

Geostrophic Uncertainty and Anomalous Current Structure in Association with Mesoscale Eddies Delineated by Altimeter Observations East of Taiwan

Y. Yang

National Center for Ocean Research, P.O. Box 23-13, Taipei, Taiwan 106, Republic of China
yy@oc.ntu.edu.tw

C.-T. Liu

Institute of Oceanography, National Taiwan University, Taipei, Taiwan 106, Republic of China

T. N. Lee, W. E. Johns

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Florida 33149, U.S.A.

Abstract. Moored velocity measurements and hydrographic surveys east of Taiwan, collaborating with altimeter and satellite-tracked surface drifters observations, are demonstrated in this paper to elucidate the influence of propagating mesoscale eddies on field measurements. Observations show that both of the current structure and hydrographic fields can be easily shaped by eddies, even for the westward-intensified swift Taiwan Current. A mechanism of interaction between Taiwan Current and propagating eddies is proposed to explain the observed phenomena. Readers are reminded that conclusions based on observations, either direct or indirect measurements, conducted over the regions where mesoscale eddy activities are prominent are possibly only snapshots of highly changeable oceanic conditions.

Keywords. Mesoscale eddies, Taiwan Current, Kuroshio, altimeter, PCM1, PR20, geostrophy

1 Introduction

Taiwan stands on the edge of the continental shelf off the mainland China and is surrounded by several water bodies. To its north is the East China Sea (ECS) which has a wide continental shelf and to its south is the semi-enclosed South China Sea (SCS). The Taiwan Strait, which is a shallow channel connecting the ECS and the SCS, is located on its west and to its east is the deep Pacific Ocean. When the westward-flowing North Equatorial Current reaches the area east of the Philippines, it bifurcates to feed the North Equatorial Counter Current in the south and to form the northward-flowing Luzon Current in

the north. The Luzon Current can be regarded as the origin of the Kuroshio near Japan. Bridging the Luzon Current and the Kuroshio is the Taiwan Current east of Taiwan, which is part of the Kuroshio system.

The Kuroshio system covers the western boundary of the North Pacific Ocean from the Philippines to Japan. Numerous routine hydrographic surveys, which were conducted by Japan mainly in the regions near Japan, in the ECS and in the pelagic western North Pacific Ocean have been continued for nearly a century. Investigations of the Taiwan Current, however, are extremely sparse. Earlier studies suggested that the high variability of current speed, current axis position and volume transport of the Taiwan Current is correlated to the presence of eddies or counter currents east of Taiwan (Nitani, 1972; Chu, 1970, 1974, 1976; Liu, 1983; Liu et al., 1986, 1998). More recently, a regular hydrographic program (PR20) was initiated in 1990 and completed in 1996 as part of the Taiwan's contribution to the World Ocean Circulation Experiment (WOCE). At the meantime a current meter array (PCM1), which is also part of WOCE, had been maintained jointly for 20 months by Taiwan and the U.S.A. over the East Taiwan Channel (ETC) to measure the Taiwan Current volume transport directly. Based on the PCM1 measurements, variation of the Taiwan Current volume transport is found to be closely related to impinging mesoscale eddies which propagated westward from the interior of the western North Pacific Ocean on time scale of 100 days (Yang, 1999; Yang et al., 1999; Johns et al., 2001; Lee et al., 2001; Zhang et al., 2001). The impact of eddies on estimating the volume transport of the Western Boundary Current (WBC) in the Pacific has been reported for a long time (Nitani, 1972;

Hasunuma and Yoshida, 1978; Lukas et al., 1991; Wijffels et al., 1995; Qu et al., 1998). Nevertheless, almost all of these studies did not show clear evidences to clarify the influence of propagating eddies on hydrographic or current velocity fields. From measurements conducted at PCM1 and PR20, some of the anomalous features presented in hydrographic and current measurements east of Taiwan are shown. These anomalies can be almost well explained by the presence of mesoscale eddies that delineated by altimeter measurements.

2 Data

The PCM1 array consisted of 11 moorings equipped with current meters and thermometers. Moorings were sustained from September 1994 to May 1996 over the submarine ridge east of Taiwan (Fig. 1). The moorings spanned over the ETC between Taiwan and the southern end of the Ryukyu Islands, of which the opening is the main entrance of the Taiwan Current to the ECS. Figure 2 shows the nominal configuration of instrumentation. Coastal shallow-water moorings of T1, T2 and T7 were vulnerable to fishing activities and only survived for few weeks. The recorded data duration and data manipulation were well presented by Yang (1999) and Johns et al. (2001).

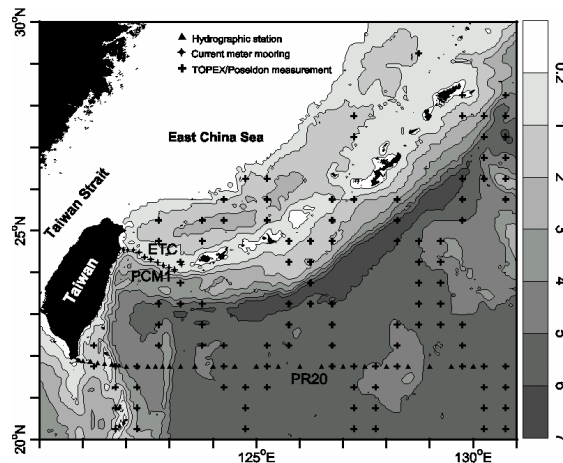


Fig. 1 Nominal locations of PCM1 moorings deployed at ETC, repeated hydrographic stations over PR20 and gridded TOPEX/POSEIDON sea surface height measurements. Units of bottom topography contours are km.

In addition to the moored measurements, repeated hydrographic surveys were carried out twice a year along PCM1 at 24.5°N and PR20 at 21.75°N from 1990 to 1996. More intensive surveys were conducted seasonally at PCM1 after the commencement of mooring observations in September 1994. Due to the shallow submarine ridge at ETC, the bottom depths were selected as the reference levels used in geostrophic computation at PCM1 and 1000 dbar was adopted at PR20. The vertical integrals of current velocity beginning from different reference levels may sometimes induce large uncertainty in volume transport. It was shown that both of the mean geostrophic volume transport and its estimation error of the Taiwan Current at PR20 are insensitive to the selection of reference levels within the depth range between 800 and 2000 dbar (Yang and Liu, 2003).

To delineate the spatial distribution and evolution of propagating mesoscale eddies, the TOPEX/POSEIDON (T/P hereafter) measurements are used in this study. The T/P sea surface height measurements look like virtual tide gauges with a nearly 10-day sampling interval. The virtual tide gauge observations are then averaged in bins of size 0.5 degrees in both longitude and latitude. From each such virtual tide gauge, a 4-year mean from January 1993 to December 1996 is removed, thus allowing the sea surface height anomalies (SSHA) to be obtained.

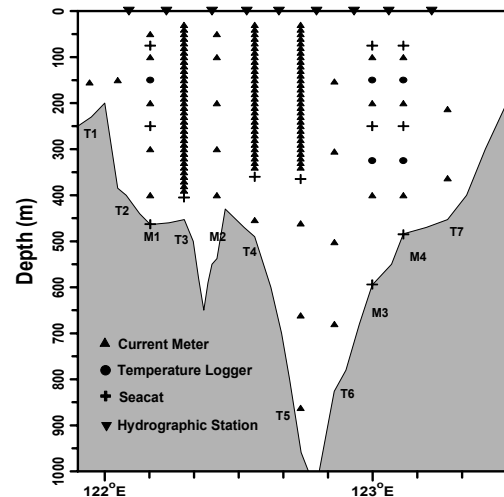


Fig. 2 Nominal instrumentation of PCM1. National Taiwan University moorings are T1-T7 and University of Miami moorings are M1-M4. Repeated hydrographic stations are shown at the top of the panel.

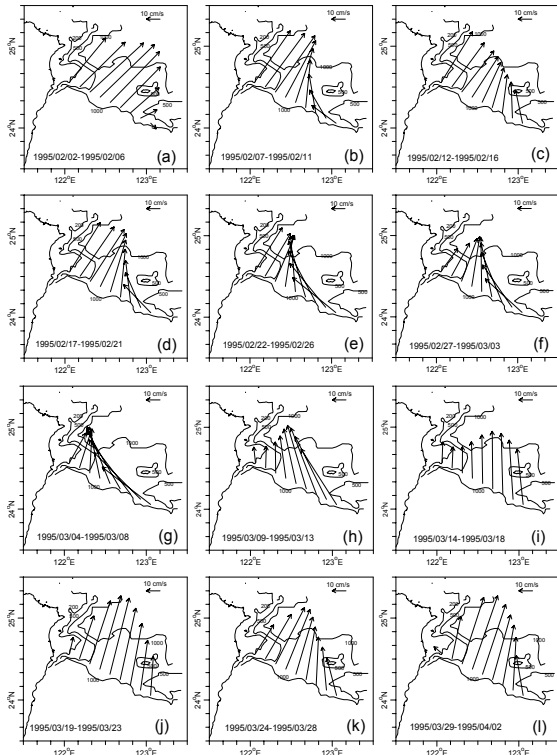


Fig. 3 Twelve consecutive current vectors derived from moored observations at PCM1 during the period from (a) 1995/02/02 to (l) 1995/04/02. Each panel shows 5-day, upper 400 m, vertical-averaged results. Part of the topography contours of 200 m, 500 m, and 1000 m are superimposed.

3 Eddy-Related Anomaly

3.1 Ocean Current Structure

The Taiwan Current, which is part of the Kuroshio east of Taiwan, is a WBC with a typical current speed of 1 m/s and a width of 100 km. In early days, the current structure was inferred mainly from sparse hydrographic measurements and highly variable results made the conclusions inconsistently from cruise to cruise (Chu, 1970; Nitani, 1972; Liu, 1983). Based on the 12 surveys of hydrographic and vessel-mounted current velocity measurements, Liu et al. (1998) depicted the distinctive asymmetric mean velocity structure of the Taiwan Current over the ETC. The spatial and temporal variations of the current structure, however, were not well explored. In contrast with the generality of quasi-stationary, slow-varying characteristics of ocean current mentioned in textbooks, the Taiwan Current structure both in speed and direction could have a remarkable change within two months (Fig. 3). It looks like that a considerable northwestward flow joins the Taiwan

Current intermittently at the south of PCM1. However, no reported evidences show that there exists noticeable currents east of the Taiwan Current. Another conceivable suggestion is that Taiwan Current is split into two parts at somewhere upstream and the offshore part rejoins the Taiwan Current before entering the ECS through the shallow ETC. Abrupt bottom topography and nearly constant prevailing winds are not responsible for this sporadic mesoscale event (Yang, 1999). Then what made the strong Taiwan Current had such a marvelous change within such a short time?

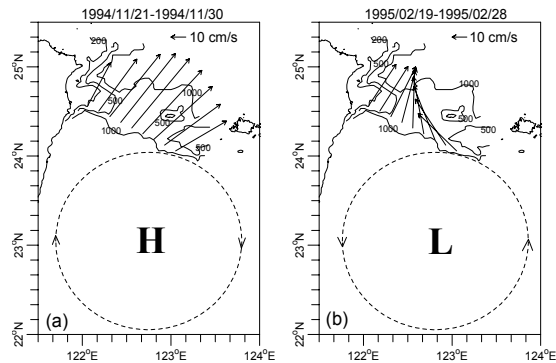


Fig. 4 Schematic presentation of the interaction between Taiwan Current and (a) anticyclonic and (b) cyclonic eddy. Two time frames of the observed 10-day, upper 400 m, vertical-averaged current vectors at PCM1 during the periods of (a) 1994/11/21~30 and (b) 1995/02/19~28 are overlapped.

Mesoscale eddies are ubiquitous in pelagic oceans. They are storms in the oceans, playing important roles in ocean dynamics as well as the transport of heat, chemical and biological properties. Their impact upon the WBC remains to be illuminated. A plausible mechanism to explain the observed anomalous current structure shown in Fig. 3 is proposed and shown schematically in Fig. 4. It is the interaction between Taiwan Current and propagating mesoscale eddies. A cyclonic eddy is qualitatively a circular water column centered with a lower-than-surrounding sea surface height and currents around the eddy are counterclockwise in the Northern Hemisphere. Situations are totally opposite for anticyclonic eddy. If an anticyclonic eddy with considerable strength presents at the area south of PCM1 and interacts with the north-flowing Taiwan Current, the current speed measured at PCM1 is likely to be enhanced and current directions tend to be divergent. On the other hand, the current speed would be retarded and current directions tend to be convergent if a cyclonic eddy is presented. Basically, the T/P

measurements east of Taiwan support the proposed mechanism (Fig. 5).

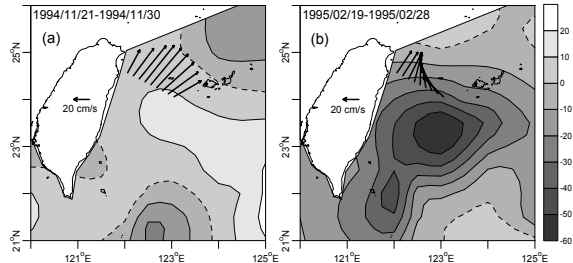


Fig. 5 Contours of the T/P SSHA corresponding to the time frames shown in Fig. 4. Contour interval is 10 cm and zero contours are plotted in dashed lines.

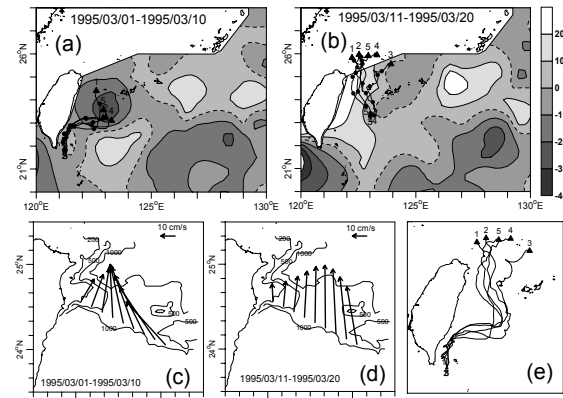


Fig. 6 Contours of T/P SSHA and the concurrent drifting buoy trajectories that are marked with solid dots in 2-day intervals during the periods of (a) 1995/03/01~10 and (b) 1995/03/11~20. The triangles are the ending positions of buoys in each panel and (e) for buoys overall trajectories. Contour interval of SSHA is 10 cm and zero contours are plotted in dashed lines. The concurrent upper 400 m, vertical-averaged current vectors at PCM1 are shown in (c) and (d), correspondingly (revised from Yang et al. (1999)).

The interaction between eddies and the Taiwan Current is also proposed partly to account for the meandering of the Taiwan Current. In early March 1995, 5 satellite-tracked surface drifting buoys were deployed at the area near the southern tip of Taiwan. Instead of going north directly by the east coast of Taiwan following the mean path of the Taiwan Current, all these 5 buoys made unusual turns east of Taiwan (Fig. 6). A cyclonic eddy, which is also verified by moored velocity measurements, is responsible. Another extreme case happened in early June 1995 that 6 buoys were deployed at nearly the same place (Fig. 7). Unexpectedly, they all went north-eastward away from the Taiwan Current and not flowing into the ECS through the ETC. An anticyclonic eddy east of Taiwan, of which diameter

was as large as 500 km, is responsible for these unusual buoy trajectories. This anticyclonic eddy 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 toward the place where it was deployed. All these buoys rode along interfaces between cyclonic and anticyclonic eddies. Another two examples of anomalous trajectories of drifting buoys were presented by Yang et al. (1999). Almost all of the anomalous drifting buoy trajectories east of Taiwan can be well explained by eddy distribution.

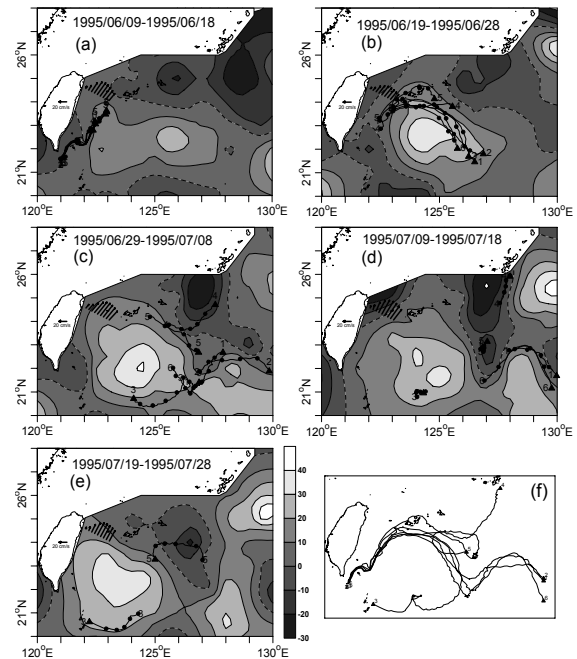


Fig. 7 Same as Fig. 6 but (a), (b), (c), (d) and (e) for five consecutive time frames in 10-day intervals from 1995/06/09 to 1995/07/28 and (f) for buoys overall trajectories. Beware that the overlapped current vectors are the vertical average of measurements between 200 m and 400 m (revised from Yang et al. (1999)).

3.2 Hydrographic Field

It is generally accepted that hydrographic survey is kind of synoptic measurement and is usually regarded as a first-order approximation of the mean state of hydrographic conditions. Fig. 8(a) shows the 16-cruise-averaged geostrophic velocity profile along PCM1 during the period between 1990 and 1996. The typical asymmetric, westward-intensified features of the WBC are well presented even the velocity magnitudes are underestimated due to the referenced bottom velocity. One of the surveys, however, showed a striking feature that the Taiwan

Current moved off shoreward in March 1995 (Fig. 8(b)). This unusual movement is certified independently both by moored velocity observations and satellite- tracked surface drifters (Fig. 6). Yang et al. (1999) suggested that the interaction between the Taiwan Current and a distinctive cyclonic eddy apparently propagated northwestward from 17°N, 129°E to the east of Taiwan is responsible for this unusual movement (Fig. 9).

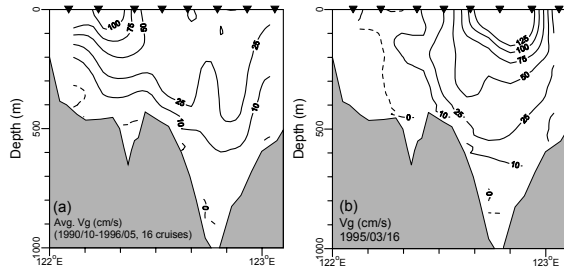


Fig. 8 Geostrophic velocity profiles along PCM1 (a) averaged from 16 cruises and (b) conducted on March 16, 1995. Triangles show the locations of repeated hydrographic stations. Units of velocity contours are cm/s (adopted from Yang et al. (1999)).

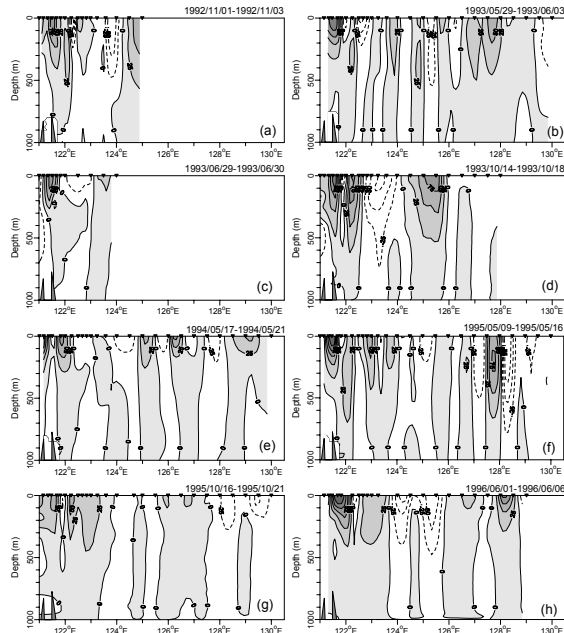


Fig. 10 Transects of geostrophic velocity profiles in unit of cm/s along PR20 with a reference level set to 1000 dbar. Regions with positive (northward) velocity components are shaded and negative (southward) velocity components are plotted in dashed lines. Date periods and hydrographic stations (triangles) of the corresponding surveys are shown on the top of each panel (revised from Yang and Liu (2003)).

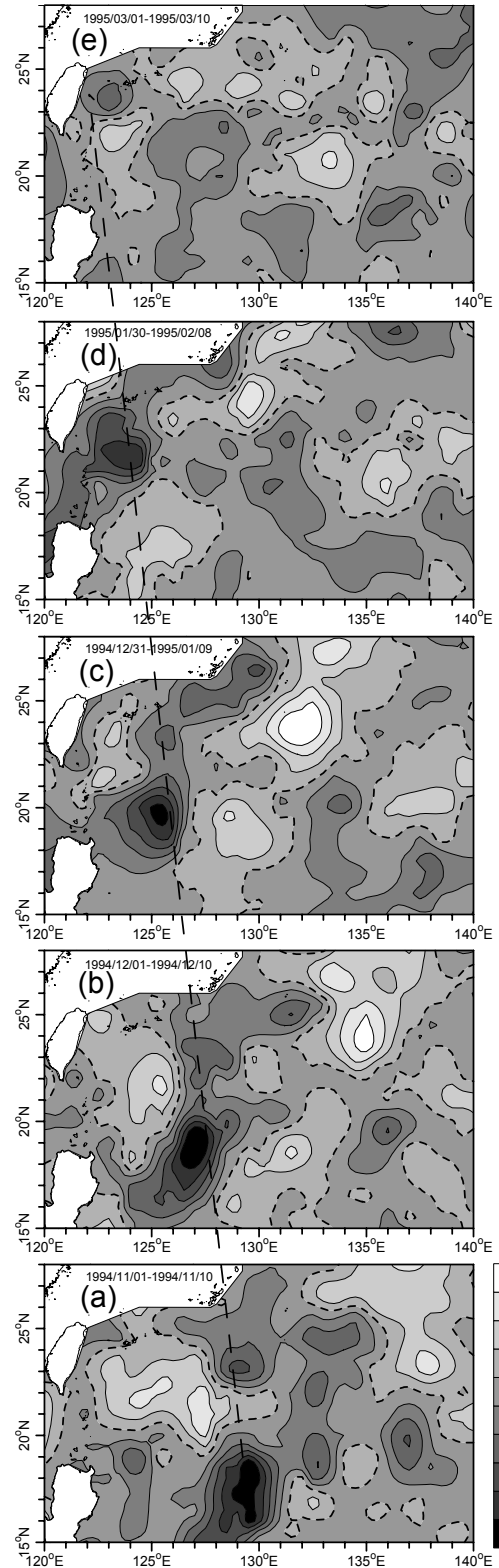


Fig. 9 Monthly advance of T/P SSHA from (a) November 1994 to (e) March 1995. A remarkable low anomaly (cyclonic eddy) east of Luzon propagated northwestward towards Taiwan is emphasized (revised from Yang et al. (1999)).

Another repeated hydrographic surveys were conducted along PR20. The banded interleaving velocity structure and noticeable velocity components far away from the Taiwan Current were observed frequently in this area (Fig. 10). For instance, northward currents east of 124°E in Fig. 10(a), at 127.5°E in Fig. 10(b) and 10(f), and at 125°E in Fig. 10(d). Dynamics of currents in open ocean are basically in geostrophic balance. Yang and Liu (2003) showed that the concurrent eddy distribution, which can be represented by T/P SSHA measurements, gives at least one of the explanations for the observed velocity structure (Fig. 11). They also showed that the estimated geostrophic Taiwan Current volume transports over PR20 are very likely being misestimated due to the presence of propagating eddies. Uncertainty of the estimated transport can be reduced significantly even only the eddy distribution is taken into account.

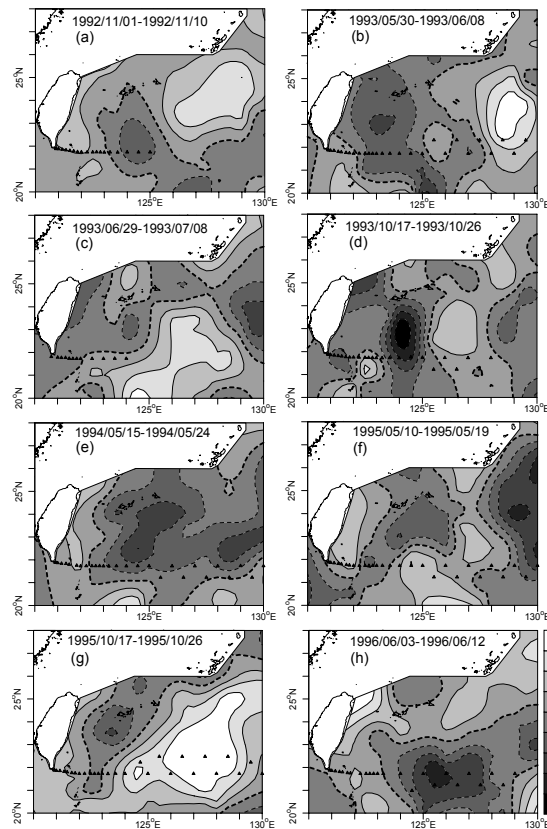


Fig. 11 Contours of T/P SSHA ((a), (b), ..., (h)) in cm over the time periods corresponding to the hydrographic surveys shown in Fig. 10. The hydrographic stations (triangles) are overlapped. Positive (negative) SSHA are shown in lighter (heavier) shading, bounded by solid (dashed) lines. The thick dashed lines represent the zero contours (adopted from Yang and Liu (2003)).

Hydrographic surveys east of Taiwan presented in Yuan et al. (1998a, 1998b) show another two examples on how the hydrographic fields could be shaped by mesoscale eddies (Fig. 12). The flow fields depicted by these two hydrographic surveys which were conducted in October 1995 and May 1996, respectively, are totally different from each other. A modified inverse method was applied on geostrophic computation for which the selection of velocity reference level is not a critical problem and the derived flow patterns are generally supposed to be the true manifestation of hydrography. A strong correlation between the eddy distribution delineated by T/P SSHA and the flow fields was proposed by Yang and Liu (2003). A tilting interface between cyclonic and anticyclonic eddies east of Taiwan shown in hydrographic survey of October 1995 corresponds well to the concurrent SSHA (Fig. 12(b)). In survey of May 1996 (Fig. 12(c)), part of the Taiwan Current made a significant detour at 23°N over where a low SSHA was present at 123.5°E, 23.5°N at nearly the same time (Fig. 12(d)). A much stronger low SSHA was located further east at 128°E, 21°N and the southwestward current at 127°E, 21°N in Fig. 12(c) also corresponds well to the prominent cyclonic eddy.

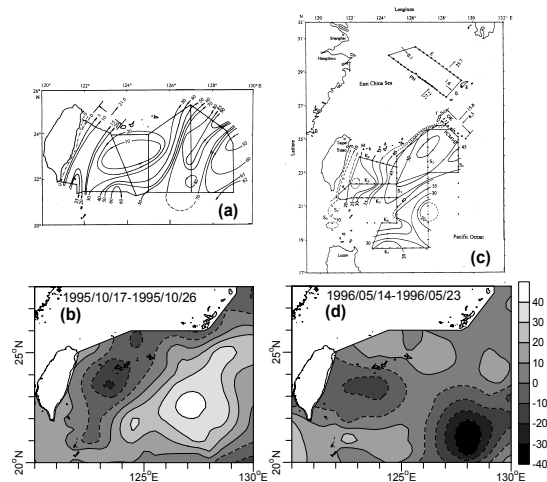


Fig. 12 Modified inverse method derived stream function of currents based on surveys conducted in (a) October 1995 and (c) May 1996. Contours of T/P SSHA in cm at nearly the same time corresponding to (a) and (c) are shown in (b) and (d), respectively (adopted from Yang and Liu (2003)).

4 Concluding Remarks

Mesoscale eddies are ubiquitous in the oceans. Hydrographic surveys, which are often used for estimating heat, nutrient and chemical material trans-

ports, are very likely being misestimated due to the presence of propagating eddies. Temporal and spatial variations of current structure and volume transport of the Taiwan Current are mainly the collaboration of interaction between impinging mesoscale eddies originating from the interior of the western North Pacific Ocean and the Taiwan Current on intraseasonal or longer time scales. Readers are reminded that conclusions based on observations, either direct or indirect measurements, conducted over the regions where mesoscale eddy activities are prominent are possibly only snapshots of highly changeable oceanic conditions. Even the continuous moored velocity measurements should also be interpreted with caution, especially for the short observations.

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