 27–28 (yd 239–240) is shown in panel B; the location of the eye of Vera at 00 GMT August 28 (yd 240) is indicated by the typhoon symbol. The drifter trajectories during the three-day period yd 239–241 surrounding the passage of typhoon Vera are indicated by the dashed paths in panel B. (See Appendix for maps of the wind field and individual drifter trajectories during Vera.)

Table 3. When drifter data is available for a complete month, crude estimates of decorrelation time scales for east and north velocity and wind stress components were made from auto-correlation functions and standard errors computed following KUNDU and ALLEN (1976). Winds over the East China and Yellow Seas during late summer 1986 were generally light and variable in direction with mean wind speeds of about 4 ± 2 m/s with one major

exception. On yd 237–238 (August 25–26), typhoon Vera swept west over the Ryukyu Islands into the East China Sea (DEANGELIS, 1987). Vera then started to weaken and curved north and moved across the East China Sea at an average speed of 6 m/s before crossing Korea on yd 240 (August 28) as a tropical storm and dying in the Japan Sea (see Appendix for maps of the surface wind field). Vera was a major typhoon, maintaining typhoon intensity from yd 231 through yd 240 and reaching super typhoon intensity on yd 235 with peak wind speed 67 m/s. The ECMWF/WCRP Level III-A surface analysis reported that Vera produced maximum 10 m wind speeds of about 24 m/s in the East China and Yellow Seas on yd 239. Beginning about yd 280 (October 6), a large-scale "fall transition" occurred in the wind field over the Yellow Sea with the onset of winter storms and an increase in the mean southeastward winds.

1. Yellow Sea

The trajectories of the five drifters deployed in the Yellow Sea are shown by month for July –October in Fig. 5. Drifter 6984 was launched in Yellow Sea surface water (YSsw) (groups 9 and 10 in Fig. 4 of KIM *et al.*, 1991) with its drogue in the base of the surface layer (water depth 78 m) just off the southwest Korean coast and generally moved north and eastward toward the Korean coast in July with a mean (vector) velocity and (scalar) speed of about 9 and 12 cm/s, respectively. In early August, 6984 became stuck near 36° N, 126.3° E. Drifter 6985 was launched in YSsw with its drogue in the upper pycnocline (water depth 30 m) just east of the Shangdong peninsula and moved slowly toward the northeast at a mean velocity of 4 cm/s in July, and then moved more quickly northward into the Gulf of Bohai with a mean velocity of 6 cm/s in August. Drifter 6985 then slowed down and moved east then west during September and toward the northwest in October. The mean and maximum speeds of 6985 increased from about 8 and 15–18 cm/s in July, to 11 and 20–25 in August, and then decreased to 5–7 and 10–15 cm/s, respectively, in September and October.

Both 6971 and 6987 were launched in YSsw off the central Chinese coast, 6971 with its drogue at the base of the surface layer (water depth 29 m) and 6987 with its drogue in the upper pycnocline (water depth 35 m). Drifter 6971 first moved northward with a mean velocity of 5 cm/s in July, then began to move slowly southward in August with a mean velocity of 2 cm/s. In September, 6971 moved more quickly toward the south-southeast roughly parallel to the Chinese coast and local topography with a mean velocity of 8 cm/s. Drifter 6971 then slowed and moved more southeastward with a mean velocity of 3 cm/s in October, ending close to the launch position of 6987. Drifter 6987 moved quickly eastward following deployment in July with a mean velocity and speed of 12 and 14 cm/s, then made a large loop to the south in August with a mean speed of 12 cm/s, resulting in a mean eastward velocity of only 3 cm/s. Drifter 6987 then turned and meandered northwestward with a mean velocity of 4 cm/s in September before turning and moving quickly toward the south-southwest with a mean velocity of 23 cm/s in early October.

Drifter 5843 was launched in YSsw in the central Yellow Sea with its drogue within the surface layer (water depth 73 m) and moved eastward in July with a mean velocity of 5 cm/s and continued to move eastward until mid-August when 5843 turned to the north and moved westward, resulting in a monthly mean velocity and speed for August of 2 and 10 cm/s, respectively. Drifter 5843 then moved slowly toward the northwest in September with a mean velocity and speed of 2 and 6 cm/s, before turning toward the south in October with a mean velocity and speed of 4 and 8 cm/s.

While vector correlations computed between drifter velocity and wind stress over one month and longer periods suggest that only 5843 and to a lesser extent, 6971 exhibited clear evidence of partial wind-driving during the summer, four of the five drifters deployed in the Yellow Sea (6984 was not working then) showed short but clear responses to typhoon Vera (see Appendix for maps of the individual drifter trajectories during Vera). The character of the response varied with drifter. Drifter 5843 in the center of the Yellow Sea moved rapidly to the right of the wind stress (angle between wind stress and current vectors varying from 50° to 110° as the wind stress veered counterclockwise) with a peak speed of 48 cm/s occurring on yd 240.25 about six hours before a peak wind stress of 10.8 dyne/cm². Both drifter speed and wind stress decreased rapidly on yd 241. Drifter 6987, located near the main channel into the Yellow Sea west of Cheju, also initially moved to the right of the wind stress (angle varying from 100° to 40°) for more than two days while the wind stress with a maximum magnitude of 6.0 dyne/cm² veered slightly clockwise. Current speed during this period of active wind forcing increased to about 28 cm/s on yd 238.75, however, as the wind stress then quickly decreased over the next several days, 6987 surged northward (to the north and northeast) for 1.5 days, reaching a peak speed of 72 cm/s on yd 239.5. After the drifter speed had decreased to a minimum of 12 cm/s on yd 240.5, 6987 veered clockwise towards the north with a speed of about 20 cm/s. In the western Yellow Sea, 6971 moved toward the southwest and south to the right of the wind stress (angle varying from 80° to 30° as the wind veered anti-clockwise) with a peak speed of 23 cm/s occurring on yd 239.75 about six hours after a peak wind stress of 5 dyne/cm². The drifter speed decreased to about 5 cm/s about 12 hours after the wind stress had rapidly decreased in magnitude. Drifter 6985 exhibited a weak response in the Gulf of Bohai despite a pronounced wind stress event with a maximum stress of 8.2 dyne/cm² on yd 240.5. Initially moving northwestward at a mean speed of 15 cm/s, 6985 made a clockwise turning loop over several days before moving northwestward again. The drifter velocity, directed from 30 to 70° to the right of the wind stress during the wind stress event, increased from about 4 to 13 cm/s in magnitude.

2. East China Sea

The initial trajectories of the four drifters deployed in the East China Sea are also shown by month in Figure 5. Drifter 6986 was launched with its drogue just in the base of surface Changjiang dilute water (a mixture of group 9 and 11, water depth 34 m) just northeast of the mouth of the Changjiang, and moved in a small anticyclonic loop in July with a mean speed of 13 cm/s. Drifter 6986 then accelerated and

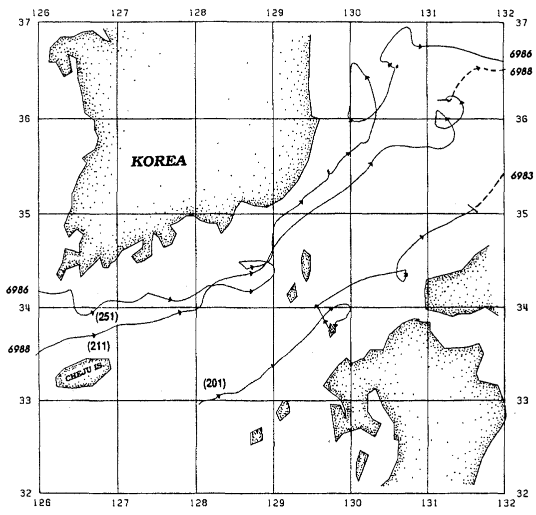

Fig. 6. Drifter trajectories in Korea Strait. Drifter number is printed at beginning and end of each trajectory. Arrows are placed along each trajectory every five days from yd 1, and the time in year-day of the first arrow on each trajectory is shown in parenthesis. The drifter trajectory during the three-day period yd 239–241 bracketing the passage of typhoon Vera is indicated by the dashed path. (See Appendix for expanded maps of 6983 and 6988 trajectories during Vera.)

moved quickly to the north and east in August in the direction of the historical mean surface plume of the Changjiang (BEARDSLEY *et al.*, 1985) with a mean velocity and speed of 14 and 20 cm/s. On yd 242, 6986 abruptly turned south and moved quickly through the western channel of the Korea Strait in September with a mean velocity and speed of 16 and 23 cm/s (with a peak speed of 51 cm/s directed westward in the small cyclonic loop near 34.4° N, 128.6° E) and into the Japan Sea in late September (Fig.6). Drifter 6988 and 6978 were deployed as a pair with drogues centered at 10 and 40 m to examine vertical shear in the main channel (water depth 91 m) west of Cheju Island. At launch, the drogue of 6988 was in the base of the YSsw while the drogue of 6978 was in a thick layer of cold saline water representing a mixture of Yellow Sea Cold Water and Kuroshio water (group 3). Both 6988 and 6978 entered the western channel of the Korea Strait and moved northeastward in July until yd 214 when 6978 was recovered by a

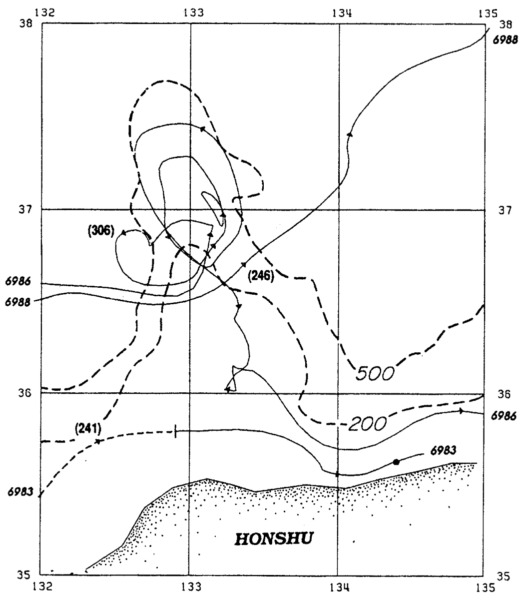

Fig. 7. Drifter trajectories in Japan Sea. Drifter number is printed at beginning and end of each trajectory. Arrows are placed along each trajectory every five days from yd 1, and the time in year-day of the first or second arrow on each trajectory is shown in parenthesis. The trajectory of 6983 during the period yd 240–241 corresponding to the passage of Vera is indicated by the dashed path. The 200- and 500-m isobaths are shown as long dashed curves.

fisherman. During the 15-day period when both drifters were moving freely, the 10 and 40 m drifter velocities tracked one another about half the time, with a mean velocity and speed at 40 m (6 and 7 cm/s) about half that at 10 m (12 and 14 cm/s). Drifter 6988 then accelerated in August and moved through the Korea Strait with a mean velocity and speed of 22 and 28 cm/s. Drifter 6988 reached a peak speed of 83 cm/s in the narrows between Korea and Tsushima Island before slowing somewhat as it entered the Japan Sea. Drifter 6983 was launched into a surface layer of Kuroshio water mixed with shelf water (group 8)(water depth 166 m) and moved quickly through the eastern channel of the Korea Strait in July with a mean velocity and maximum speed of 12 and 28 cm/s until it went ashore in the lee of Iki Island. After being redeployed back in the center of the eastern channel, 6983 continued to move quickly northeastward through the strait reaching a peak speed of 53 cm/s on yd 227 before slowly entering the Japan Sea.

Drifter 6971 moved slowly toward the northeast in the Yellow Sea with a mean velocity and speed of 2 and 8 cm/s in November (see Figs. 4 and 5), then turned toward the southeast and moved into the East China Sea in December with a mean velocity and speed of 8 and 14 cm/s. Drifter 6971 continued to move toward the south and southeast across the East China Sea with monthly mean velocities and speeds of 5–7 and 12–16 cm/s in January and February 1987 until about yd 83 (1987, Fig. 8) when 6971 began to accelerate sharply and entered the Kuroshio near 29.3°N, 127.7°E. 6971 then remained in the Kuroshio until it stopped operating on yd 109 (1987). While in the Kuroshio, 6971 had a mean and maximum speed of 76±64 and 371 cm/s.

Vector correlations computed between drifter velocity and wind stress over one month and longer periods suggest that of the three drifters which remained in the East China Sea for at least one month, only 6971 exhibited clear evidence of partial wind-driving during the winter (December–January). Drifter 6986, located off the southwest tip of Korea (Fig.5), gave a complex response to typhoon Vera (see Appendix). The eye of the typhoon passed near 6986 so that the wind stress on yd 239.5 had a peak of 3.4 dyne/cm^2 toward the southwest and then veered clockwise to a peak of 6.0 dyne/cm^2 toward the east on yd 240.5. On yd 239, 6986 accelerated to the right of the wind stress (angle varying from 120° to 0°) to a peak speed of 42 cm/s on yd 239.75, then decreased in speed rapidly on yd 240 (moving against and to the left of the wind stress). Then as the wind stress decreased from its peak on yd 240.5, 6986 accelerated rapidly to the north to a peak speed of 36 cm/s on yd 241.75.

3. Japan Sea

Three drifters entered the Japan Sea and followed quite different trajectories (Fig. 4). Drifter 6983 left the eastern channel of the Korea Strait about yd 236 and moved roughly parallel to the coast of Honshu with a mean velocity and speed of 41 and 45 cm/s (peak speed 82 cm/s) until about yd 244 when it moved

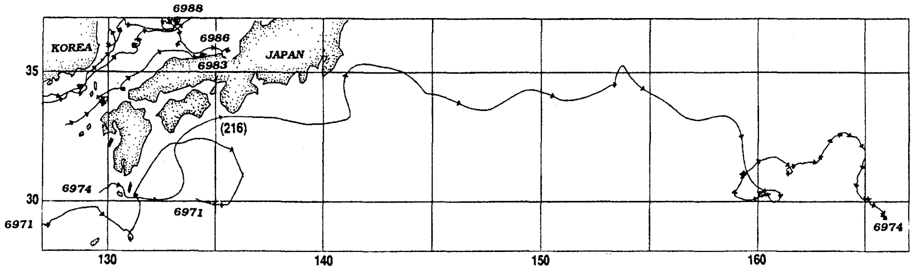

Fig. 8. Drifter trajectories in the Kuroshio and Kuroshio Extension. Drifter number is printed at beginning and end of each trajectory. Arrows are placed along each trajectory every five days from yd 1. The time in year-day of one arrow for 6974 is shown in parenthesis.

quickly close to the coast and became stuck near 35.6° N, 134.3° E four days later. Drifter 6988 left the western channel about yd 230 and began to move quickly toward the northeast, making a small cyclonic loop near 36° N, 131° E before turning east and then northeast and making a larg meander between 38 and 40° N (Fig. 8). During this 35-day period (yd 251–286), 6988 had a mean speed of 32 cm/s, and reached peak speeds of 67 and 76 cm/s in the first northward and southward legs of the large meander. After about yd 286, 6988 slowed on average and drifted generally northward with mean velocities and speeds of 6–9 and 12–13 cm/s. Drifter 6986 left the western channel about yd 276 and moved northeastward, making one cyclonic loop near 36° N, 130° E. On yd 296, 6986 began to accelerate toward the east and made three large and one small cyclonic loops centered near 37° N, 133° E during yd 299–330 (Fig.7). During this period, the mean and maximum speed of 6986 were 26±14 and 68 cm/s, and the average radius of the three large loops was 35±14 km. Then 6986 slowed, drifted southeast and then accelerated and moved quickly along the coast on Honshu with a peak speed of 71 cm/s near 35.9° N, 135° E before slowing and moving onshore and becoming stuck near 35.8° N, 135.6° E on yd 346. The mean drifter eddy kinetic energy in the Japan Sea west of 138° E was 415±91 cm^2/s^2; only 6988 moved east of 138° E where its eddy kinetic energy was only 81±9 cm^2/s^2.

The two drifters in the Japan Sea during tropical storm Vera both exhibited a clear response (see Appendix) but otherwise showed no consistent response to wind forcing based on vector correlations between drifter velocity and wind stress computed over monthly intervals. Drifter 6983 accelerated rapidly toward the northeast to the right of the wind stress (angle varying from about 80° to 30°), reaching a peak speed of 82 cm/s on yd 240.5 even though the wind stress maximum was only 2.4 dyne/cm^2 on yd 240. Drifter 6988 also accelerated rapidly to the northeast to the right of the wind stress (angle varying from about 75° to 30°), reaching a peak speed of 51 cm/s on yd 240.5 about 12 hours after the wind stress reached its maximum of 2.6 dyne/cm^2. For both drifters, the increase in speed over one day from pre-storm speeds was roughly 50 cm/s. Since this acceleration does not seem locally wind-driven, we speculate that the moving wind stress pattern of typhoon Vera forced a strong eastward current pulse through the Korea Strait during yd 240–242.

4. Kuroshio

Drifter 6974 was deployed in Kuroshio surface water (group 7, water depth 1060 m) and moved northeastward at speeds of 20–30 cm/s for several days in July before turning southeastward in the Ohsumi branch of the Kuroshio and continuing eastward (Fig. 8). Drifter 6974 began to accelerate rapidly after passing 130.8° E and joined the core of the Kuroshio by 132° E. Drifter 6974 then moved quickly eastward in the Kuroshio and Kuroshio Extension until about yd 250 when 6974 passed 160° E and slowed dramatically, moving southward on average in the Kuroshio recirculation. Between yd 211–250 when 6974 moved from 132° E to 160° E, 6974 had a mean east velocity and mean speed of 76 and 105 cm/s, reaching a peak speed of 218 cm/s on yd 217 near 33.3° N, 137° E. The initial path of 6974 in the Kuroshio Extension between 140–152° E illustrates the two quasi-stationary meanders described by QIU *et al.* (1991). While in the Kuroshio and Kuroshio Extension, 6974 had a mean and eddy kinetic energy of 0.29 and 0.38 m^2/s^2; after leaving the Kuroshio Extension at 160° E, its mean and eddy kinetic energy dropped to 13 and 148 cm^2/s^2. This variation of drifter eddy kinetic energy with longitude is generally consistent with the analysis of altimeter data by QIU *et al.* (1991). Neither 6974 nor 6971 after entering the Kuroshio appeared to be wind-driven.

4. Discussion

The trajectories of the five drifters deployed in the Yellow Sea support the historical concept of a large-scale cyclonic gyre in the surface waters of the Yellow Sea during late summer. The center of the gyre was located in 1986 near 35.6° N, 123.8° E based on 5843, and the mean velocities along the Korean and Chinese coasts varied from 2 to 6 cm/s. Within the Yellow Sea, the distribution of eddy kinetic energy was relatively uniform spatially at 30–50 cm^2/s^2 except with an increase to about 80 cm^2/s^2 near the Korean coast and higher near the southeast entrance of the Yellow Sea.

The trajectories of drifters deployed in the East China Sea contradict the historical concept of the Tsushima Current as a simple branch of the Kuroshio (as shown in Fig. 1). Instead, the drifter trajectories clearly demonstrate eastward flow into the Korea Strait through both western and eastern channels in late summer and suggest that shelf water (perhaps including some dilute Changjiang discharge) may be drawn directly into the Tsushima Current through the Cheju Strait so that the Tsushima Current may represent a mixture of varying amounts of Kuroshio and shelf water. This idea is supported by direct current measurements made in Cheju Strait by CHANG (1984) which indicate eastward flow with mean speeds of 5–10 cm/s. CHO (1988) argues that this eastward flow through Cheju Strait may contribute as much as one-third of the total Tsushima Current. Although we cannot rule out the possibility that subsurface currents in the western channel of the Korea Strait may originate from the Kuroshio, it is unlikely that the surface current in the western channel comes from the Kuroshio exclusively as indicated by UDA (1934) and NITANI (1972). These drifter trajectories also question the existence of the Yellow Sea Warm Current as a coherent and continuous current in summer, since such a current would have to cross the near-surface currents flowing eastward into Cheju Strait. In winter, the continued drift of 6987 and 6971 toward the south and southeast along the Chinese coast supports the idea of a weak flow of shelf water across the shelf break into the Kuroshio in the East China Sea.

The trajectories of drifters entering the Japan Sea do not support the simple model of branching of the Tsushima Current originally introduced by SUDA and HIDAKA (1932) and UDA (1934). They proposed that the Tsushima Current splits into several branches as it leaves the Korea Strait, and UDA (1934) named the branch along Honshu the Tsushima Warm Current (TWC) and the branch along the east coast of Korea the East Korean Warm Current (EKWC). The concept of branching of the Tsushima Current has been widely accepted, motivating YOON (1982a,b,c) and KAWABE (1982) to simulate it numerically in a model of the Japan Sea with inflow and outflow. In particular, KAWABE (1982) concluded that three branches develop; two branches corresponding to the EKWC and TWC are permanent due to the planetary beta-effect and stratification on the continental shelf, and a third branch located between the two permanent branches is transient, occurring only when the inflow through the Korea Strait increases in summer as shown by MIYAZAKI (1952) and YI (1966).

However, KIM and CHUNG (1984) conducted an intensive hydrographic survey in an area of the Korea Strait where the incipient stage of branching was anticipated, and found that branching did not occur in September 1981. Later KIM and LEGECKIS (1986) analyzed satellite infrared and additional hydrographic data for the period 1981–83 and confirmed that the EKWC did not develop at all in 1981. Instead, abnormally cold water prevailed in the southwestern part of the Japan Sea in 1981, and the

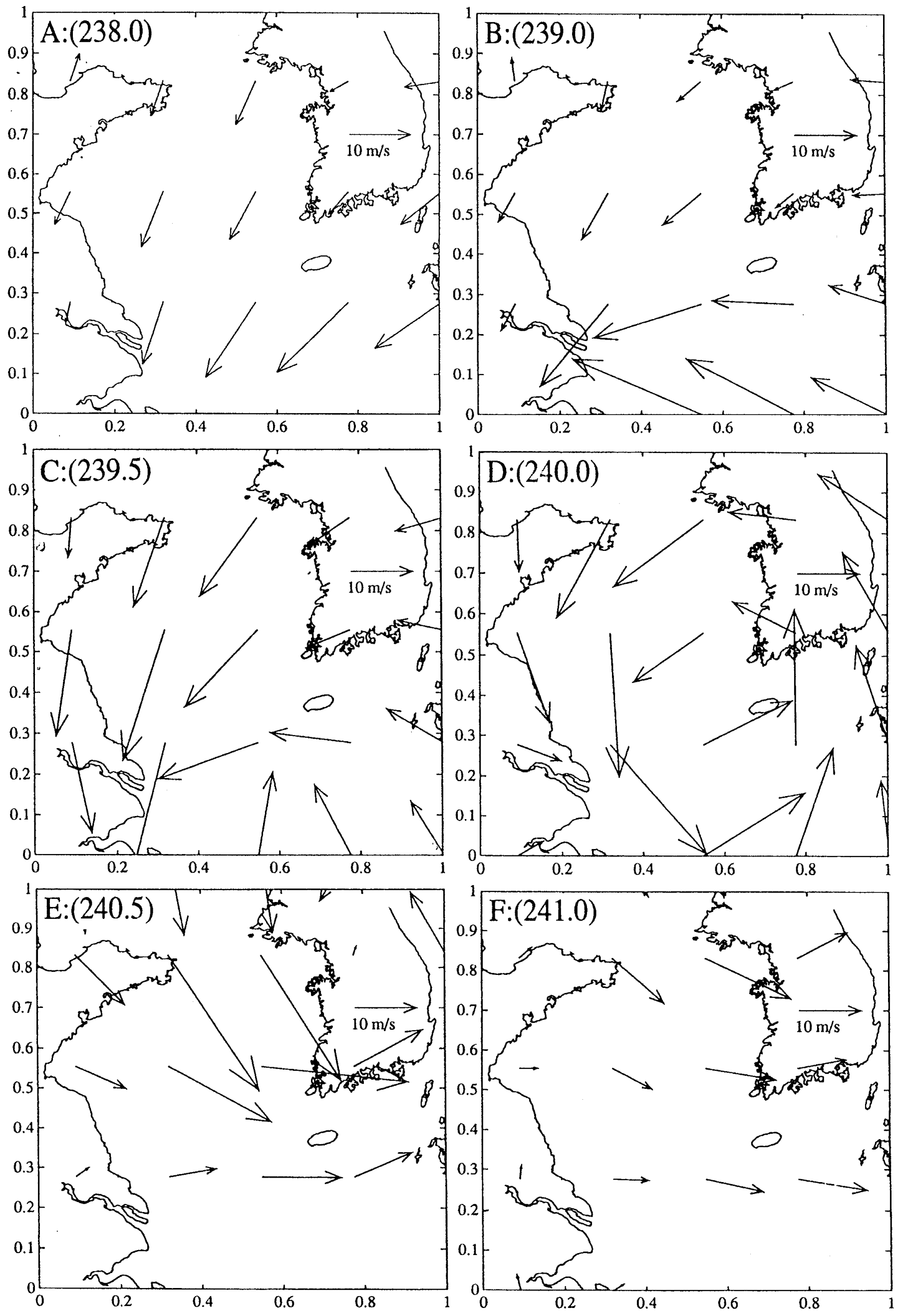

Fig. A1. ECMWF/WCRP-derived surface winds over the Yellow and East China Seas during the passage of typhoon Vera. Panels A-F correspond to a sequence of wind maps starting at 00 GMT August 26 (yd 238.0) through 00 GMT August 29 (yd 241.0). The time of each panel in year-day is given in parenthesis in the upper left of each panel. The horizontal scale in each panel is 1000 km.

entire Tsushima Current flowed along Honshu with no branching. In 1982 and 1983, the EKWC formed in April but was much weaker in 1983.

In summer 1986, we may consider 6983 to be in the TWC but neither drifter exiting the western channel (6986 and 6988) followed the proposed

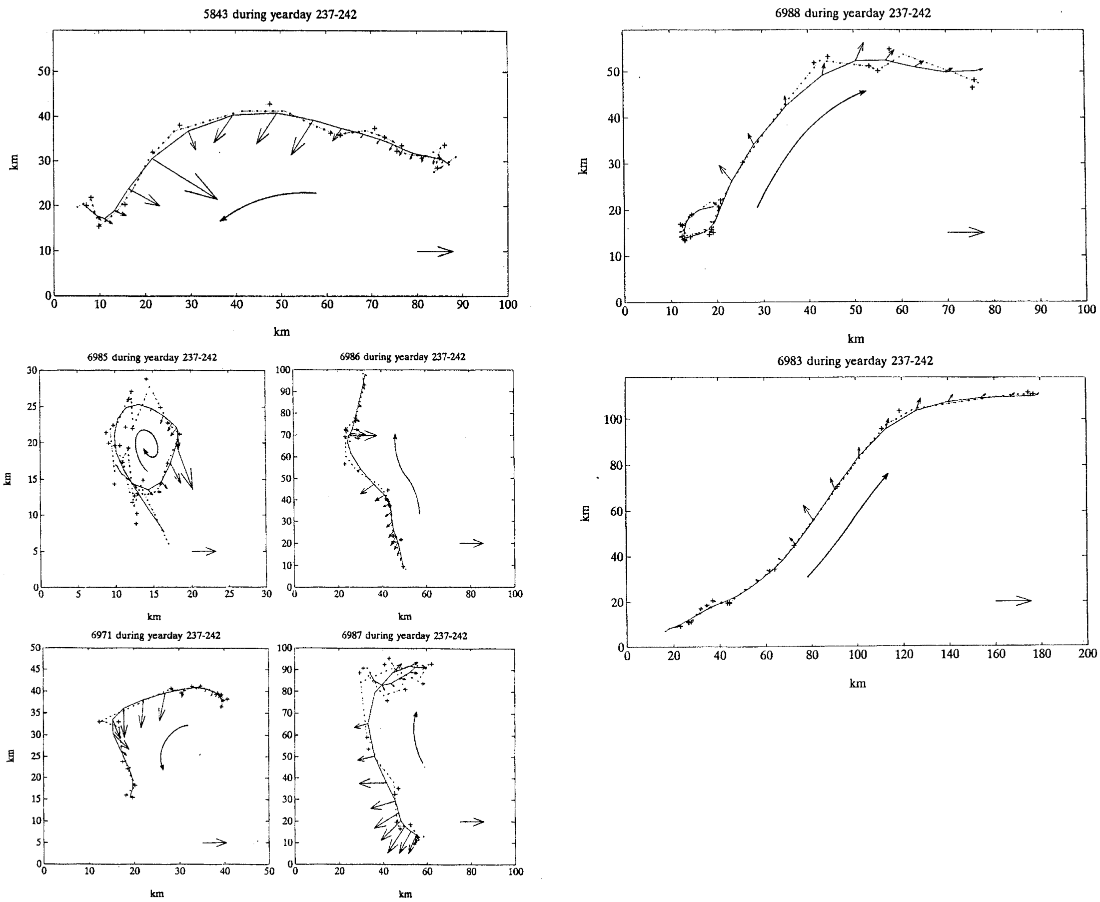

Fig. A2. Drifter trajectories during the five-day period yd 237–242 bracketing the passage of typhoon Vera. Each panel shows the raw drifter positions (crosses), the six-hour interpolated positions (dotted line), and the low-pass filtered trajectory (solid line). The wind stress is superimposed on the low-pass drifter position every six hours. The wind stress vector in the lower right of each panel corresponds to 5 dynes/cm^2.

path of the EKWC. These direct current measurements, plus the recent examination of sea surface temperature variability using synoptic satellite infrared imagery by KIM and LEGECKIS (1986), demonstrate that the behavior of the Tsushima Current in the Japan Sea is quite complex both spatially and temporally.

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Appendix

Typhoon Vera passed across the East China Sea on August 28, 1986 (yd 240). While the primary focus of this paper is on the long-term behavior of each drifter, a brief description of the response of individual drifters to typhoon Vera is given in the text. In this appendix we complete this description by presenting maps of the surface wind field during the passage of Vera (Fig. A1) and maps of the individual drifter trajectories during the five day period August 25 30 (yd 237–242) bracketing the passage of Vera (Fig.A2). The wind field maps show the 10 m gridded winds produced by the ECMWF/WCRP Level III-A surface analysis. The drifter trajectory maps show the raw dirfter positions (which are irregularly spaced in time), the six-hour interpolated positions and the six-hour low-pass filtered positions, in part to illustrate the density of raw position data and how well the interpolation and filtering procedure works to create a smoothed drifter trajectory without tidal and inertial variability. A close look at the raw position data from drifter 6985 in the Gulf of Bohai indicates a significant north-south semidiurnal excursion which is eliminated in the low-pass drifter path. In general, however, the temporal spacing of the raw drifter position data were inadequate to clearly identify significant tidal or inertial motion. Superimposed on the low-pass drifter trajectories is the surface wind stress, computed from the 10 m winds interpolated in space and time to the drifter position from the ECMWF/WCRP Level III-A surface analysis wind field. A wind stress of 5 dyne/cm^2 directed eastward is shown in each map to provide a common scale for the drifter wind stress time series. The speed of a drifter is indicated by the relative length of the trajectory or spacing between the six hourly wind stress vectors.

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