PERGAMON

Deep-Sea Research II 50 (2003) 1107–1115

DEEP-SEA RESEARCH
PART II

www.elsevier.com/locate/dsr2

Lagrangian observations of surface flow patterns in the vicinity of Taiwan

Ruo-Shan Tseng*, Yung-Ting Shen

Department of Marine Resources, National Sun Yat-sen University, Kaohsiung 804, Taiwan

Accepted 12 September 2002

Abstract

Two satellite-tracked surface drifters were launched off the southwestern coast of Taiwan on October 7, 1997. Both traveled northward along the Taiwan Strait (TS) and into the seas north of Taiwan, lasting 20 and 53 days, respectively. From the drifter trajectories, their rotary spectra and satellite infrared imagery, several oceanic features have been detected and are discussed in this paper. Our results indicate that in the southern and central portions of the TS, the floats followed a northward flow with a mean speed of 30–50 cm/s. Upon reaching the northwestern Taiwan coast, the trajectories were strongly affected by the semidiurnal tides and interacted with the Kuroshio water in the southern East China Sea. The onset of the strong northeastern winter monsoon in early November decelerated the northward movement and eventually reversed the direction. This process was accompanied by wind-generated, near-inertial motion. One drifter was then captured by a counterclockwise circulation of a cold dome at the continental shelf break northeast of Taiwan. Finally the drifter was entrained by the mainstream of the Kuroshio and flowed towards the northeast.

1. Introduction

Taiwan is located in an oceanic region filled with intriguing dynamic processes (see the bottom topography of Fig. 1). To the west is the Taiwan Strait (TS), a shallow channel with complicated topographic variations connecting the East China Sea (ECS) and the South China Sea (SCS). A distinguishing feature of the flow pattern east of Taiwan is the northward-flowing Kuroshio, the principal western boundary current of the North Pacific. The Kuroshio occasionally intrudes onto the northern shelf of Taiwan, forming a cold dome with upwelled subsurface water at the eastern edge of the shelf (Liu et al., 1992). At times the Kuroshio loops into the SCS at the Luzon Strait to the south of Taiwan. The temporal and spatial variations of these water masses as well as the interactions among them suggest a rather complicated flow pattern in this region.

It is well known that the TS is made up of three different water masses from the ECS, the SCS, and the Kuroshio. The flow pattern in the TS is mainly controlled by the East Asian monsoon and bottom topography. Current-meter observations in the central and southern TS reveal a generally northward flow (Wang and Chern, 1988; Chuang, 1985).

*Corresponding author. Fax: +886-7-5255033.
E-mail address: rstseng@mail.nsysu.edu.tw (R.-S. Tseng).

0967-0645/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0967-0645(03)00012-2

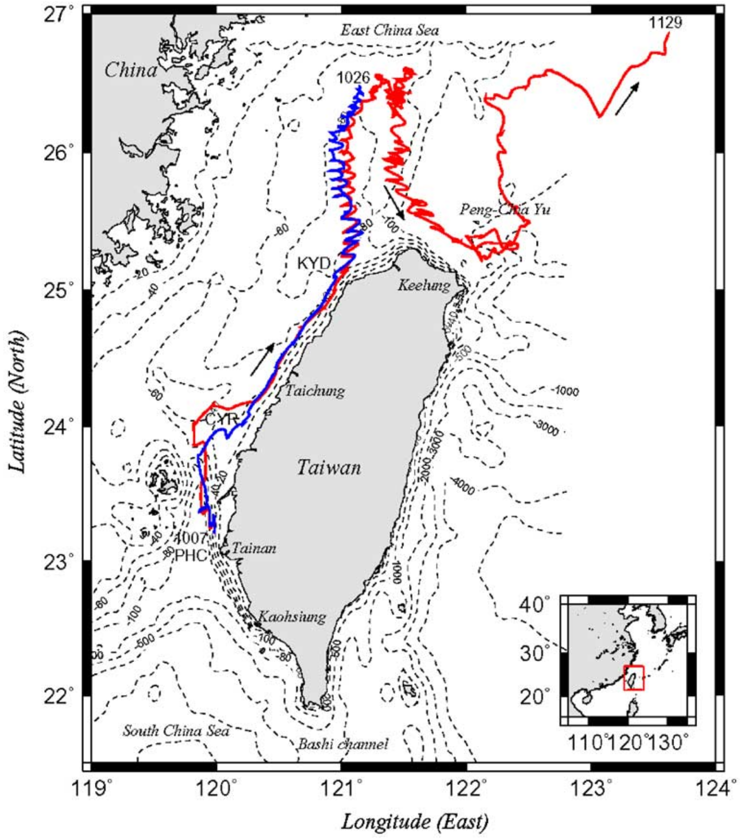

Fig. 1. Trajectories of drifter 1 (blue line) and drifter 2 (red line) from October 7 to November 29, 1997. Isobaths (in meters) in the Taiwan Strait and in its adjacent seas are shown. The numbers by the trajectories show months and days. The direction of motion is indicated by an arrow next to the trajectories. PHC is the Peng-hu Channel. CYR is the Chang-yuen Ridge. KYD is the Kuan-Yin Depression.

Such a northward mean flow probably originates from the SCS water during the summer southwestern monsoon season. This northward flow is somewhat weakened during the winter northeastern monsoon season and is more likely associated with water masses originating from the Kuroshio (Shaw, 1989, 1991). Hydrographic and numerical studies (Jan et al., 1995; Chern and Wang, 2000) suggest that a zonal sand ridge north of the Peng-hu Channel (PHC) in the TS exerts strong influences on the flows. Chern and Wang (2000) also found from numerical simulations that the flow patterns in the TS are modulated by bottom topography, and stratification and inflow from the PHC.

In the northern end of the TS, water generally flows from the strait to the southern part of the ECS (Wang and Chern, 1988). The flow interacts with the intruding Kuroshio, the latter is a result of the collision of the Kuroshio with the zonally running shelf breaks northeast of Taiwan. The migration of the Kuroshio and the mesoscale flow pattern north of Taiwan have been studied using ship-board ADCP, hydrographic measurements, and moored current data (Tang and Yang, 1993; Tang et al., 1999, 2000). The general flow pattern in this region consists of a deflected Kuroshio to the east, intrusion Kuroshio water on the continental shelf, a counterclockwise circulation over the Mien-Hwa Canyon (MHC) immediately northeast of Taiwan, and a deep southwestward counter current along the northern wall of the MHC. The flow pattern north of Taiwan is significantly influenced by the seasonal migration of the Kuroshio (Tang et al., 2000).

The above-mentioned studies on the flow pattern of the TS and the northern shelf of Taiwan were based mostly on data collected from hydrographic measurements and Eulerian current measurements. A Lagrangian description of the velocity field in the TS, such as those done in the study on the Gulf Stream by Shaw and Rossby (1984) and the Kuroshio cold ring by Cheney et al. (1980), would provide us with additional information and might lead to a better understanding of the flow pattern. However, the existing data of float trajectories in the TS and ECS do not cover long enough periods or enough details to investigate the flow pattern adequately. In this paper, observations from two satellite-tracked surface drifters launched off the southwestern coast of Taiwan on October 7, 1997 are presented and discussed. One drifter failed after 20 days at sea. The other began an extensive journey in the TS and off northern Taiwan. It will be demonstrated that some of the aforementioned flow features can be detected from drifter trajectories, and new findings may be gained from the Lagrangian results.

2. Data and analysis methods

The surface drifter (Clearwater Inc., USA) used in this study is the CODE type. It consists of batteries, GPS, ARGOS PTT and an antenna. Drag-producing vanes are made of plasticized cloths (100 cm × 50 cm), which are situated just beneath the water surface. Four floats provided adequate buoyancy for each drifter. Drifter positions were fixed using a GPS every 20–30 min and the zonal, (x) and meridional, (y) positions as a function of time were transmitted back via the ARGOS system. Bad data were eliminated by inspecting the raw velocity and position time series. A cubic-spline algorithm was then used to interpolate the irregularly spaced data to equally spaced (30 min) time series of latitude and longitude. The zonal and meridional components of velocity were obtained by centered differences except at the end points, and where one-sided difference is used. Because the drifter had a large drogue-to-non-drogue drag ratio, velocity errors arising from wind drag on the surface element of the drifter and from slippage between the water and the drogue were small. With commonly achieved drifter position accuracy $\Delta x \approx 60$ m and time interval of $\Delta t \approx 30$ min between successive ARGOS fixings, the velocity errors $u_e \approx \Delta x / \Delta t$ are about 3.3 cm/s. These errors are random so their net effect on the velocity estimates will be small compared to the 10–200 cm/s currents typically found in the surface layer of the TS and its adjacent sea.

Thomson et al. (1997) used the rotary spectrum of a 2.5-year velocity time series derived from a near-surface satellite-tracked drifter to illustrate the flow characteristics in the North Pacific Ocean. Cyclonic and anticyclonic rotating, circularly polarized vectors with amplitudes $A^+ = (S^+)^{1/2}$ and $A^- = (S^-)^{1/2}$ were obtained as functions of frequency and time. Here S^+ and S^- are the counterclockwise and clockwise rotary spectra. The advantage of the rotary current representation is that current oscillations can be described in terms of a single scalar rather than a vector time series. In this study the same technique of multiple filter analysis (Emery and Thomson, 1997) was adopted to analyze our drifter data.

3. Drifter trajectories and flow features

On October 7, 1997 two surface drifters were deployed at a depth of 40 m at a location about 10 km off the southwestern coast of Taiwan. Drifter 1 traveled northward to the northern TS but then ran out of power and ceased data transmissions 20 days later. The second drifter began a 53-day journey in the TS and into a region north of Taiwan and the southern ECS. Fig. 1 summarizes the trajectories of these two drifters spanning the period from October 7 to November 29. It is clearly seen that the two trajectories show quite similar characteristics from October 7 to October 26 except for some small disparities in the first several days. Satellite infrared (IR) images of the sea-surface temperature (SST) derived from NOAA-12 AVHRR data during this period were received and processed by the HRPT station located in Kaohsiung, Taiwan. The SST images during the drifter experiment were used to identify the surface features of physical processes and to relate features in the drifter trajectories to events at the surface.

3.1. Currents in the TS

The NOAA/AVHRR SST image in the TS on October 11, 1997 was overlaid on the drifter trajectories, as shown in Fig. 2. A patch of warm water with temperatures higher than 28°C occupied the region along the western coast of Taiwan at that time. The drifters were apparently following the northward movement of this patch of warm water as the drifter trajectories are mostly parallel to the isotherms. A notable topographic feature, as illustrated in this figure, is the Changyuen Ridge (CYR) near 24°N north of the PHC and the Kuan-Yin Depression (KYD) near 25°N at the northern end of Taiwan. The average northward velocity of the drifters for the first 5 days of the experiment varied between 30 and 50 cm/s, which is consistent with Jan and Chao's (2003) observations of a nearly 40–50 cm/s near-surface northward mean flow in the PHC, using shipboard ADCP measurements in October of 1999. Chuang (1985) also reported a nearly 30 cm/s northward mean flow using a near-bottom current meter in the PHC in April–May of 1983. Note that the drifters show the surface velocity, which is greater than the bottom velocity. Both previous measurements and the present study show that existence of the northward flow in fall is a general feature of the PHC. The source of this northward mean flow may be of either the SCS or the Kuroshio origin, depending on the prevailing winds. In summer and early fall when the southwestern monsoon is fully established, the currents in this region follow the winds quite closely and the source of the northward flow in the PHC is the SCS water. In winter and spring the Kuroshio enters the SCS and water of the northward flow is more likely of the Kuroshio.

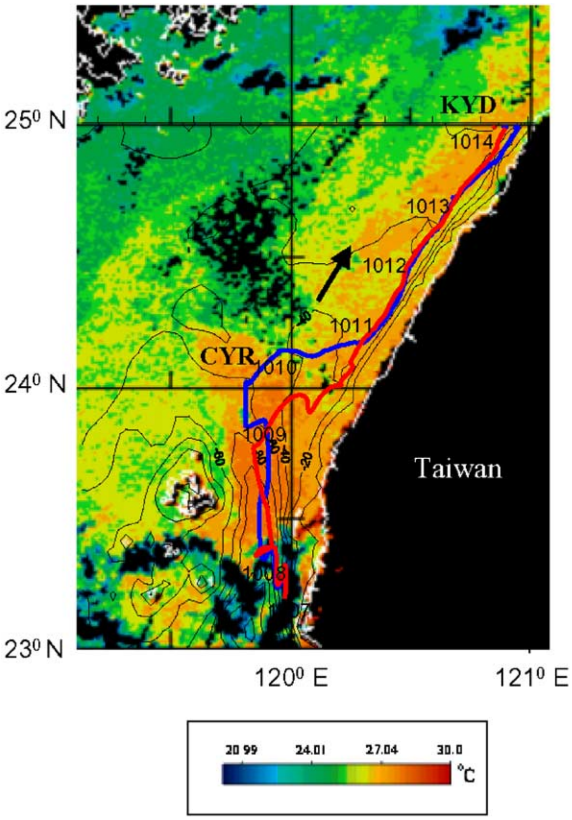

Fig. 2. SST image of October 11, 1997. Trajectories of drifter 1 and 2 are marked by red and blue lines, respectively. The numbers by the trajectories are months and days. Thin lines indicate isobaths at 20 m intervals.

Soon after passing the PHC, the northward flow impinged on the zonal sand ridge of CYR. If the northward mean flow in the PHC originates from the SCS the stratification of the incoming SCS water should be strong since the SST is warm (Chern and Wang, 2000). Fig. 2 indicates that each drifter made a separate track parallel to the local isobaths around the CYR, and then converged eastward to hug the west coast of Taiwan. The numerical results of Jan et al. (1995) suggest that when a stratified flow impinges on the CYR, the lighter surface waters will flow over the ridge and converge eastward due to the potential vorticity conservation associated with the shoaling topography further north. Our measurements appear to be the first direct evidence showing the veering of stratified SCS water entering the PHC around the CYR in satellite-tracked drifter trajectories.

3.2. The TS outflow

The satellite image of SST in northern Taiwan on October 22, 1997 was overlaid on drifter trajectories in Fig. 4. Both drifters moved with the northward flow along the western coast of Taiwan before October 14. Afterwards, both drifters departed from the coast of Taiwan and continued to move towards the north into the southern ECS. Trajectories of both drifters show a remarkable consistency with the spatial distribution of the warm-water patch spreading over the northern shelf of Taiwan in IR imagery (Fig. 4). The northern extent of both the warm patch and the drifter trajectories was around 26.6°N on late October, consistent with the intensification of the northeasterly winds (Fig. 3). Liang et al. (2003) compiled all the available shipboard ADCP data around Taiwan during 1992–2000. Their composite current velocity showed that the main stream of the TS outflow moved continuously to the north, interacting partially with the intruding Kuroshio. Our drifter trajectories also revealed a somewhat similar result, except that the northward TS outflow was blocked by the intensified NE winter monsoon and forced to turn southward and then became influenced by the intruding Kuroshio.

Another prominent feature in the drifter trajectories displayed in Fig. 4 is the semidiurnal motion in the TS outflow. The existence of both clockwise and counterclockwise rotary currents with a dominant M_2 frequency in the trajectory of drifter 2 can be clearly seen from day 5 to 13 after the

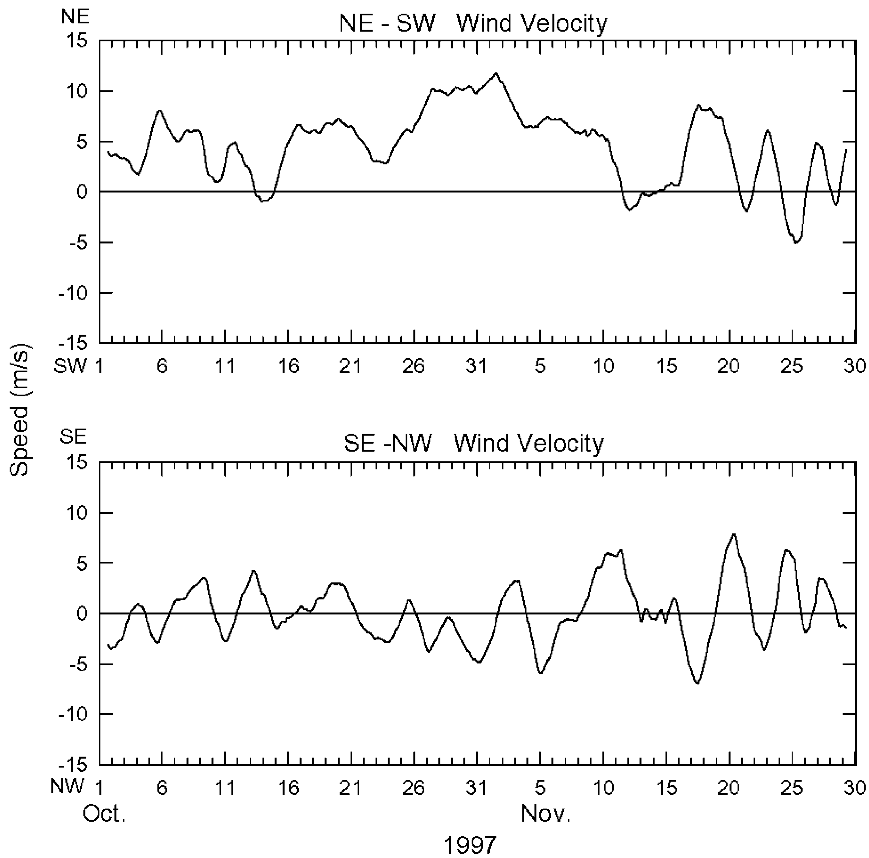

Fig. 3. 38-h low-pass filtered wind-velocity time series from the Peng-chia Yu weather station in October and November 1997.

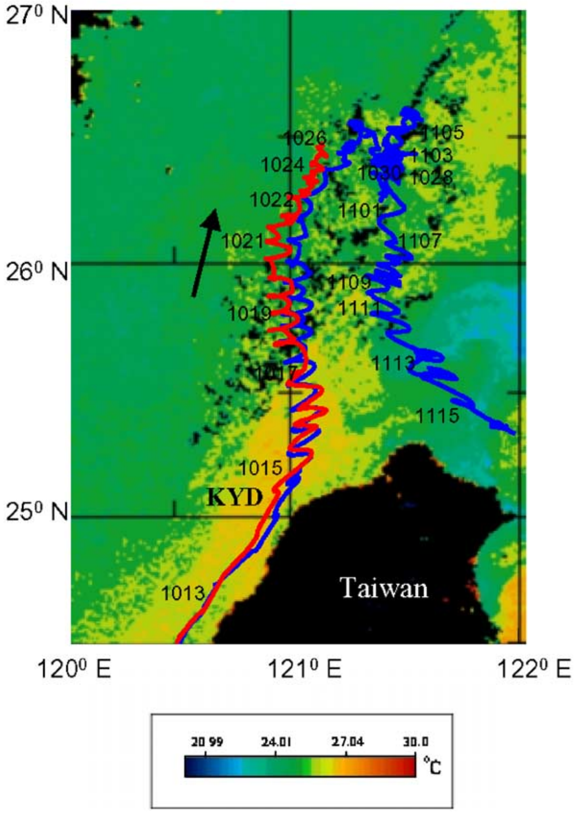

Fig. 4. As in Fig. 2 except for the SST image on October 22, 1997.

deployment (Fig. 5, upper two panels). The drifter trajectory apparently followed the local KYD isobaths (Fig. 4). A numerical simulation of flow-topography interaction in the TS was conducted by Chern and Wang (2000). The flow pattern in the TS near the KYD derived from their numerical results is generally consistent with the Lagrangian trajectory. As the northeastern winter monsoon strengthened on October 27 (Fig. 3), the northbound drifter 2 began to decelerate and strolled around in the southern ECS for about 10 days. At that time, the trajectory of drifter 2 shows the characteristics of near-inertial oscillations. If $T_f = \pi/(\Omega \sin \phi)$, Ω is Earth's angular rotation, and $\phi \cong 26.5^\circ$N the mean latitude of the drifter, the period is about 26.9 h. The predominantly counterclockwise rotary motions at the inertial frequency persisted from day 20 to 25 in the trajectory of drifter 2 (Fig. 5, lower right panel) with a mean rotational speed of 0.5 m/s. From November 5 on, drifter 2 began a southward semidiurnal excursion and gradually reached the region immediately north of Taiwan as a result of wind forcing of the northeastern monsoon. Both the clockwise and counterclockwise rotary components at the M_2 period existed in this region for about 13 days. The counterclockwise motion continued to dominate for another 3 or 4 days (Fig. 5, upper right panel).

3.3. Flow pattern northeast of Taiwan

Satellite SST on November 11, 1997 was overlaid on the trajectory of drifter 2 in Fig. 6. The isobaths are marked in this figure to illustrate a major topographic feature of the MHC at the continental shelf-slope junction northeast of Taiwan. Beginning from November 16, drifter 2 was obviously captured by a counterclockwise circulation at the shelf break immediately northeast of Taiwan. A belt of anomalously cold water extending from just north of the Taiwan coast to the shelf of the ECS can be seen from the SST image. The counterclockwise circulation centered at the MHC is about 40 km in diameter. The location of the cold dome generally agrees with the counterclockwise circulation in the trajectory (Fig. 6). This is not the first time that a small cyclonic eddy is reported at this location. A similar feature was first observed based on phase-averaged current vectors using shipboard ADCP measurements during August in 1994 and 1996 (Tang et al., 1999, 2000). Tang et al. (2000) suggested this counterclockwise circulation is associated with cold dome formed from intrusion of the subsurface Kuroshio water in summer. In winter the westward migration of the Kuroshio dominated the flow pattern north of Taiwan, causing the disappearance or obscuration of the counterclockwise circulation and the cold dome. The Lagrangian observation in this study provides direct evidence of the existence of this counterclockwise circulation. Our results indicate that this counterclockwise circulation not only occurred in summer, but also existed in early winter. Note that the presence of the counterclockwise circulation modulated the direction of the TS outflow and

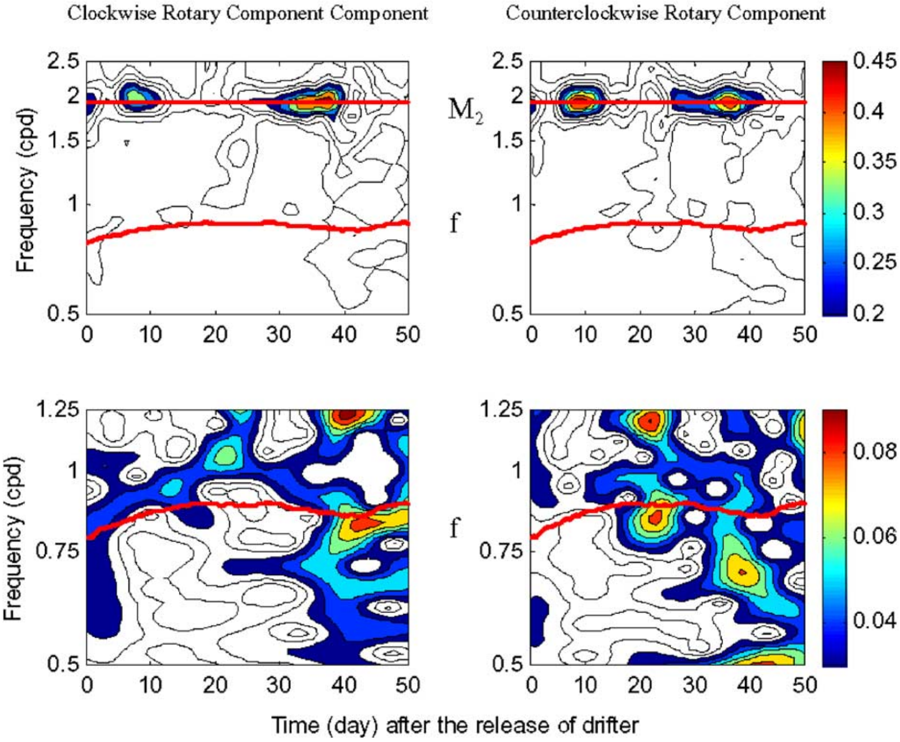

Fig. 5. Rotary velocity components as functions of frequency and time for the first 50 days of the trajectory of drifter 2. Rotary amplitudes are the positive square roots of the clockwise and counterclockwise rotary spectra. Upper panels: Rotary components in the high-frequency range, $0.5 \leqq f \leqq 2.5$ cpd. Lower panels: Rotary components for the low-frequency range, $0.5 \leqq f \leqq 1.25$ cpd. M_2 denotes the semidiurnal tidal frequency, and f the inertial frequency.

kept it from going northward, as observed from the ADCP measurements of Tang et al. (2000). The energy spectrum indicates that the drifter trajectory displayed near-inertial clockwise motion again from day 40 to 43 (Fig. 5, lower left panel). The northeastern monsoon intensified on November 17, with the wind direction gradually shifted easterly on November 20 (Fig. 3), suggesting that the burst of inertial energy was linked to the changing winds.

Fig. 7 shows the trajectory of drifter 2 overlaid with SST on November 25, 1997. After making one circuit around the cyclonic eddy, the drifter detached from the eddy on November 19. Afterwards, the drifter moved northward and turned eastward with meanders of the Kuroshio. The drifter trajectory generally coincided with a sharp temperature front between the cold shelf water and the warmer Kuroshio water on the northern shelf of Taiwan. The maximum speed of the drifter in the Kuroshio is approximately 2 m/s.

In short, this report used two drifter trajectories to characterize a wide range of processes in the upper ocean along the western and northern shelves of Taiwan. In particular, the topographically modulated flow patterns around the CYR and KYD in the TS and the counterclockwise circulation over the MHC northeast of Taiwan in winter. The drifter tracks have provided direct support to the results of numerical models and shipboard ADCP measurements reported earlier. Depending on the prevailing winds, the TS outflow may reach 26.6°N in the ECS, but will eventually recede to the south as winter progresses. The flow pattern on the shelf north of Taiwan was affected by both the TS outflow and the intruding Kuroshio. Flow along the western and northern coast of Taiwan was dominated by strong

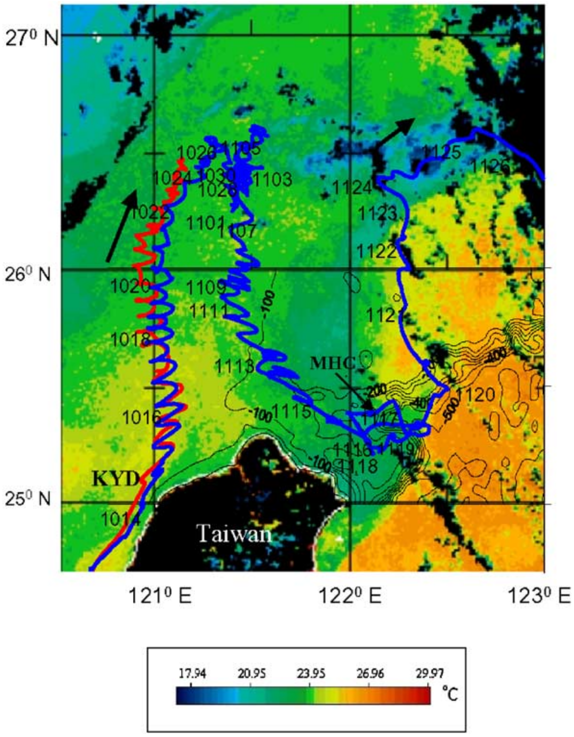

Fig. 6. As in Fig. 2 except for the SST image on November 11, 1997.

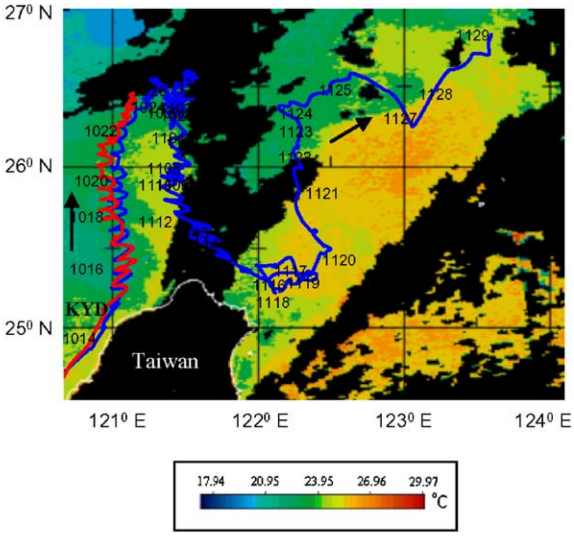

Fig. 7. As in Fig. 2 except for the SST image on November 25, 1997.

semidiurnal currents, and flow in the southern ECS was characterized by wind-generated inertial motions during the northeastern winter monsoon.

Acknowledgements

This study was sponsored by the National Science Council of R.O.C. under grant NSC88-2611-M110-003-AP7. We thank Prof. Richard E. Thomson of IOS for assisting us with the rotary spectra analysis. The HRPT station in NSYSU for the SST images was established with the assistance of Prof. Cho-Teng Liu of NTU.

References

Cheney, R.E., Richardson, P.L., Nagasaka, K., 1980. Tracking a Kuroshio cold ring with a free-drifting surface buoy. Deep-Sea Research I 27A, 641–654.

Chern, C.-S., Wang, J., 2000. Some aspects of the flow-topography interactions in the Taiwan Strait. Terrestrial, Atmospheric and Oceanic Sciences 11, 861–878.

Chuang, W.-S., 1985. Dynamics of subtidal flow in the Taiwan Strait. Journal of the Oceanographical Society of Japan 41, 65–72.

Emery, W.J., Thomson, R.E., 1997. Data Analysis Methods in Physical Oceanography. Pergamon Press, Oxford.

Jan, S., Chao, S.-Y., 2003. Seasonal variation of volume transport in the major inflow region of the Taiwan Strait: The Penghu Channel. Deep-Sea Research II, this issue, doi: 10.1016/S0967-0645(03)00013-4.

Jan, S., Chern, C.-S., Wang, J., 1995. A numerical study on currents in Taiwan Strait during summertime. La Mer 33, 23–40.

Liang, W.-D., Tang, T.Y., Yang, Y.J., Ko, M.T., Chuang, W.-S., 2003. Upper ocean current around Taiwan. Deep-Sea Research II, this issue, doi: 10.1016/S0967-0645(03)00011-0.

Liu, K.-K., Gong, G.-C., Shyu, C.-Z., Pai, S.-C., Wei, C.-L., Chao, S.-Y., 1992. Response of Kuroshio upwelling to the onset of the northeast monsoon in the sea north of Taiwan: observations and a numerical simulation. Journal of Geophysical Research 97, 12511–12526.

Shaw, P.-T., 1989. The intrusion of water masses into the sea southwest of Taiwan. Journal of Geophysical Research 94 (12), 18213–18226.

Shaw, P.-T., 1991. The seasonal variation of the intrusion of the Philippine Sea water into the South China Sea. Journal of Geophysical Research 96 (1), 821–827.

Shaw, P.-T., Rossby, H.T., 1984. Towards a Lagrangian description of the Gulf Stream. Journal of Physical Oceanography 4, 528–540.

Tang, T.Y., Yang, Y.J., 1993. Low frequency current variability on the shelf break northeast of Taiwan. Journal of Oceanography 49, 193–210.

Tang, T.Y., Hsueh, Y., Yang, Y.J., Ma, J.C., 1999. Continental slope flow northeast of Taiwan. Journal of Physical Oceanography 29, 1353–1362.

Tang, T.Y., Tai, J.H., Yang, Y.J., 2000. The flow pattern north of Taiwan and the migration of the Kuroshio. Continental Shelf Research 20, 349–371.

Thomson, R.E., LeBlond, P.H., Rabinovich, A.B., 1997. Oceanic odyssey of a satellite-tracked drifter: north pacific variability delineated by a single drifter trajectory. Journal of Oceanography 53, 81–87.

Wang, J., Chern, C.-S., 1988. On the Kuroshio branch in the Taiwan Strait during wintertime. Progress in Oceanography 21, 469–491.