J Oceanogr (2011) 67:395–404
DOI 10.1007/s10872-011-0033-4

SPECIAL SECTION: ORIGINAL ARTICLE

Regional Environmental Oceanography in the South China Sea and Its Adjacent Areas (REO-SCS): I

Currents in the Taiwan Strait as observed by surface drifters

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Received: 7 August 2010 / Revised: 6 April 2011 / Accepted: 3 May 2011 / Published online: 13 July 2011

Abstract The trajectories of 110 satellite-tracked surface drifters from 1989 to 2007 were analyzed to elucidate near-surface circulation in the Taiwan Strait. Although the summer circulation observed generally agrees with previous studies, several aspects of the winter circulation were revealed by the analyses. Unlike many earlier studies, which have suggested that a northward (southward) current prevails in the eastern (western) part of the Taiwan Strait during the northeast monsoon season, this study shows that almost all winter drifters that entered the Taiwan Strait eventually moved southward. Inside the Taiwan Strait, northward moving tracks can only be found in the Penghu Channel. After passing the Penghu Channel, the drifters were blocked by the northeast monsoon wind and the Yun-Chang Rise, and turned southward. None of the drifters flowed persistently northward through the Taiwan Strait in winter. In the southern Taiwan Strait, three typical patterns of circulation were observed for the winter trajectories—the "throughflow" pattern that enters the South China Sea flowing westward along the slope; the loop current pattern that circulates anticyclonically and returns to the Kuroshio; and the blocked intrusion pattern that penetrates into the Taiwan Strait through the Penghu Channel.

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Keywords Surface flows · Taiwan Strait · South China Sea · Drifters

1 Introduction

The Taiwan Strait (TS), bounded by the mainland to the west and the island of Taiwan to the east, is a narrow passage that connects the East China Sea (ECS) in the north to the South China Sea (SCS) in the south (Fig. 1). The seasonal circulation in the TS, primarily dominated by monsoons and the bottom topography (Jan et al. 1994), is regionally important, because the TS is a key path for the exchange of water in the SCS with that in the ECS, the Yellow Sea and even the Sea of Japan (Kondo 1985; Isobe 1999).

Seasonal circulation in the TS has been elucidated comprehensively by use of in situ data, remote sensing, and numerical models (Hu et al. 2010). In summer, a generally northward flow dominates the entire strait (Chuang 1986; Hu and Liu 1992; Jan et al. 1994), with a fairly large northward volume transport of the order of 3 Sv from the south (Fang et al. 1991; Wang et al. 2003). In contrast, the characteristics of wintertime currents in the strait are complex and controversial. Guan (2002) argued that in winter, while the southwestward China Coastal Current is present in the western strait, the northeastward flowing Taiwan Strait Warm Current (Guan and Fang 2006) prevails in the central and eastern strait, connecting the SCS Warm Current with the Taiwan Warm Current of the ECS. Direct measurements of currents, using a Shipboard Acoustic Doppler Current Profiler (Sb-ADCP), from 1991 to 2000 demonstrated northward flow in the eastern TS all-year round (Liang et al. 2003). However, Wang and Chern (1988) identified a quasi-stationary front in the eastern TS

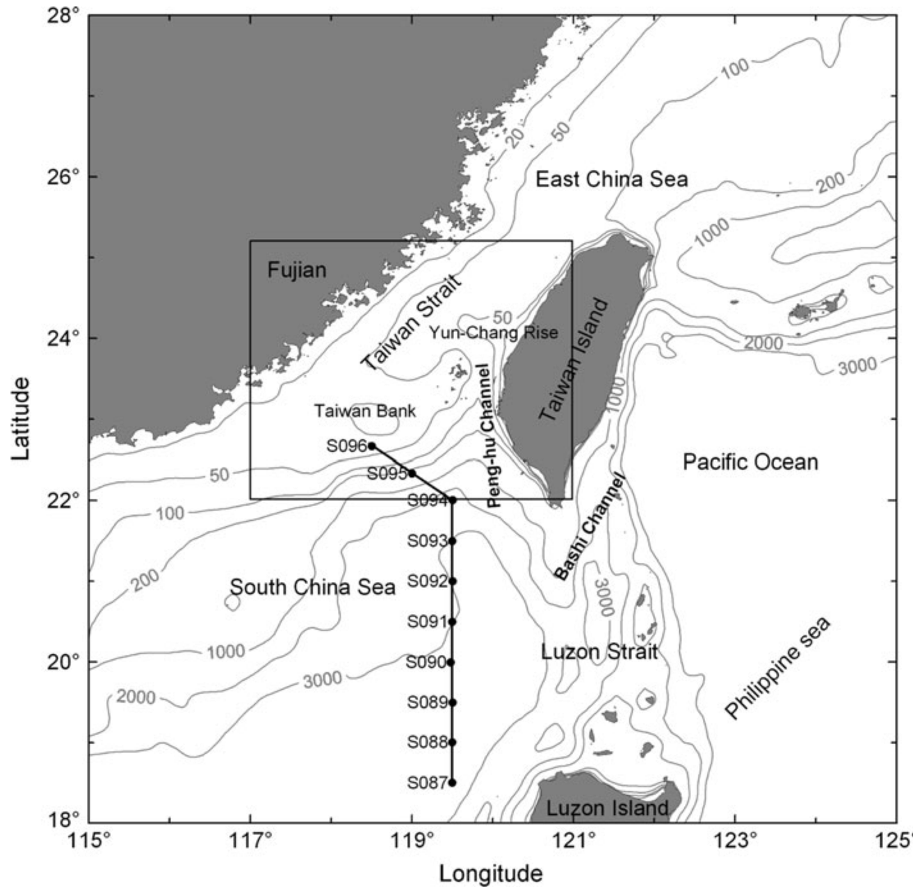


Fig. 1 Bathymetric chart of areas around Taiwan. *Area within box* (117°–121°E, 22–25.5°N) is proxy for the TS. The Sb-ADCP transect for the cruise of November–December 1998 is marked by the *thick line with dots*

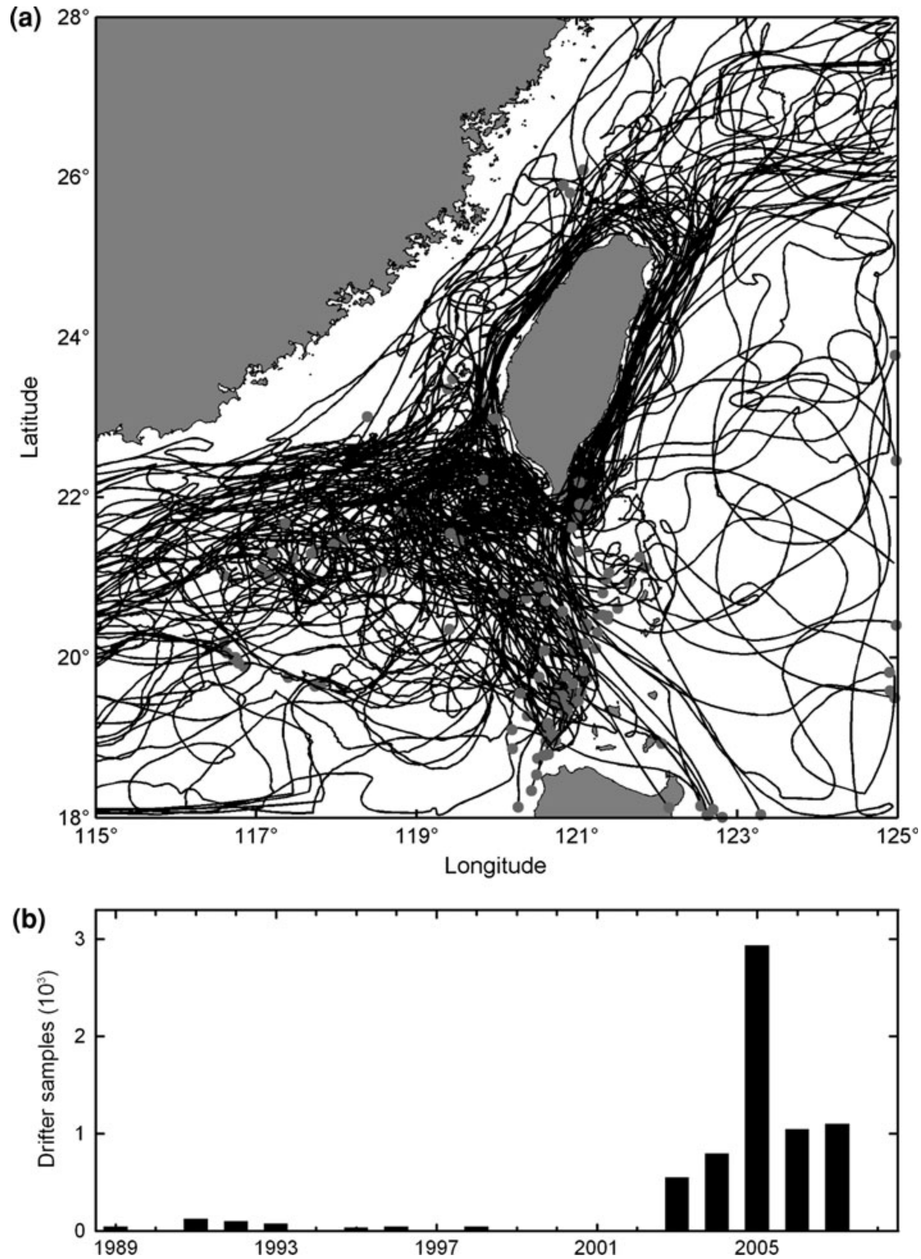
that was aligned approximately perpendicular to the transverse of the strait, and suggested that cold water north of the front prevented further northward movement of Kuroshio water. On the basis of the distribution of chemical properties, Chen (2003) also asserted that most of the water in the TS in winter comes from the ECS. Episodic relaxation of the northeast monsoon has been suggested to drive the observed northward flow through the Penghu Channel (PHC) (Wang et al. 1993; Chen 2003). Similarly, other, more recent studies (Jan et al. 2002, 2006; Ko et al. 2003; Wu and Hsin 2005; Chen and Sheu 2006) have suggested that wintertime transport is to the southwest, because of strong and stable northeast monsoons, and no northward current flows persistently throughout the strait. These findings raise a fundamental question concerning whether the northward counter-wind flows are stable or transient phenomena in the TS under the influence of the strong and persistent wintertime monsoon.

Most of the cited studies of the flow pattern of the TS are based on hydrographic and Eulerian current measurements. Observations of the velocities of satellite-tracked drifters provide new and direct evidence of near-surface flow in a Lagrangian framework. Accumulated multi-year surface drifter data now support the compilation of a general image of the circulation in the TS. On the basis of these data, this study investigates the seasonal circulation in the TS with focus on its winter currents. The paper is organized as follows. Section 2 introduces the datasets and methods. The Lagrangian flow features of the TS are discussed in the Sect. 3, and Sect. 4 discussed the results and conclusions are drawn.

2 Data and methods

The Argos satellite-tracked surface drifter data that were used herein cover 6-h interpolated current velocities and positions of the drifter. The drogues of most drifters are tethered at a depth of 15 m to measure mixed layer currents (Lumpkin and Pazos 2006). From 1989 to 2007, a total of 110 drifters were deployed in, or drifted into, the region of the TS from 22° to 25.5°N and from 117° to 121°E (Fig. 2a). The yearly distribution of the number of observations is presented in Fig. 2b. The numbers of annual observations were largest between 2003 and 2007, with a maximum of 2,936 observations in 2005. Data were relatively few before 2002. The distribution of data was not uniform among either seasons or geographic areas (Fig. 3).

Fig. 2 **a** Trajectories of all drifters that entered the TS between 1989 and 2007 (*grey dots* indicate initial locations); **b** yearly distribution numbers of 6-hourly measurements of position and velocity



The number of observations in winter was nearly twice that in summer. The southern and eastern parts of the TS were extensively sampled in both seasons whereas grid cells along the western coast contain few or even no samples, especially in summer. Importantly, the box-averaged current velocity is meaningful only in the grids in which enough observations were made.

In the analyses, suspect drifter positions and current velocities faster than 1.5 m s^{-1} were removed first. To eliminate high-frequency tidal and inertial components, the time series were low-pass-filtered by seven-point moving average. The mean root-mean-square value of zonal (meridional) current velocities between each individual unfiltered and filtered drifter is 0.13 (0.12) m s^{-1}. The tracks thus obtained were then used to investigate the Lagrangian flow characteristics in the TS, and the corresponding current velocities were used to obtain the Eulerian mean flow field with a spatial resolution 0.5° × 0.5°. To prevent the over-representation of slow-moving drifters in the statistics, the Eulerian average was not equally weighted for all 6-hourly samples inside a bin. Instead, the data from each individual drifter segment that fell into a bin were averaged first and treated as a single record in the bin average. The winter and summer are defined herein as October to March and June to August, respectively.

3 Results

3.1 Summertime drifter trajectories

The summertime near-surface currents in the TS are presented by a total of 32 drifter trajectories (Fig. 3a). All available drifters were released in the SCS, and were carried into the TS by the northward-flowing SCS Warm Current. Their trajectories bifurcate upon migration into the TS southwest off Taiwan, where six drifters left the SCS through the Bashi Channel drifting pole-ward along the east coast of Taiwan with the Kuroshio, and the others (26 drifters) continued to move northward within the strait. Among these, 65% (17 in total) show tracks converged on the PHC and congested along the west coast of Taiwan. After migrating out of the TS through its northern boundary, their trajectories proceed northward entering the ECS and end up there, but four of them turn east at approximately 27°N and merge into the Kuroshio main path.

The track pattern is thus characterized by drifters that all come from the SCS (rather than the Luzon Strait, LZS) and travel northward throughout the TS to the ECS. This is in good agreement with the earlier study of Li et al. (2000b), which showed that although numerous drifters pass through the LZS, none could enter the SCS in summer. The general flow patterns of the TS in summer revealed in this study are consistent with those in previous studies (Jan et al. 2002; Liang et al. 2003; Zhu et al. 2008), which show that the near surface current in the TS is northward in summer and is intensified near the coast of Taiwan, although currents in the lower layer might behave differently. The estimated mean along-strait drifting speed (approx. 0.3 m s^{-1}) is somewhat weaker than the currents at 30 m depth derived from Sb-ADCP measurements (Liang et al. 2003). It is likely that drifters are retarded by bottom friction, because most of their drifting paths are very close to the coast where the water is rather shallow.

3.2 Wintertime drifter trajectories

The wintertime current in the TS, especially in its southern part, is very complex, because it is the confluence of the large-scale circulation over the northern SCS with the monsoon-driven coastal current in the TS and the intruding Kuroshio branch through the LZS.

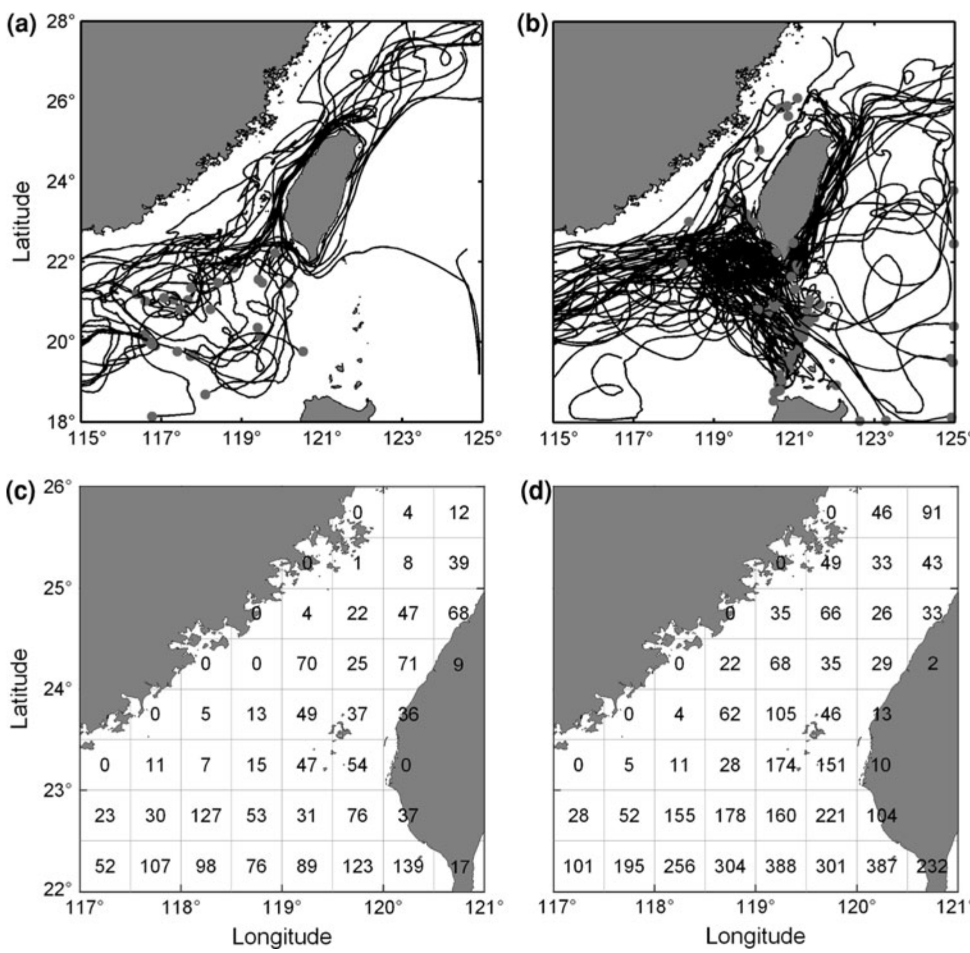


Fig. 3 Trajectories of drifters in the TS for **a** summer and **b** winter (*grey dots* indicate initial locations), and geographical distribution of number of drifter measurements in summer (**c**) and winter (**d**)

A total of 78 drifters that entered the study area were available for the northeast monsoon season (Fig. 3b); they mostly come from the LZS and enable more comprehensive analysis. After entering the SCS, most of the drifters went westward along the continental slope of the northern SCS, several intruded into the interior of the TS, and some looped anticyclonic southwest off Taiwan returning to the Kuroshio main path (Fig. 3b). By careful, case-by-case analysis we managed to identify these trajectories into four basic categories, including those entering the TS from the north, although 13 drifters could not be sorted because of their short life history.

Among the 65 drifters left, 24 were classified into the "throughflow" category, which travel counterclockwise along the slope of the northern SCS continental shelf (Fig. 4a). Most of the drifters were released in the LZS and the Philippine Sea, and four were deployed inside the SCS to the west of Luzon Island. In the northern SCS, the drifter trajectories are approximately parallel to the isobath of 200 m with a northern extent at approximately 22.5°N (Fig. 4a). The drifters continue to drift southward along the coast of Vietnam, with speeds in excess of 0.8 m s^{-1} (Li et al. 2000b; Centurioni and Niiler 2004). Careful examination reveals that, besides the general basin-scale cyclonic motion, several drifters also have a smaller-scale looping feature modulated by mesoscale eddies.

The second category includes 17 drifters that migrate northwestward into the SCS through the LZS, and return to the Kuroshio main path along the southwest coast of Taiwan after they have traveled a half circuit (Fig. 4b), forming a loop. This pattern is called the loop pattern, caused by a loop-like intrusion of the Kuroshio into the SCS (Li and Wu 1989; Farris and Wimbush 1996; Jing and Li 2003). The loop is confined to the north of the LZS in winter, when it extends westward to 118°E. The spatial pattern is very similar to that simulated numerically by Metzger and Hurlburt (1996). Most of the drifters rejoin the Kuroshio to the east of Taiwan and move northward after they exit the SCS. Beyond the north of Taiwan, two veer toward the ECS shelf, suggesting possible intrusion of the Kuroshio northeast of Taiwan, as discussed in the next section. The remaining drifters continue to follow the mainstream of the Kuroshio.

A total of 15 drifters were classified in the category blocked intrusion, which drifts up through the PHC (Fig. 4c) carried by northwestward flows branching off

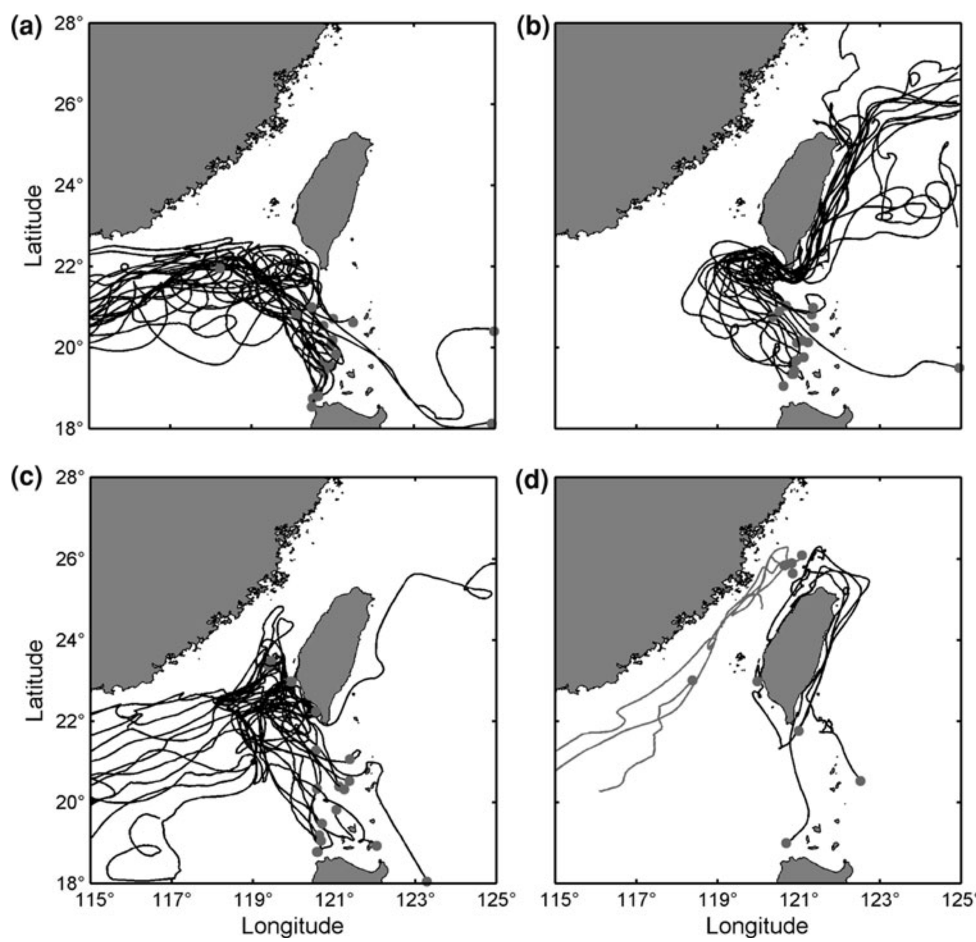


Fig. 4 Major patterns of drifter tracks in winter: **a** the "throughflow" pattern, **b** the looping pattern, **c** the northward intruding pattern, and **d** the southward drifting pattern. *Grey* dots represent initial locations of drifters

from the Kuroshio through the LZS. However, most of these drifters are blocked as they reach the southern flank of the Yun-Chang Rise (YCR) and deflect southwestward returning to the SCS. Only one drifter moved over the ridge, but it did not pass 25°N before turning southward. Interestingly, this drifter seems to merge into the north flank of a Kuroshio loop after leaving the Taiwan Bank and eventually returns to the Pacific Ocean. Accordingly, all the drifters passing through the PHC cannot move persistently northward along the western coast of Taiwan, because they are prevented from doing so by the strong northeast monsoon and the YCR (Jan et al. 2002).

Finally, in contrast with above three patterns, nine drifters were classified in the fourth category that enter the TS from the north. Persistent southward movement was observed in the TS (Fig. 4d) in the same direction as the prevailing wind. It seems that these drifters could be further subdivided into two groups. The first group includes five drifters seeded close to the mainland coast and which migrate southward continuously and are finally brought into the SCS by the downwind China Coastal Current. The second group includes four drifters that deflect from the Kuroshio, take a cyclonic turn around the north tip of Taiwan, and enter the TS along its eastern boundary. None of these, however, reaches the PHC. Trajectories of this group might suggest another possible winter pathway for waters from the ECS to come into the TS in the upper layer along its eastern side on some occasions.

4 Discussions and conclusions

4.1 Rare northward surface flow in the TS during winter

An important point suggested by the Lagrangian current pattern described above is that there is no northward throughflow on the surface of the TS in winter. In fact, none of the available drifters in this study could move northward passing through the TS during the northeast monsoon season.

To provide further statistical evidence, the climatological winter surface circulation in the Eulerian Framework is considered. Based on all surface drifters available in the plotted area (as indicated in Fig. 1), Fig. 5a shows the mean Eulerian current field for winter derived using the method given in the Sect. 2. In the figure, the distribution of velocity vectors clearly indicates that the TS is dominated by southward flows and that northward current vectors could only be found in the PHC. There is no persistent northward flow passing through the strait.

Further statistical evidence is given in Fig. 5b, which presents the number of drifters in each 0.5° × 0.5° cell in winter and the number of drifters among those whose mean drifting speed within the cell is to the north. Cells north of 24°N in the TS contain few drifters that migrate northward. Each cell has less than one drifter and the ratio of the number of northward-moving drifters to the total number of drifters in each cell is less than 25%. The ratio becomes high, approximately 70%, in the PHC suggesting that northward currents predominate in this area in winter.

The characteristic flow in winter obtained from the drifters herein supports results from earlier studies based on hydrographic and tracer measurements, which suggest rare northward flows in the TS during winter (Chen 2003; Chen and Sheu 2006). The combination of forcing from the winter monsoon and the topography may lead to blocking of the northward current (Jan et al. 2002; Teague et al. 2003; Lin et al. 2005) and induce a cross-shore front off the coast of central Taiwan (Wang and Chern 1988; Li et al. 2000a).

It should be noted that winds can induce downwind slip of the drifters (Niiler and Paduan 1995), and since velocity data obtained from surface drifters generally represent currents in the surface Ekman layer. The analyses above, therefore, merely reflect circulation in the upper layer; the lower layer may be different. On the basis of historical measurements in the 1960s, it has long been suggested that winter currents off the southeastern China coast flow northward against the northeast monsoon (Guan and Fang 2006). Direct measurements also show that the near-bottom current in the PHC (Chuang 1986) and that below the surface Ekman layer east to the Taiwan Bank (Zhu et al. 2008) are both northward during winter. And, according to shipboard (Liang et al. 2003) and moored (Lin et al. 2005) ADCP observations, currents in the lower layer in the TS flow primarily in a northward direction. However, there is still a lack of sound evidence for lower-layer throughflows that link currents north of the YCR with that in the PHC. More comprehensive investigation is thus expected, especially mooring measurements in the central TS west to the YCR.

4.2 Circulation patterns in the southern TS

As revealed by the trajectories of the drifters, three major circulation patterns may present in the southern TS. In addition to the well-known "throughflow" pattern that enters the SCS flowing westward along the slope of the southern TS and the loop current pattern that circulates anticyclonically and returns to the Kuroshio (Caruso et al. 2006; Hu et al. 2010), a blocked intrusion pattern was identified that penetrates the interior of the TS through the

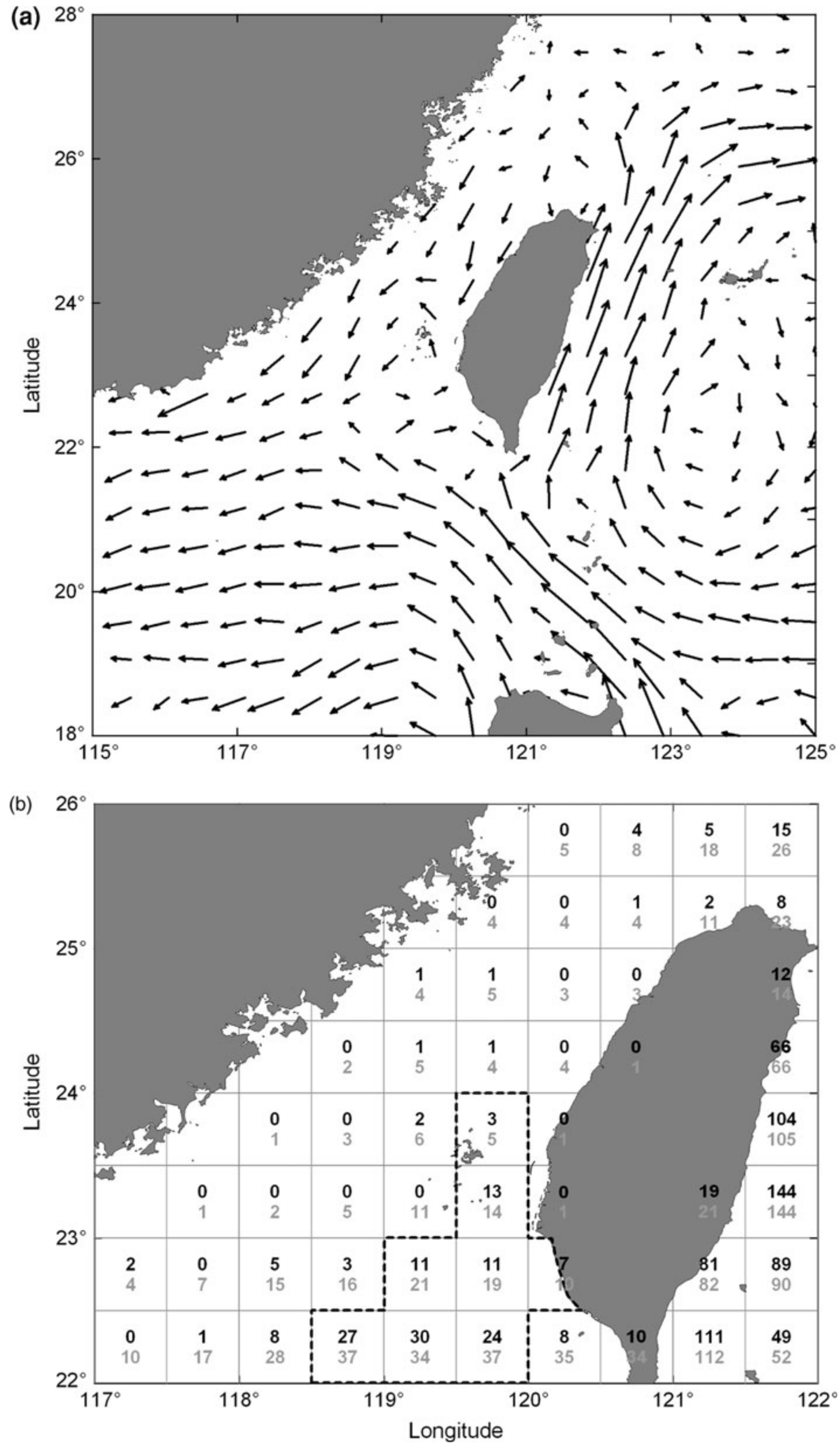


Fig. 5 **a** Surface current (m s^{-1}), and **b** number (*grey*) of drifters and number (*black*) of drifters that follow northward along-strait current in 0.5° × 0.5° cells in winter. Cells with the ratio of northward-moving drifters to total samples higher than 0.5 are bounded by *dashed lines*

PHC but is obstructed by topography. All of these patterns are closely related to the behavior of the Kuroshio in the northeastern SCS (including the southern TS) after entering the LZS.

Approximately 43% of the drifters that entered the TS from the south follow a direct route from the LZS to the interior of the SCS along its northern slope, which in fact is the common pathway for most drifters that enter the LZS

(Centurioni and Niiler 2004). They finally merge into the monsoon-driven western boundary jet (Li et al. 2003; Centurioni et al. 2009)—an important component of the SCS throughflow (Lebedev and Yaremchuk 2000; Fang et al. 2003; Qu et al. 2005). It seems that, in the near-surface layer, the most important circulation feature (the basic mode) of the southern TS is the steadily westward along-slope flow south of the Taiwan Bank (Fig. 5a), which is fed from the Kuroshio through the LZS and is closely related to the large scale winter circulation of the SCS.

In addition to the basic "throughflow" mode, the drifters that looped back to the Kuroshio (30%) and that intruded into the TS (27%) indicate two secondary modes of circulation in the southern TS. The looping pattern is apparently associated with loop-like intrusions of the Kuroshio into the area southwest of Taiwan (Nitani 1972; Li and Wu 1989), which occur frequently in winter when the northeast monsoon is favorable to its development (Farris and Wimbush 1996). Although most arguments for these intrusions are based on results from surface drifters and satellite remote sensing on the sea surface, the loop-like intrusion of the Kuroshio into the SCS is not just a near-surface phenomenon; it has been suggested to have a vertical scale of approximately 1,000 m (Li and Wu 1989). This point is supported by newly available evidence in Fig. 6, which shows currents perpendicular to the ship track for a meridional Sb-ADCP cross-section in the LZS with its northern tip turned shoreward (Fig. 1). A loop-like intrusion with a horizontal scale of approximately 150 km is clearly revealed in the northern LZS, which shows inflows over 80 cm s^{-1} centered at approximately 21.6°N and weaker outflows (>60 cm s^{-1}) at approximately 22.3°N. Most importantly, both features extend beyond the effective range of the instrument, indicating a vertical scale greater than 400 m. The size of this is very close to that suggested by Li and Wu (1989) and is consistent with that of the rings detached from the Kuroshio (Li et al. 1998).

Our knowledge about winter circulation in the TS seems controversial, with questions rising mainly from the fate of waters that pass through the PHC. Most historical studies believe that there is a year-round current in the TS flowing northward along the coast of Taiwan from the SCS toward the ECS, although some (Nitani 1972) suggest it is a branch the Kuroshio and others (Guan and Fang 2006) regard it as an extension of the SCS Warm Current. Recent studies, however, tend to suggest that the northward flows passing through the PHC are intermittent processes governed by the fluctuating winter monsoon, which is blocked by the topography of YCR and does not persist throughout the strait (Wang and Chern 1988; Jan et al. 2002; Chen 2003; Ko et al. 2003; Teague et al. 2003; Wu and Hsin 2005; Lin et al. 2005; Isobe 2008). The results from our drifter analyses add support to the latter view. The trajectory of the drifters suggests there exists an anticyclonic circulation pattern around Penghu Island that causes the drifters to turn around after leaving the PHC.

4.3 Possible inflows along the west coast of Taiwan

As mentioned previously, there are two types of trajectory for drifters that enter the TS from the ECS, which indicates that, in addition to a southward flowing coastal current close to the mainland, a coastal current may also develop, at least occasionally, in the northern TS along its east coast, carrying waters from the ECS into the strait.

As Fig. 4c, d shows, most drifters that travel northeastward along the mainstream of the Kuroshio east of

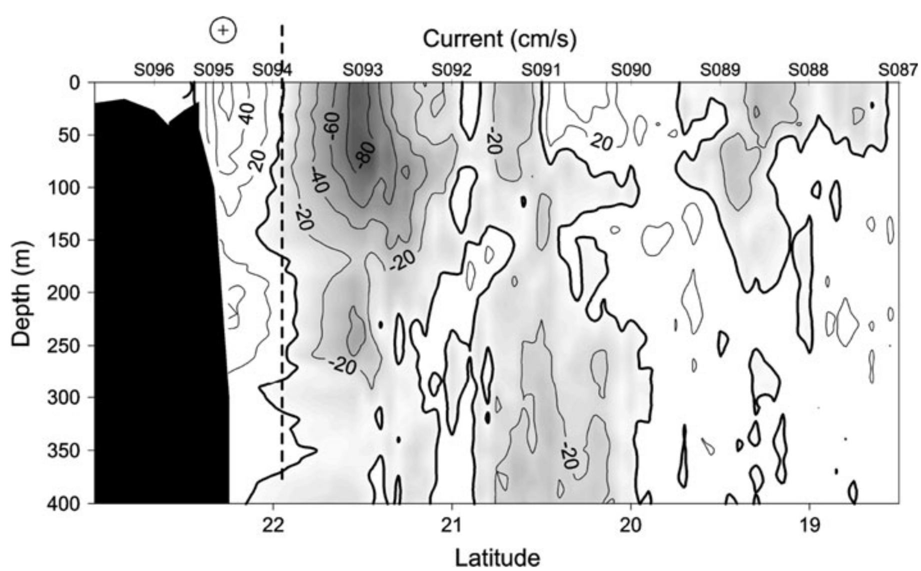


Fig. 6 Cross-section currents along 119.5°E measured with Sb-ADCP from 30 November to 2 December 1998, showing a loop-like Kuroshio intrusion into the SCS with vertical scale greater than 400 m. The location of this section is shown in Fig. 1. The *crossed circle* indicates outflows from the SCS

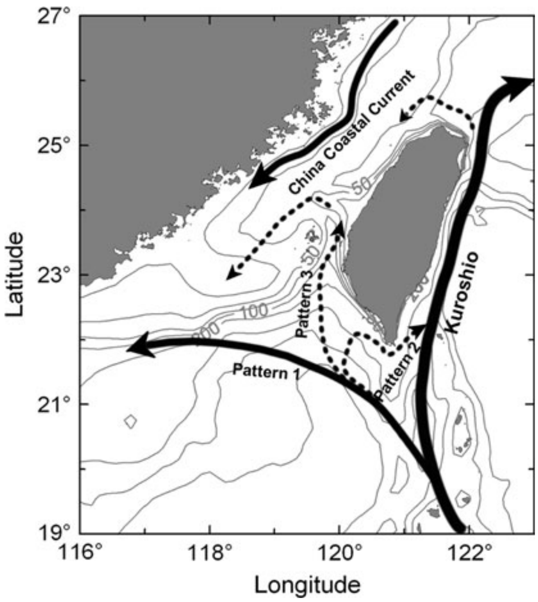


Fig. 7 Schematic diagram of near-surface circulation around the TS in winter. *Patterns 1–3* denote three major circulation patterns in the southern TS as shown in Fig. 4a–c

Taiwan encroach westward on to the shelf after leaving the northern tip of Taiwan (Fig. 4b, d). Some veer sharply to the left, directed northwestward; some turn even further around the northern tip of Taiwan and drift southward into the TS along the coast (Fig. 4d). It is likely that they merge into the shoreward intrusion of the Kuroshio just off the northern tip of Taiwan (Hsueh et al. 1992; Tang et al. 2000) in the first place, and then reach the interior of the TS while falling into the southward flowing coastal current.

As a summary, Fig. 7 schematically depicts the near-surface circulation patterns around the TS in the winter, based on observation of the drifters. The China Coastal Current flows southward along the mainland coast and finally reaches the SCS. On the surface, the intrusion of the Kuroshio through the LZS may follow three possible pathways. The dominant pathway is a near-surface branch that extends westward from the LZS and passes the southern TS into the interior of the SCS. This pathway is associated with two secondary types: the looping pathway for intermittent intrusions into the southwest TS, and the pathway through the PHC representing the northward intrusion of waters from either the Kuroshio or the SCS into the TS, which is blocked at the southern flank of the YCR. Although further evidence is needed, a coastal current around the northern tip of Taiwan is also proposed; this may also transport waters from the ECS into the TS. It seems that the central TS is an important area, and understanding its circulation should be a major focus of future research.

Acknowledgments The authors would like to thank the Chinese Ministry of Science and Technology under the National Basic Research Program (contract no. 2009CB421205, 2011CB403502), the National Natural Science Foundation of China (contract no. 40806014) and the Chinese Offshore Investigation and Assessment Project (contract no. 908-ZC-I-01) for financially supporting this research. C. T. A. Chen acknowledges the National Science Council of Taiwan (contract nos NSC 97-2621-M-110-002 and NSC 96-2621-Z-110-002) and the Aim for the Top University Program for their support. Thanks to the three anonymous reviewers for constructive comments. Ted Knoy is appreciated for his editorial assistance.

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