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Taiwan Current (Kuroshio) and Impinging Eddies

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Considerable westward or northwestward propagating eddies were found east of Taiwan that cross-explains the anomalies in the repeated hydrography, trajectory of drifting buoys and altimetric analyses. The sea level differences (SLD) across the Taiwan Current (Kuroshio) in the East Taiwan Channel (ETC) are utilized in order to examine the possible implication of eddies in the Taiwan Current transport. It is concluded that Taiwan is impinged by both cyclonic and anticyclonic mesoscale eddies at an interval of about 100 days. An approaching anticyclonic eddy will result in a higher SLD across the ETC and a larger mass transport of Taiwan Current, and, vice versa, a reduction of both SLD and the mass transport in the ETC as a cyclonic eddy arrives. The SLD-inferred northward transport in the ETC is highly coherent at the 100-day band with westward propagating eddies that originated in the interior ocean. The generation mechanism of these eddies are, however, still unclear. Leakage of the Kuroshio water to the east of the Ryukyu Islands is suggested due to the presence of cyclonic eddies. This 100-day rate of eddy-impingement invalidates any observation of 4 months or less, whether with direct or indirect measurements, because any conclusions depend on the presence or absence of eddies. To minimize the contamination from eddies, either long-term observations or eddy-removal procedures are required.

Keywords:
· Taiwan Current,
· Kuroshio,
· eddy,
· PCM1.

1. Introduction

When the westward-flowing North Equatorial Current reaches the region east of the Philippines it bifurcates to feed the North Equatorial Counter Current in the south and to form Luzon Current which flows northward as the origin of Kuroshio near Japan. Bridging the Luzon Current and Kuroshio is the Taiwan Current east of Taiwan. The Kuroshio system includes all the three currents. The circulation east of Taiwan was considered crucial for understanding the dynamics of the subtropical gyres in the western North Pacific (Hasunuma and Yoshida, 1978). However, the Taiwan Current is poorly understood, compared to the Kuroshio east of the East China Sea (ECS) or south of Japan. Nitani (1972) discussed the anticyclonic warm eddy east of Taiwan (23°N, 125°E) and estimated the eddy transport being about 10 Sv (1 Sv = 10^6 m^3/s), or 30% of the average Kuroshio transport. Common conclusions from earlier hydrographic surveys are that the Kuroshio's geostrophic transport is highly variable east of Taiwan and eddies or counter currents existed east of the Taiwan Current (Chu, 1965, 1967, 1970, 1974, 1976). During repeated hydrographic sections across the Taiwan Current, eddy-like velocity structure are often found (Liu *et al.*, 1986, 1998). The satellite-tracked surface drifters also showed eddy-like trajectories east of Taiwan (Lie *et al.*, 1998). All of these studies suggest that mesoscale eddies or counter currents exist east of Taiwan where the Taiwan Current flows northward. Is the Taiwan Current being influenced by eddies? How much is the influence and what are the consequences?

Ocean eddies are the storms in the ocean, playing important roles in ocean dynamics as well as the transport of heat, salt, and other chemical properties. Mesoscale eddies are a ubiquitous and energetic feature of the open oceans, but their role in the general circulation remains to be quantified. The U.S./France TOPEX/POSEIDON (T/P) satellite uses a radar altimeter system to determine the sea surface height relative to a reference ellipsoid. It has a maximum equatorial ground track spacing of 316 km and is specially designed to study global ocean dynamics. Although the spatial resolution of T/P data is less than satisfactory, it may clearly illustrate the evolution and propagation of mesoscale eddies (Gründlingh, 1995; Soong *et al.*, 1995) that can hardly be done with *in situ* data. The purpose of this study is to corroborate the anomalous hydrographic sections and buoy tracks east of Taiwan which are the results of impinging eddies from the southeast, and to assess its implication on the volume transport measurements of the Taiwan Current. Data of hydrographic surveys, drifting buoy trajectories, and T/P altimetry measurements will be cross-examined for their anomalies. Sea level difference across the Taiwan Current will be utilized to examine the influence of mesoscale eddies on the measurements of the Taiwan Current transport.

2. Eddy Manifestation

2.1 Hydrographic surveys

The main entrance of the Kuroshio to the ECS is the channel between Taiwan and Iriomote at 24.5°N. The East Taiwan Channel (ETC) has a width of about 100 km and a mean depth of about 500 m. Regular hydrographic surveys of the Taiwan Current in the ETC were carried out more than twice a year from October 1990 to May 1996. This transact was designated as PCM1 in the WOCE program. The PCM1 experiment is a major contribution of the Republic of China (ROC) to the WOCE Direct Measurement program. Nominal hydrographic stations and bottom topography along PCM1 are shown in Fig. 1. The 16-cruise averaged geostrophic velocity profile (referenced to 1000 m or bottom whichever is shallower) along the PCM1 transact shows a typical western boundary current (Fig. 2(a)). Table 1 lists the 16 hydrographic cruises. However, in mid-March 1995 (Fig. 2(b)), the velocity core

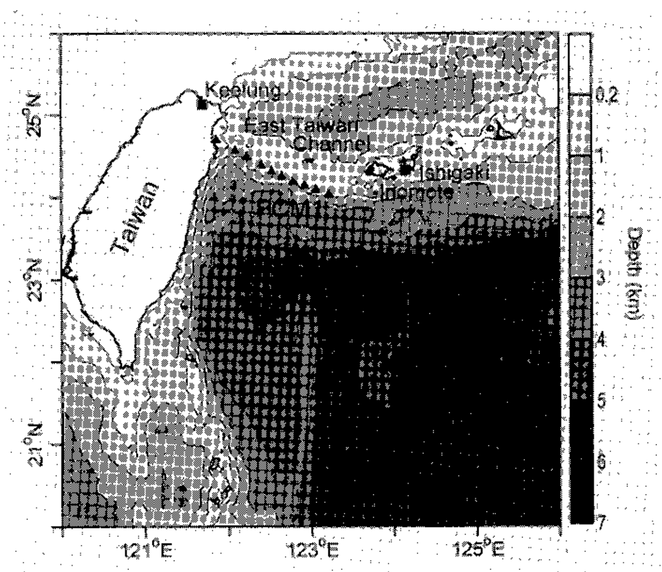

Fig. 1. Nominal locations of hydrographic stations (triangles) along PCM1 and tidal stations (squares) across the Taiwan Current in the East Taiwan Channel.

Table 1. Cruise numbers and dates of the 16 hydrographic surveys conducted over PCM1 aboard R/V Ocean Researcher I (OR1) and Ocean Researcher II (OR2).

Cruise No.	Cruise date
OR1_257	1990/10/18
OR1_294	1991/09/07–08
OR1_307	1992/01/06
OR1_323	1992/07/11
OR1_334	1992/10/29
OR1_354	1993/05/26
OR1_370	1993/10/21–22
OR1_387	1994/05/14–15
OR2_056	1994/09/16–17
OR1_401	1994/09/17–19
OR1_407	1994/12/29–30
OR1_412	1995/03/16–17
OR1_418	1995/05/04–05
OR1_433	1995/10/13–14
OR1_443	1996/03/12–13
OR1_452	1996/05/30–31

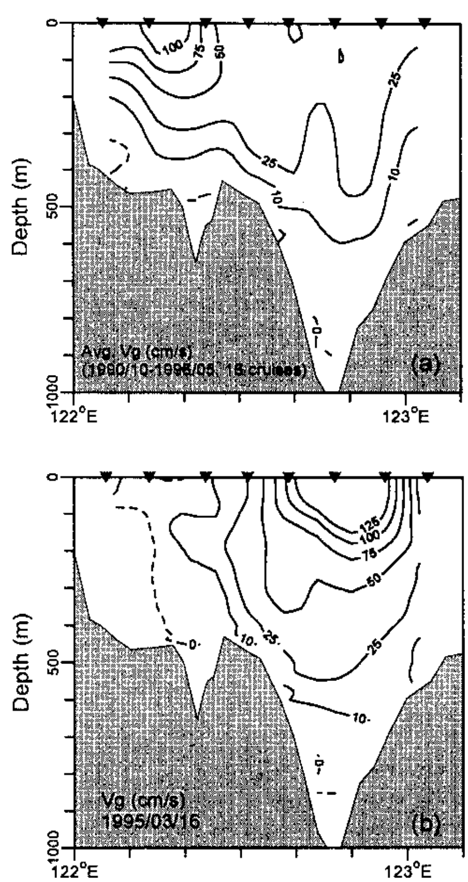

Fig. 2. Geostrophic velocity section profiles along PCM1 (a) averaged from 16 cruises and (b) conducted on March 16, 1995. Units of velocity contours are cm/s.

moved eastward which is generally categorized as Kuroshio meandering. The difference between sea level anomalies at Ishigaki of Ryukyus and Keelung of Taiwan decreased at this time and during many other periods (Fig. 10(c)). The immediate questions are: (1) Are these changes of sea level difference results of the change of the Taiwan Current volume transport, or the Kuroshio's meandering that originated upstream? and (2) What are the causes of the change of the Kuroshio transport, or the Kuroshio's meandering? We found that the northwestward propagating cyclonic eddy was responsible for the event of 1995 March.

2.2 Surface drifting buoys

To study the Lagrangian motion of Kuroshio's system, 4 to 5 satellite-tracked surface drifting buoys were

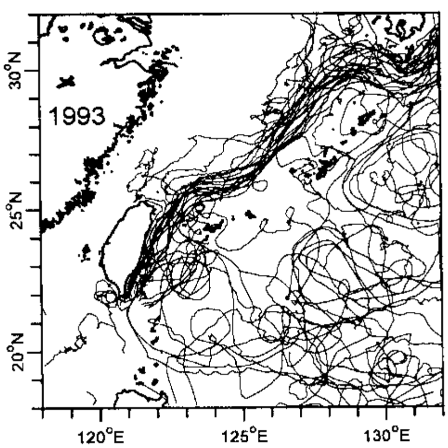

Fig. 3. Trajectories of the WOCE/TOGA drifting buoys near Taiwan in 1993.

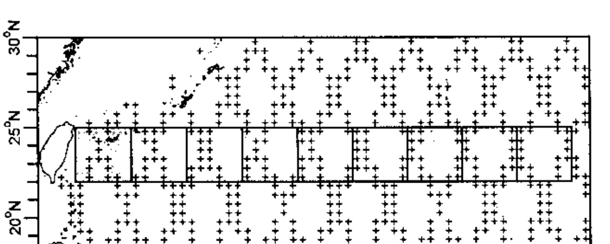

Fig. 4. Distribution of averaged TOPEX/POSEIDON measurements (crosses). The T/P sea surface height anomalies (SSHA) in the shaded box were averaged to represent the strength of eddies east of Taiwan. Averaged SSHA in open boxes were lag-correlated to that in the shaded box.

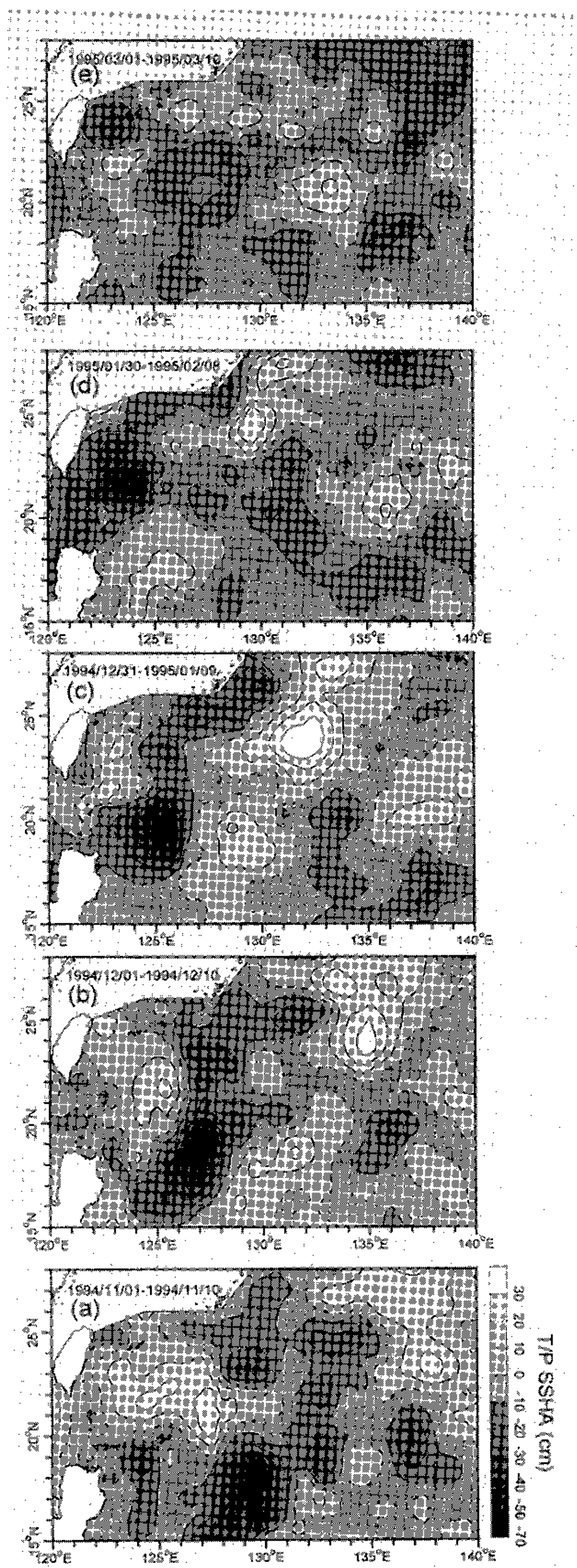

Fig. 5. Monthly advance of T/P SSHA from November 1994 to March 1995. A remarkable low anomaly propagated northwestward towards Taiwan. The zero contours of SSHA are plotted in dashed lines.

deployed bi-monthly or quarterly southeast of Taiwan, from 1991 to 1996 as a contribution of the ROC to the WOCE/TOGA Surface Velocity Programme. Figure 3 shows an example of buoy trajectories near Taiwan in 1993. The Kuroshio main stream is characterized by the dense buoy trajectories along the east coast of Taiwan. Meandering or eddy-like motions are frequently detected east of Taiwan. Among them, 21 buoy trajectories are selected to exemplify the influence of mesoscale eddies. They include 5 buoys deployed in March 1993, 5 in September 1993, another 5 in March 1995 and the rest in June 1995. All of them were equipped with a 7 m long holey-sock drogue at 15 m depth, namely to measure the current at the depth which represents the flow of the mixed layer.

2.3 Altimetry data

TOPEX/POSEIDON, in orbit since August 1992, is the first space mission specially designed and constructed for studying the circulation of the world's oceans. It measures the precise height of sea level, from which information on the ocean circulation is obtained. The T/P measurements look like virtual tide gauges with a sample interval of 9.91 days. The virtual tide gauge observations are then averaged in bins whose size is 0.5 degrees in both longitude and latitude, and 10 days. Figure 4 shows the distribution of spatially averaged altimetry data east of Taiwan. For the data from each of these virtual tide gauges, a 4-year mean (January 1993 to December 1996) were removed and therefore the sea surface height anomalies (SSHA) were obtained (Benada, 1997).

To explain the anomalous velocity section of mid-March 1995 (Fig. 2(b)), we plotted the monthly advances of SSHA (Fig. 5) from November 1994 to March 1995. A distinctive cyclonic eddy apparently propagated northwestward from 17°N, 129°E to the east of Taiwan at about 10 cm/s. The amplitude of this powerful low anomaly is estimated to be O (40 cm) which is compat-

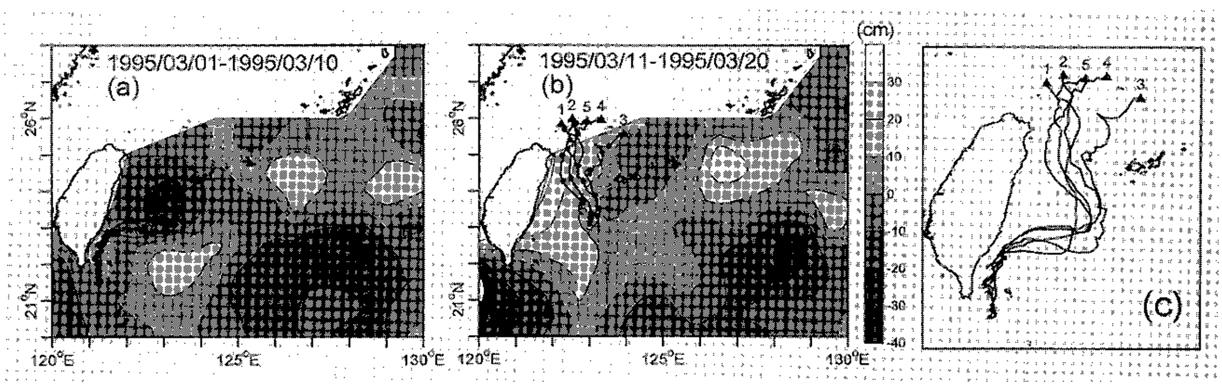

Fig. 6. The T/P SSHA and the concurrent drifting buoy trajectories that are marked with solid dots for 2-day increments. The triangles are the ending locations of buoys in the time frame of (a) 1995/03/01 ~ 3/10, (b) 1995/03/11 ~ 3/20, and (c) 1995/03/01 ~ 3/20 of the whole time period. Cyclonic features are centered with heavier shading. Contour interval is 10 cm and the zero contours are plotted in dashed lines.

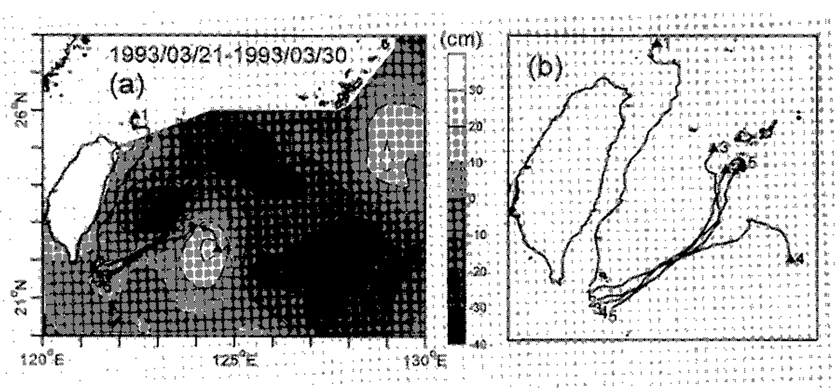

Fig. 7. Same as Fig. 6 but (a) for the period of 1993/03/21 to 3/30, and (b) their overall trajectories.

ible to the sea surface difference of O (100 cm) across the Kuroshio system. The northward flowing Taiwan Current will therefore be affected significantly by the impinging eddies, and the eastern part of the Taiwan Current would be forced to make a detour when the cyclonic eddy closes in. In early March 1995, 5 drifting buoys were deployed southeast of Taiwan, the expected location of the core of Taiwan Current. These buoys were therefore expected to be carried downstream and their trajectories will show the mean path of the Taiwan Current that is nearly parallel to the east coast of Taiwan. Instead, all of these 5 buoys made unusual cyclonic turns following the low SSHA detected by T/P (Fig. 6(a)). After circum-passing the cyclonic eddy, all buoys passed the eastern part of the ETC (Figs. 2(b) and 6(b)) and returned to its normal path to join Kuroshio in the ECS.

Three more examples are presented in Figs. 7, 8, and 9. Almost all the circular trajectories of buoys matched with contours of SSHA from T/P measurements. Among the 5 buoys deployed in March 1993 (Fig. 7), 4 buoys made a 300 km diameter detour from the normal path of the Taiwan Current, and three of them re-joined the westernmost buoy and entered the Kuroshio in the ECS. The T/P measurements (Fig. 7(a)) show that these buoys went through the middle of a pair of eddies. Figure 8 illustrates the trajectories of 5 buoys near Taiwan. Four of them were deployed in early September 1993 near the southern tip of Taiwan and they followed the normal routes of the Taiwan Current towards the ECS. Buoy No. 5 in Fig. 8 was deployed at 141.51°E, 6.09°N on June 12, 1990, transported westward by the NEC and trapped by a high SSHA east of Taiwan.

The extreme case of the eddy's influence on the western boundary current happened in June 1995 (Fig. 9). Six buoys were deployed closely in the Taiwan Current for studying the eddy diffusion rate along the Kuroshio system. Unexpectedly, they all went northeastward away from the western boundary. The anticyclonic eddy east of Taiwan was as large as 500 km in diameter. It swept all buoys to the east. Only one buoy managed to return to the Kuroshio through the Ryukyu Islands, and one stayed in this big eddy and moved clockwise towards the place that it was deployed. The majority rode along interfaces between cyclonic and anticyclonic eddies and continued flowing eastward.

In summary, cyclonic or anticyclonic mesoscale eddies occurred frequently east of Taiwan, they are energetic enough to detour the Taiwan Current, and sometimes split it into two branches (Fig. 7(b)). The clockwise stationary gyre east of Taiwan (Nitani, 1972) may not be detectable nor verifiable by the de-meaned T/P measurements, but it was certainly overwhelmed by the propagating eddies from the southeast.

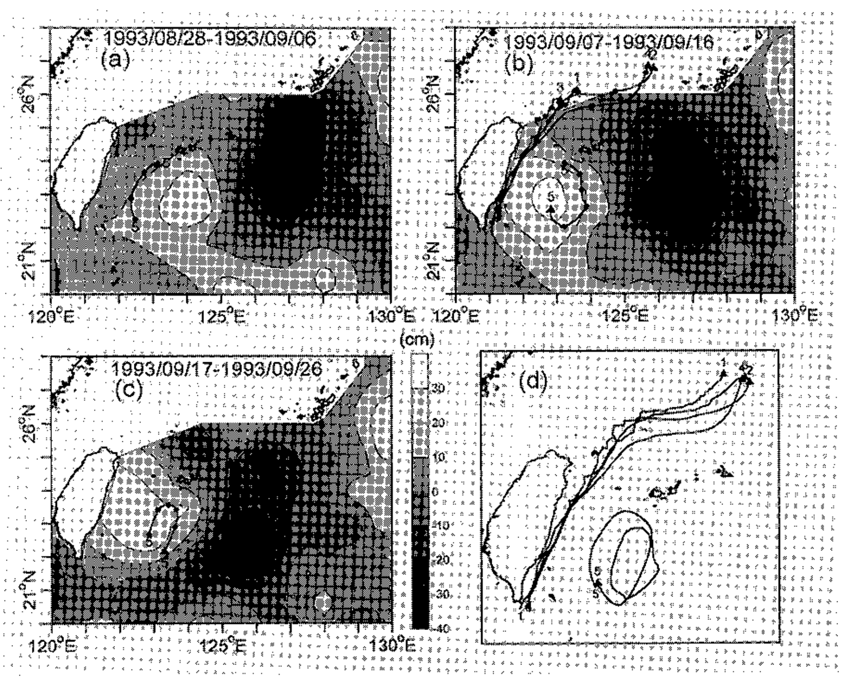

Fig. 8. Same as Fig. 6 but (a), (b) and (c) for three consecutive 10-day time frames from 1993/08/28 to 1993/09/26 and (d) their overall trajectories.

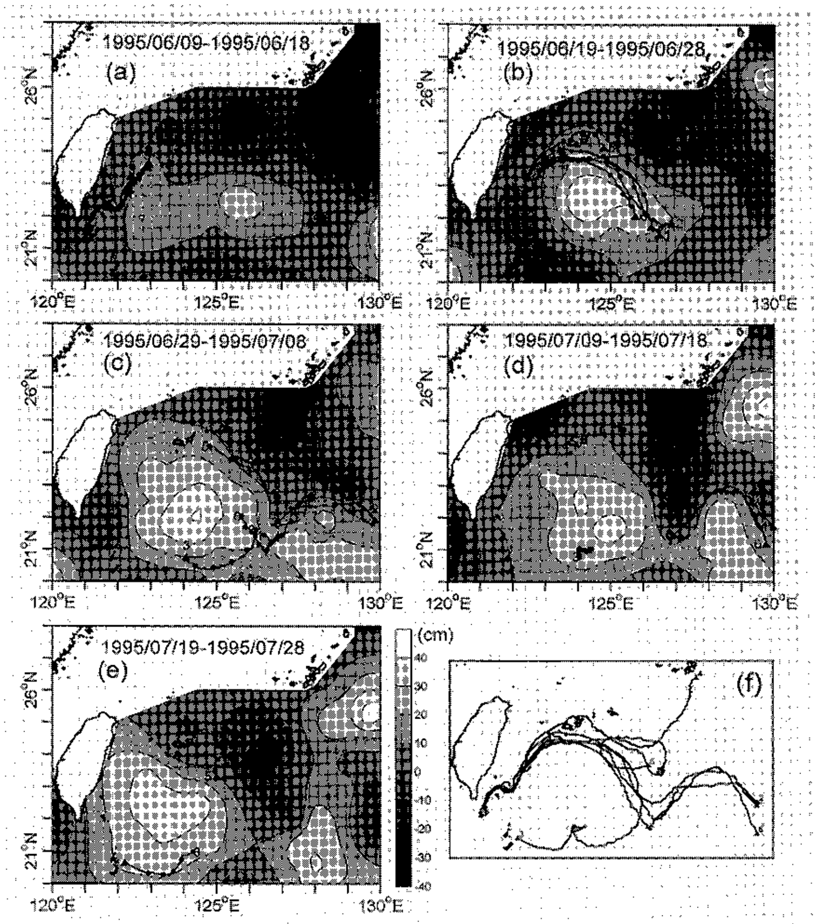

Fig. 9. Same as Fig. 6 but (a), (b), (c), (d) and (e) for five consecutive 10-day time frames from 1995/06/09 to 1995/07/28 and (f) their overall trajectories.

3. Discussion

Eddies were frequently observed east of Taiwan and many of them had the current speed comparable to that of the Kuroshio. Their presence caused difficulties in estimating the Kuroshio transport east of Taiwan because the volume transport may be overestimated if the integration from the Taiwan coast ends in a clockwise eddy, and underestimated for a counter-clockwise eddy. Also, we may spatially under-sample eddies that are "thin" in the east-west direction.

Geostrophic Taiwan Current transport across PCM1 will certainly be underestimated across shallow regions. The amount of underestimation may decrease with the eastward movement of the Taiwan Current into the deeper section of PCM1. Instead, the sea level difference (SLD) across PCM1 is used to examine the possible impact of eddies on the Taiwan Current transport. SLD across an ocean current is an indirect but generally accepted first-order measure of ocean surface current velocity in extra-tropical regions. Chu (1976) was the first to try to assess the correlation among SLD between Ishigaki, Japan and Keelung, Taiwan, dynamic height difference, and geostrophic transports of 6 cruises across the Taiwan Current. Though nor as good as the difference of dynamic height, the SLD does correlate with geostrophic transport in the comparison of 6 cruises. Because the transport between two tidal stations is highly correlated with their SLD (Blaha and Reed, 1982; Maul *et al.*, 1985; Kawabe, 1988; Greatbatch and Goulding, 1990; Maeda *et al.*, 1993), barometry-corrected SLD at Keelung and Ishigaki are utilized for studying the variations of Taiwan Current transport. Figure 10 shows the sea level anomalies of Ishigaki, Keelung, and their differences from October 1992 to June 1996. Apparently, Keelung's has much higher frequency signals than that of Ishigaki, because Keelung faces the shallow ECS where storms and weather fronts are common. The strength of eddies east of Taiwan is represented by the SSHA averaged over the

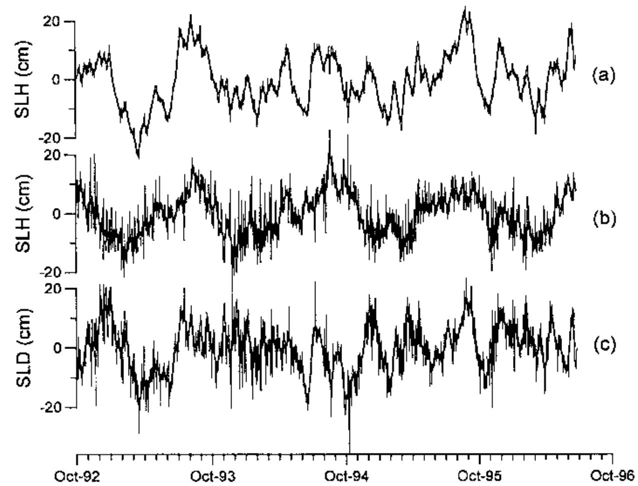

Fig. 10. Air-pressure adjusted daily sea level height anomalies (thin lines) at (a) Ishigaki, (b) Keelung, and (c) the sea level difference anomalies of Ishigaki minus Keelung. The 10-day low-passed data are overlaid in thick lines.

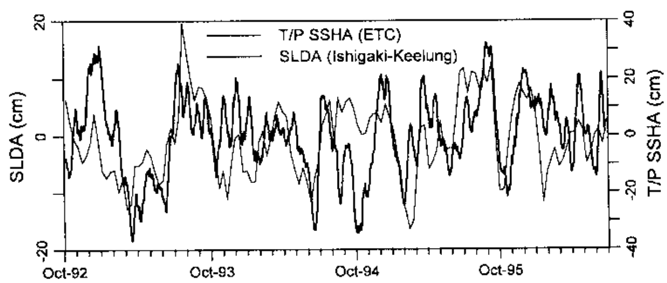

Fig. 11. Variations of the 10-day low-passed SLD anomaly between Ishigaki and Keelung (thick line) and the averaged T/P SSHA (thin line) in the ETC (East Taiwan Channel).

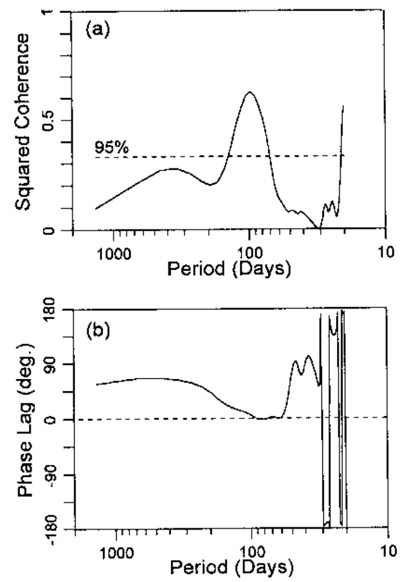

Fig. 12. (a) Squared coherence and (b) phase spectra between the SLD anomaly and the SSHA in the ETC. The SSHA leads the SLD anomaly if the phase lag is positive.

region of 22°N to 25°N and 122°E to 125°E (Fig. 4). Generally, the agreement between SLD (representing the Taiwan Current transport) and SSHA (representing eddy's contribution) is good (Fig. 11).

An averaged high SSHA is associated with a larger SLD which means a larger northward transport. A low anomaly corresponds to a smaller northward transport. Figure 12 shows that they are highly coherent in a nearly 100-day period band. Similar fluctuations have been addressed in several studies such as Kawabe (1987) in the Tokara Strait south of Japan, Lee *et al.* (1990, 1996) in the Bahamas, and Mata *et al.* (1998) in Australia. All the areas studied are in the regions of intense western boundary current. The 100-day coherent fluctuations are expected to be associated with the westward propagating eddies in the form of Rossby waves (Mitchum, 1995). The dispersion relation of the extratropical Rossby waves is given by

$$\omega = -\beta k / \left(k^2 + l^2 + f_0^2 / c^2\right) \tag{1}$$

where ω is the frequency, k and l are the zonal and meridional wavenumbers, respectively, f_0 is the local Coriolis parameter where the β-plane is centered, and c is the speed of the freely propagating, first-mode baroclinic waves. For Rossby waves in the open ocean, they can be simplified with longwave approximation and the resulting dispersion relation is

$$\omega = -\beta k L_R^2 \tag{2}$$

where $L_R = c/f_0$ is the internal Rossby radius. Using c = 2.4 m/s from *in situ* density profiles at 23.5°N east of Taiwan, the zonal wave speed ω/k is approximately 3.6 cm/s. For a given latitude, also known as the turning latitude, with which there is a maximum frequency associated with Rossby waves can exist, is given by

$$\omega_{\max} = \frac{1}{2}\beta L_R = \frac{c}{2R}\cot\varphi \tag{3}$$

where R is the radius of the Earth and φ is the latitude. Alternatively, this may be interpreted as giving the maximum latitude at which waves of a certain period can exist and beyond which it becomes evanescent. For a first-mode baroclinic wave of c = 2.4 m/s at 23.5°N, the maximum frequency corresponding to a minimum period of

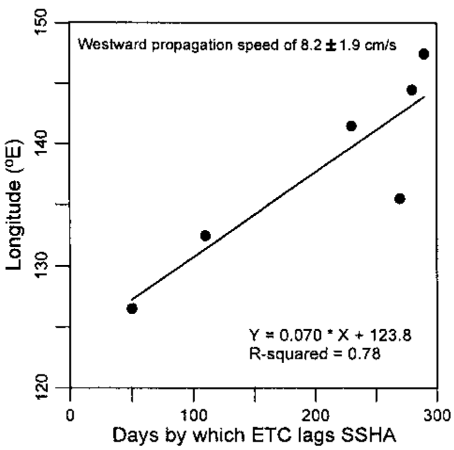

Fig. 13. The solid dots show the time lags at maximum correlation against the longitudes between 122°E to 150°E in lagged correlation analyses. The T/P SSHA measurements inside each of the 3-degree squares in a latitude band centered at 23.5°N are averaged. Two out-of-range data are not shown.

fluctuation is around 170 days. This is, however, the intrinsic period of the oscillations. If mean current is present, then the observed frequency will be Doppler shifted. A lagged correlation analysis was applied to 3° × 3° boxes between 122°E and 150°E centered at 23.5°N, to check for possible propagating SSHA (Fig. 4). The westward propagating speed of the highest correlation has the best fit of 8.2 ± 1.9 cm/s (Fig. 13), which is more than twice as fast than that predicted by standard theory. This indicates that free, linear Rossby waves in the standard theory is an incomplete description of the observed waves (Chelton and Schlax, 1996). The discrepancy between standard theory and observations was recently explained by the inclusion of baroclinic flow (Killworth *et al.*, 1997).

4. Concluding Remarks

Nearly all of the hydrographic surveys southeast of Taiwan showed multi-core structure of currents with interleaving northward and southward flows. Usually, this phenomenon is interpreted as meandering or inhomogeneity of the Kuroshio, the existence of gyre, or the interaction of eddies. Without satellite mapping of sea surface heights, we cannot decide which one is the case for each hydrographic section. The volume transport (either geostrophic computation or the ship-board ADCP-section) has an intrinsic uncertainty on the eastern limit of the integration for volume transport. To summarize our findings:

(1) Taiwan is frequently visited by both cyclonic and anticyclonic mesoscale eddies, as seen in the T/P SSHA analysis. Some of the eddies have a comparable current speed to the Taiwan Current.

(2) Since the SLD across a current is related to the transport of the current, it is reasonable to use SLD across the channel to measure the variability of Taiwan Current transport in the ETC; a higher (lower) SLD across the ETC means a larger (smaller) transport of Taiwan Current northward.

(3) The SLD in the ETC is coherent at a 100-day period with the arrival of westward propagating eddies that originated in the interior ocean. An approaching anticyclonic eddy results in higher SLD and, vice versa, a larger Taiwan Current mass transport for a cyclonic eddy that reduces the SLD and the Taiwan Current transport in the ETC.

(4) Since the Kuroshio system is part of the basin-wide circulation, its transport is independent of a propagating eddy, therefore the decrease of Kuroshio transport in the ETC implies leakage of the Kuroshio water to the east of the Ryukyu Islands.

(5) This 100-day correlation period implies that any observation of 4 months or less, either direct or indirect measurement, could lead to eddy-dependent conclusions. To minimize the contamination from eddies, either long-term observations or eddy-removal procedures are necessary.

Some studies proposed a large northward transport east of the Ryukyu Islands that is comparable to the Kuroshio transport in the ECS (Sekine and Kutsuwada, 1994; Yuan *et al.*, 1995, 1998). Since their conclusions were based on hydrographic and other indirect observations, it will be better to assure that the observations and conclusions were free of eddy-contamination.

Acknowledgements

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