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Seasonal and interannual variations of surface current in the southern Taiwan Strait to the west of Taiwan Shoals

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Seasonal and interannual variations of surface currents in the southern Taiwan Strait to the west of Taiwan Shoals were investigated by using measurements of high frequency (HF) ground wave radars from January 2006 to April 2009. The results demonstrate that surface currents in the water channel to the west of Taiwan Shoals are composed of a significant, seasonally fluctuating component and a relatively stable northward component. Forced by the East Asia monsoon, the annual variation of the surface longshore current is linearly correlated with the longshore wind. Behind the seasonal signal is a stable northward flow with speeds of O (10 cm/s). The observations also show that surface currents in the area are subject to distinct interannual variation, and the southward surface flow was more profound in winter 2007/2008 than in other winters. Observations from bottom-mounted ADCP also indicated that, in that winter, longshore currents in the west side of the Taiwan Strait are very different from the previous winter. The northward flow appeared much weaker, the currents were southward in most layers, and the interannual differences were observed throughout the water column. Hydrographic observations in the same period suggest that the large-scale southward intrusion of the Zhe-Min coastal water is the direct cause of the interannual difference. The enhancement of the East Asian monsoon during the 2007/2008 La Niña event is considered as the main reason for the winter current anomalies in the study area.

Taiwan Strait, HF radar, surface currents, seasonal variation, interannual variations

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High frequency (HF) ground wave radar detects the surface current on the basis of the electromagnetic Bragg Scattering and Doppler frequency shift [1]. After decades of development, HF radar, relying on its all-weather and long-term abilities of continuous measurement, has become an important tool for marine environment monitoring and oceanographic studies of the coastal area [2,3]. Adopted the OSMAR (Ocean State Measuring & Analyzing Radar) HF radar system developed by the Wuhan University [4], two radar stations were established in Dongshan and Longhai (Figure 1) of southern Fujian Province in June 2005 by the "Fujian Demonstration Site" of the ocean technology subprogram of the National High-Tech Research and Development Program of China, and has been operating continuously for six years. The data quality has been analyzed [5] and validated [6], which shows that error level of current measurement has met the standard of available facilities worldwide, and the observational results have been used to study the circulation in the Taiwan Strait [7]. The time series for the year 2006 based on observations from the system has shown that surface currents in the southern Taiwan Strait are highly variable seasonally. Moreover, based on the analysis of the relationship between monthly longshore components of wind and surface current, and the results of current measurements from ADCP moorings, it was revealed that there is a persistent northward current in the western Taiwan Strait throughout the year. In contrast, in the upper 10 m, the current direction varies seasonally according to the monsoon cycle, with northward flows prevailing in summer, but southward flows dominated by the

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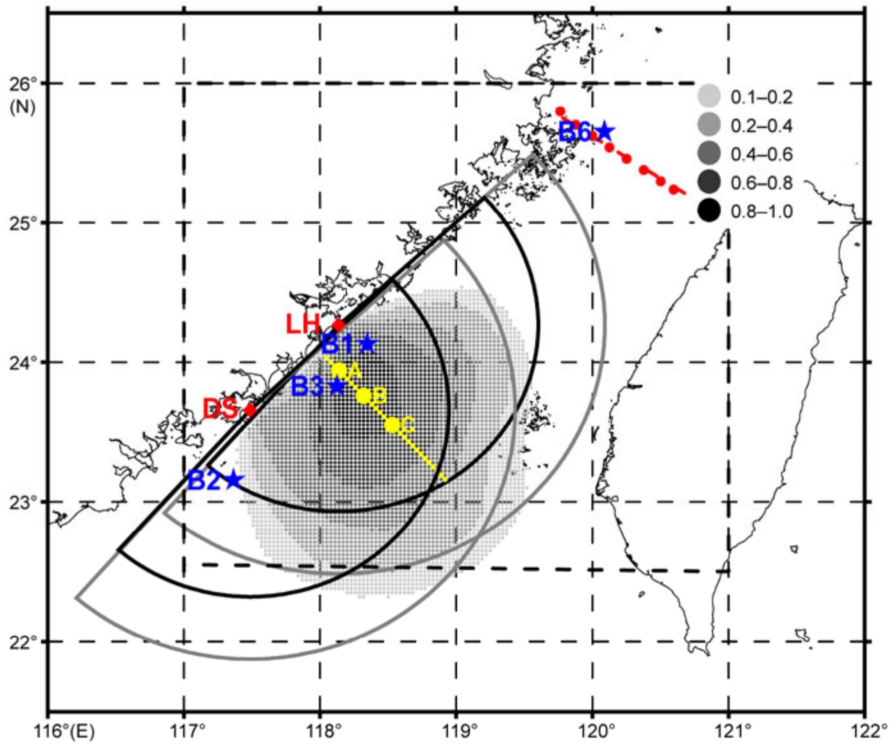

Figure 1 Map of the southern Taiwan Strait showing the distributions of effective sampling rate in 2008 (grey scales); radar stations (red diamonds) at Dongshan (DS) and Longhai (LH); the 200-km specified range (gray lines) and the 150-km effective range (dark lines) of radar coverage; the cross-shore section off LH (yellow line) and its three cells discussed (yellow dots); the mooring sites of bottom-mounted ADCPs (blue stars); CTD casts (red dots with dash line); and the area that QuikSCAT winds were used (rectangular box in dark broken lines).

Zhe-Min coastal current in winter [8,9] even though currents in lower layers are still northward [7].

The Taiwan Strait is the major channel that connects the South China Sea (SCS) with the East China Sea, which is an areas greatly affected by the East Asia monsoon. After years of study, people have acquired a good understanding to the seasonal variation of currents in the Taiwan Strait [10,11], but little has been learnt about their interannual variability. Because of the "narrow channel effect" induced by topography constraint, the winter monsoon is strengthened in the strait, which may act as an "amplifier" to the signals of a climate event [12]. By using principal component analysis, Kuo et al. [13] studied the variability of wind field in the strait during ENSO and discovered that the northeast monsoon was weaker than normal years during the 1997/1998 El Niño event. Since satellite remote sensing shows that the sea surface temperature at the year is higher than normal, they suggest that variations of the wind field may have affected the regional current field and therefore raised the sea water temperature. The numerical model results of Wu et al. [14] also show that in winter 2002, when the northeast monsoon was relatively weak because of El Niño, the southward invasion of the Zhe-Min coastal water was weaken, and the Taiwan Strait is warmer than usual. On the contrary, during the La Niña winter of 2000, the northeast monsoon was strengthened and so was the intensity of the Zhe-Min coastal water, which suppressed the northward flowing warm water from the SCS and reduced the water temperature in the strait [14].

ENSO effects on the Taiwan Strait have also been reported in biogeochemical works [15]. For example, some authors found no Kuroshio intrusion into the Taiwan Strait during the beginning of 2008 and attributed that to the La Niña event [16], which might be a cause of the unusual cold event of the winter of 2008 in the strait, which caused serious damage of fishery resources around the Penghu Islands [17,18].

Generally speaking, the previous studies have shown that current field in the Taiwan Strait is highly variable inter-annually in response to the change of local wind field associated with major climate events. However, the conclusion has yet to be testified by long-term current observations. In this paper, we report the results of continuous current measurement for three years and four months from the HF radar system in southern Fujian Province, and that of ADCP moorings deployed in the strait. The interannual variations of the current field in the west side of the Taiwan Strait and its responses to ENSO are investigated.

1 Data and methods

The observation system is composed of two OSMAR radars, respectively located in Dongshan (DS) and Longhai (LH) (Figure 1) [5]. The surface current data available from January 2006 to April 2009 were provides by the "Fujian Demonstration Site" of a key ocean technology subproject under the Hi-Tech Research and Development Program of China. The data sampling interval is 10 min and the spatial resolution is 0.03° by 0.03°. Figure 1 displays the spatial distribution of the grid cells with an effective sampling rate greater than 10% for the year 2008, which shows that the sampling rate is higher in the central area of the overlapping sector of the radar coverage, and decreases outward. In order to be comparable with our previous work, the 135° True section southeast off LH was adopted as well following Zhu et al. [7]. The two ends of the section were determined with a cutoff of effective sampling rate above 40%, and a total of 30 equal intervals were divided for statistics. Quality control was conducted over current data for each cell on the section month by month that leaved out the samples with anomaly over three times of the standard deviation for each current component. Vector average was then applied to the cells with a monthly sample size greater than 1000 [7], and the longshore (45° True) and cross-shore (135° True) components of monthly current vector were thus derived. Among which three cells (A: 118.14°E, 23.94°N; B: 118.32°E, 23.76°N; C: 118.53°E, 23.55°N) with effective sampling rates above 75% were chosen for further analysis (Figure 1).

The QuikSCAT L3 daily wind field data for the same period were downloaded from PO.DAAC of JPL, NASA. Time and space average were applied to the daily data to yield the monthly wind vectors and their anomalies to the climatological annual cycle. Their longshore and cross-shore components were calculated in the same manner as that of the current.

The paper also presents current data from four bottom-mounted ADCPs labeled B6, B1, B3, B2 from north to south (Figure 1) deployed along the west coast of the Taiwan Strait. The measurement periods are from Dec 1 2007 to Mar 31 2008 for B1; from Nov 30 2007 to Feb 22 2008 for B1; from Nov 1 2007 to Feb 22 2008 for B3; and from Dec 11 2007 to Mar 26 2008 for B2. In addition, the data from Feb 5 2007 to Mar 30 2007 observed at B6 were also used for interannual comparison. A similar procedure of quality control was applied to these data as well.

2 Results and analysis

2.1 Spatiotemporal variations of surface current

Figure 2 shows the spatiotemporal evolution of longshore and cross-shore components of the monthly mean current along the LH section from January 2006 to April 2009, with the area of insufficient samples blanked. From Figure 2, it is obvious that the pattern of annual variation of surface currents in both 2007 and 2008 is similar to that of 2006 [8]. The longshore flows are southwestward in winter but northeastward in summer, showing a longer transitional period in spring and a rapid reversion in fall. Although the cross-shore component is generally weak, similar to 2006, the surface current tends to be offshore in each summer.

A more careful comparison can find the distinct differences from year to year: the northward longshore current

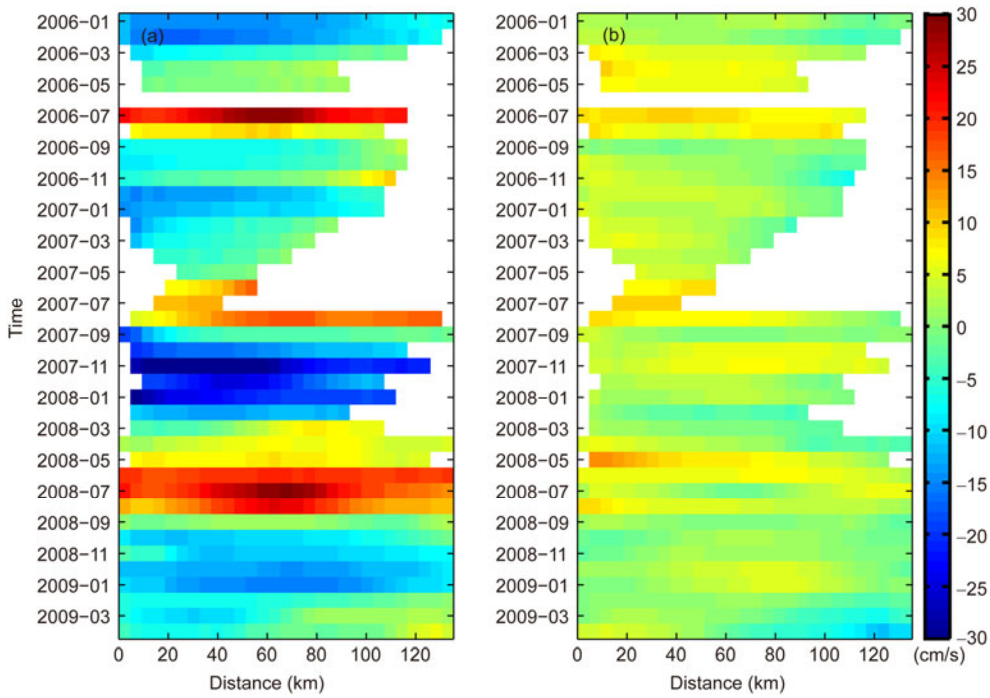

Figure 2 The spatio-temporal evolution of (a) longshore and (b) cross-shore current components along the section off Longhai (January 2006 to April 2009).

in summer 2007 was weaker than the other two years, and the southward longshore current was so strong in the winter of 2007/2008 that differs significantly from the winters of 2006/2007 and 2008/2009. The maximum of the southward longshore flow appeared in November 2007, when the monthly mean current reached a maximum of 37.7 cm/s at about 40 km offshore. In addition, interannual variation is also observed in cross-shore currents, of which both annual maximums of 2006 and 2007 appeared in July with offshore speeds of about 10.0 cm/s, while in 2008 it occurred in May and reached 14.0 cm/s nearshore.

2.2 Correlations between wind and current alongshore

Figure 3 presents the correlations between the monthly means of longshore wind and current for three cells of the LH section. The results are similar to that of 2006 reported previously [7]. The longshore wind speed appears linearly correlated with the surface longshore current of each cell (Table 1), which indicates that seasonal variation of near surface current in the area is dominated by the monsoon. It is also found that the intercepts of the linear regression lines on the vertical axis are all positive, which suggests that, in addition to the seasonally varying surface current component, there is a stable current superimposed, flowing northward in the western Taiwan Strait all year around [7]. Besides, the intercepts of the regression lines increase with the distance offshore, which indicates the underlying northward current is weaker nearshore and becomes relatively strong in the mid-channel. Significant interannual variation of the northward current can also be seen in Table 1. The northward current speeds of the three cells range between 8.5 and 12.0 cm/s in 2006; between 4.7 and 7.9 cm/s in 2007 (about two-thirds of that in 2006); but up between 11.1 and 17.2 cm/s in 2008 (about one and a half times of 2006). Generally, the northward current strength was close to the average level in 2006, weaker in 2007 and much stronger in 2008. From Figure 3, it is easy to see that the interannual differences are more remarkable in winter, of which the annual maxima of the southward current reached 37 cm/s in 2007, but were only 17 and 26 cm/s in 2006 and 2008 respectively.

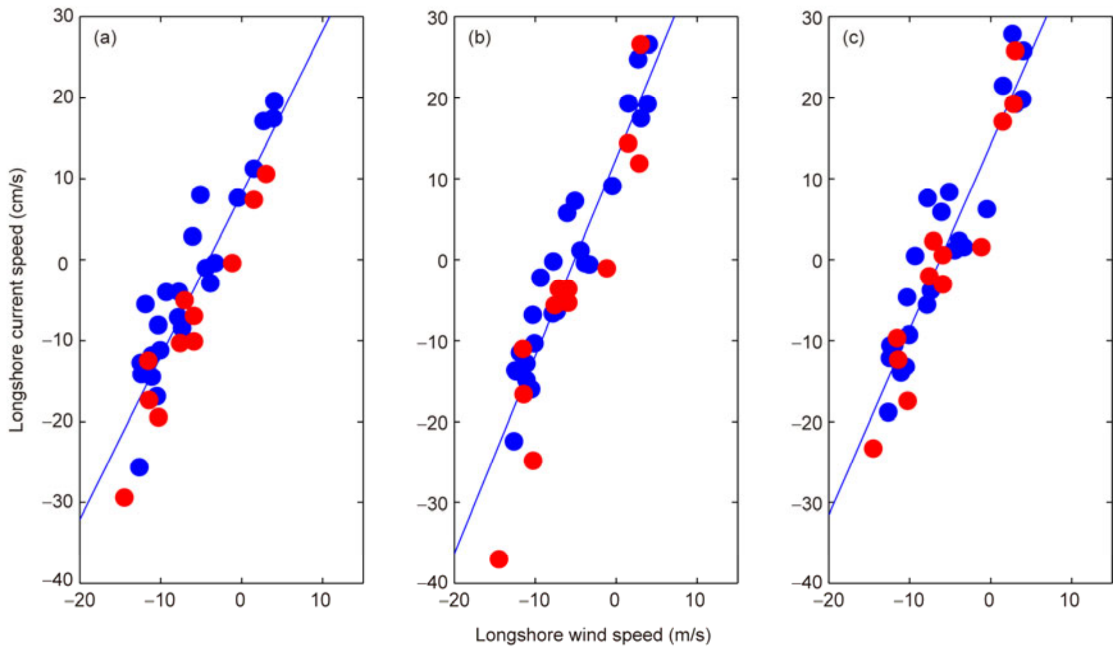

Figure 3 Correlations of longshore current with longshore wind (red dots for 2007).

Table 1 Linear regression coefficients of longshore current with longshore wind[a)]

Year	Cell A			Cell B			Cell C		
	k	y_0	r	k	y_0	r	k	y_0	r
2006	1.98	8.5	0.95	2.26	12.0	0.94	2.01	11.6	0.92
2007	2.02	4.7	0.96	2.32	7.2	0.92	1.87	7.9	0.93
2008	2.02	11.1	0.92	2.44	15.4	0.97	2.44	17.2	0.95
Total	2.01	8.2	0.92	2.44	12.5	0.93	2.29	14.2	0.94

a) k, slope; y_0, intercept on y axis; r, correlation coefficient.

2.3 Vertical features of longshore current

Over three years of radar observation has revealed the significant differences of the surface current field in the winter of 2007/2008 with those of the other years, and has illustrated the notable interannual variability of circulation in the Taiwan Strait. There is evidence that the variations are not limited to the sea surface but also permeates through the entire water column.

Figure 4 displays the vertical profiles of monthly longshore current at the four ADCP mooring sites of B6, B1, B3, and B2, deployed from December 2007 to February 2008, with positive (northward) values shaded. The longshore currents are mostly southward throughout the water column at each mooring site in that winter, with speeds decreasing with depth. The exceptions only appear in the southern strait at site B3 off LH where northward undercurrents were observed in the layers below 20 m in December 2007 and February 2008, and at site B2 to the south of DS in the layers below 30 m in December 2007. The speeds of the undercurrent are about 5 cm/s at B3 and a bit less than 2 cm/s at B2. Hence, there was no continuous northward undercurrent in the west side of the strait observed in the period.

For interannual comparison, Figure 4(e) also shows the monthly mean profiles of B6 for February and March 2007. The shaded areas in Figure 4(e) are remarkable, which indicates a strong northward undercurrent of ~10 cm/s in the lower layer (below 10–15 m) with southward current lying on the top, which is similar to that observed in the southern strait in the same period [7]. The magnitude of the northward longshore current observed in early 2007 is about twice that in the winter of 2007/2008, which is in good consistency with the radar observation. Obviously, currents in the western Taiwan Strait in the winter of 2007/2008 is very different from that in the winter of 2006/2007, when the northward undercurrent was suppressed by strong southward currents in the upper layer and became much weaker than normal years.

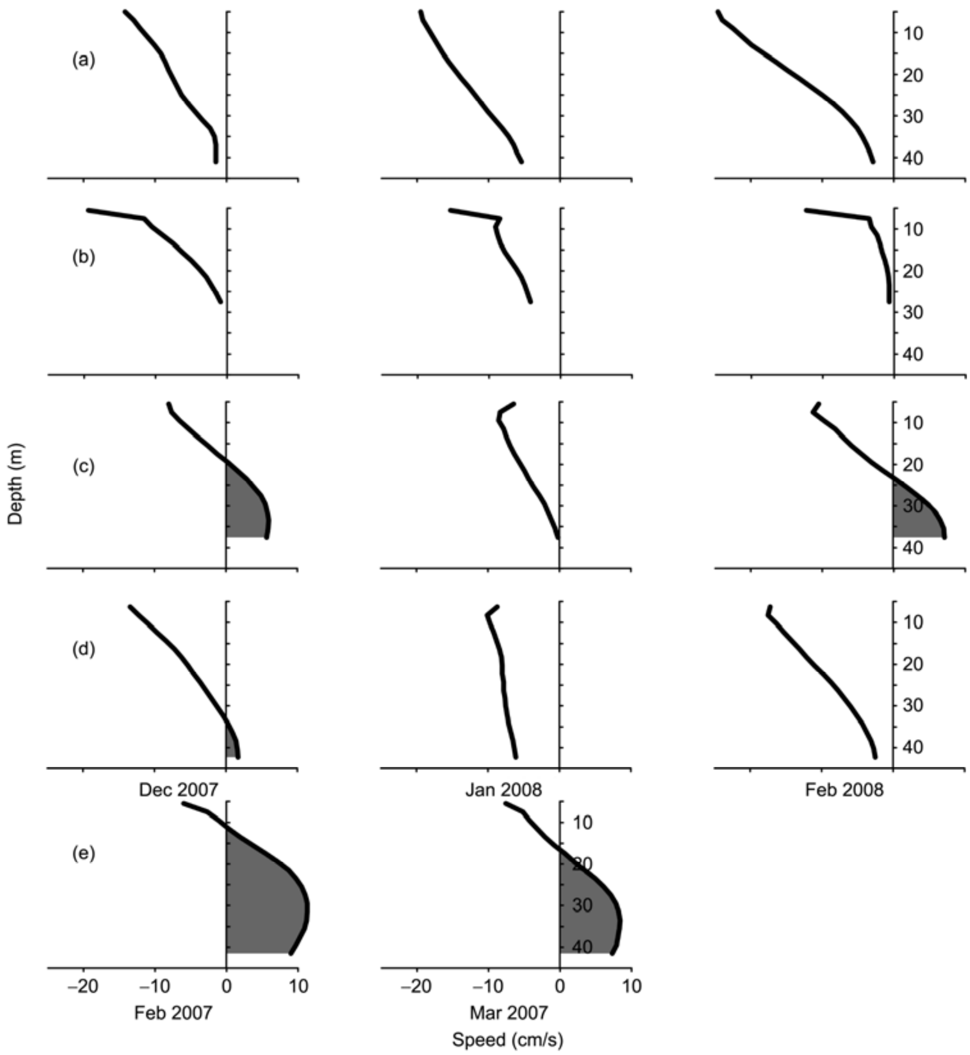

Figure 4 Vertical profiles of monthly longshore current for (a) B6, (b) B1, (c) B3, and (d) B2 in the winter of 2007/2008 and for (e) B6 in early 2007, all observed with bottom-mounted ADCP.

2.4 Interannual variation of hydrographic conditions

Generally speaking, currents in the west side of Taiwan Strait are mainly composed of two components: the relatively stable northward current with a magnitude at ~10 cm/s and the superposed seasonal varying longshore current driven by the wind. However, the wind effects are not limited to the near-surface layer but may sometime penetrate through the water column and alter the stratification in the strait. These changes are clearly presented in Figure 5, which shows the distributions of temperature, salinity and density along the section near B6 (Figure 1) observed in the winters of 2006/2007 and 2007/2008.

Along the section, the temperature was vertically homogeneous in the winter of 2006/2007 (Figure 5(a)), which shows a nearshore low of ~13°C with increase of temperature offshore. While in the winter of 2007/2008, it was vertically stratified with colder waters of temperature below 18ºC in the upper layer but warmer water down below in the western strait (Figure 5(b)). The distributions of salinity and density were similar to the temperature. They were vertically homogeneous basically in the winter of 2006/2007 (Figure 5(c),(e)), but stratified in the winter of 2007/2008 (Figure 5(d),(f)). The nearshore area was covered by waters with salinity lower than 31 in the winter of 2007/2008, and the halocline was well evident. On the whole, the results indicated that all three parameters tend to increase offshore in both winters, however, their stratification conditions are rather different between the two years: horizontally stratified in the winter of 2006/2007 but vertically stratified in the winter of 2007/2008.

It can be seen from Figure 5 that in the winter of 2006/2007 the intrusion of the Zhe-Min coastal water was limited to the coastal area only and vertical mixing appeared to be more vigorous, which prevailed over the advection effect of the intruded coastal cold water and resulted in a vertical homogeneous situation with horizontal stratification (Figure 5(a),(c),(e)). In the winter of 2007/2008, almost the entire section was vertical stratified with a thermocline at about 30 m depth and the 32.0 isohalines extended eastward to ~90 km offshore (Figure 5(b),(d),(f)). It indicates that a large amount of low-salinity water had intruded onto the strait from the north, and therefore the low-salinity coastal cold water covered a much wider area than the previous winter (~40 km offshore). Because of the buoyancy effect prevailed over the effect of local mixing, vertical stratification

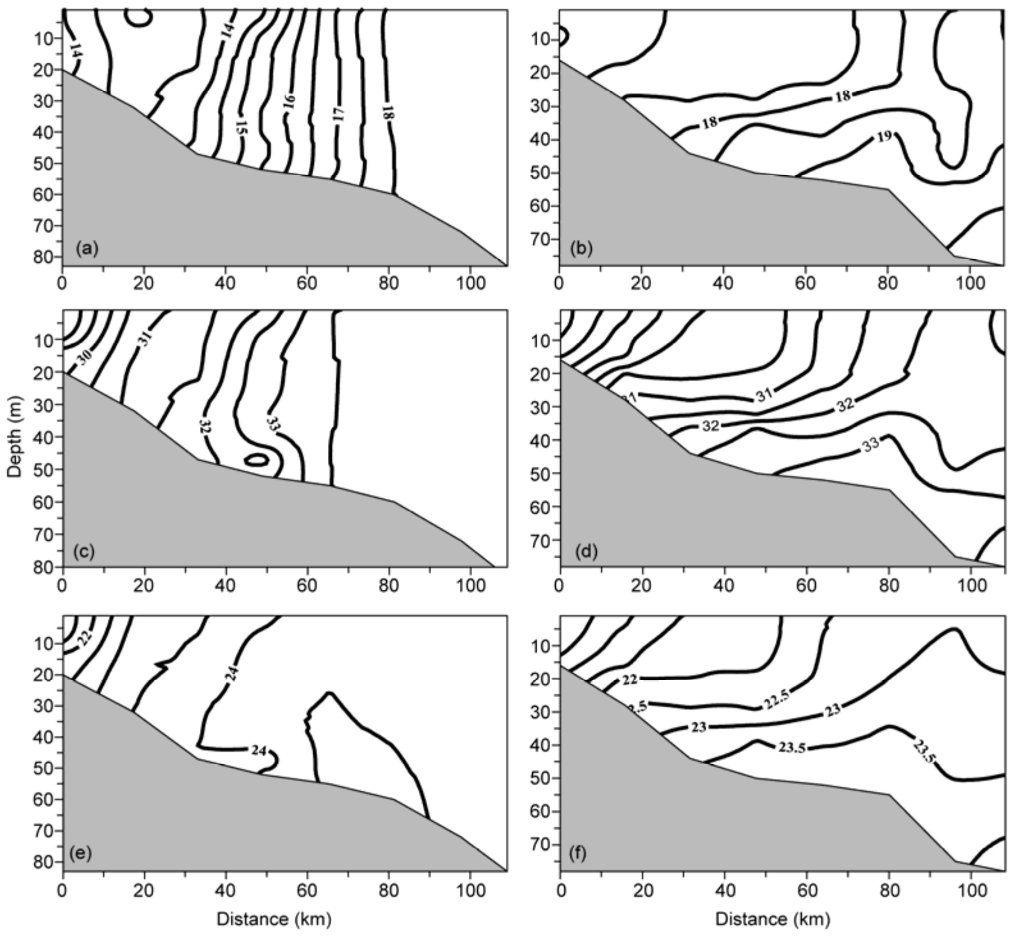

Figure 5 Temperature ((a), (b) unit: °C), salinity ((c), (d) unit: ‰), and density ((e), (f) unit: kg/m^3) distributions in the winters of January 6, 2007 (left) and December 12, 2007 (right) along the CTD section near mooring B6.

came into being.

The analyses above show that the Zhe-Min coastal water is more active in the winter of 2007/2008 than in the winter of 2006/2007, which not only confirms the interannual variation of circulation in the Taiwan Strait but further indicates that the variation is not restricted to the area close to its west coast but may spread all over strait. It is worth noting that although current observations indicate strong southward longshore flows in the winter of 2007/2008, which weakened the northward under current and affected the whole water column, the baroclinic structure of hydrographic distributions (Figure 5(b),(d),(f)) does not fully match with the current observation, especially in the lower layers. It is thus suggested that the strengthened southward current might contain some barotropic or ageostrophic components, and thus affect the lower layers.

2.5 Impact of the 2007/2008 La Niña

The analysis from NOAA's (National Oceanic and Atmospheric Administration) Climate Prediction Center shows that the winter of 2007/2008 is a winter of La Niña event (www.cpc.ncep.noaa.gov), and the northeast monsoon in the Taiwan Strait must be strengthened then [14,16]. Because the circulation in the upper layer of the strait are dominated by the monsoon, the interannual differences of longshore current and hydrographic conditions of the winter of 2007/2008 from normal winters could be attributed to variation of monsoon winds over the Taiwan Strait during the La Niña event.

Figure 6(a) and (b) presents, respectively, the time series of the monthly mean longshore wind over the strait and its anomaly during the HF radar measurement period derived from QuikSCAT data. And, the anomaly values are also given in Table 2. The annual variation of winds in the strait are well presented (Figure 6(a)) with mild southwesterly of longshore speeds less than 5 m/s in summer (June to August), and powerful northeasterly of about 10 m/s in winter (November to February), significantly stronger than its counter part in summer. Figure 6(b) shows that there are substantial interannual variations of the winter monsoon. The negative anomaly in the winter of 2007/2008 is especially remarkable, which is very different from the previous and next years. The southward longshore wind is extremely strong in November 2007 when it reached a maximum close to 14.0 m/s, which are 2.4 and 4.7 m/s greater than the same month of 2006 and 2008 respectively. Similar differences of longshore wind from the other years can also be found in both January and February of 2008.

The linear relationship between the longshore wind and current (Figure 3) and the enhanced monsoon in the winter of 2007/2008 suggest that the energetic northeast monsoon during the La Niña event is the main driving mechanism responsible for the enhancement of winter southward currents along the west coast of the Taiwan Strait. Take the longshore wind speed anomaly of February 2008 (–2.84 m/s, Table 2) as an example, the estimated increase of monthly southward longshore current based on Table 1 would be about 5–7 cm/s comparing with the other years, and so the northward undercurrent would reduce significantly. The finding supports the model results of Wu et al. [14], which points out that although current variations in the Taiwan Strait is mainly controlled by the change of winds in the region, they are in fact local responses to the large-scale climate event such as ENSO as well. This kind of variation may bring out the change of biogenic elements in the strait

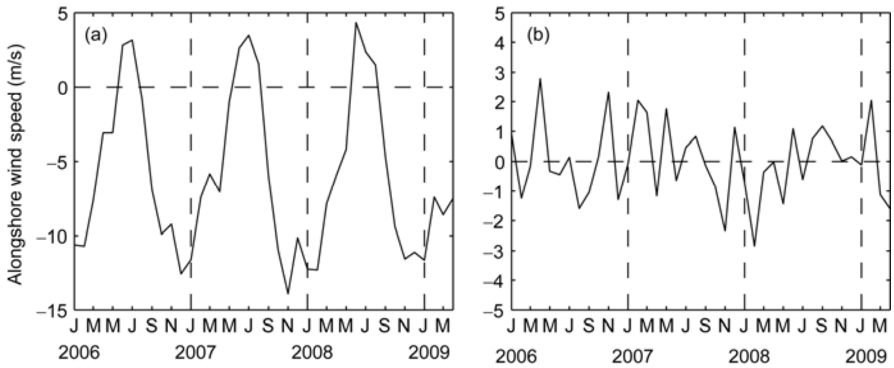

Figure 6 Variations of (a) monthly longshore wind speed in the Taiwan Strait and (b) its anomaly referred to the mean seasonal cycle.

Table 2 Anomalies of longshore wind speed from January 2006 to April 2009 (m/s)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006	0.91	–1.24	–0.16	2.79	–0.33	–0.44	0.14	–1.59	–1.04	0.18	2.33	–1.29
2007	–0.08	2.04	1.64	–1.16	1.76	–0.64	0.47	0.83	–0.14	–0.85	–2.35	1.13
2008	–0.72	–2.84	–0.36	–0.02	–1.43	1.09	–0.61	0.76	1.18	0.67	0.02	0.16
2009	–0.12	2.04	–1.12	–1.61	–	–	–	–	–	–	–	–

that acts on the ecology system [15,16], and even trigger ecologic disasters [17,18].

3 Conclusion

The results confirmed that, affected by the seasonal alternative monsoon, the surface current in the western strait varies significantly annually, and the longshore current is linearly correlated with the longshore wind speed. Behind the seasonal signal, there is a relatively stable northward current in the background with a magnitude of ~10 cm/s.

More importantly, the observations from 2006 to 2009 revealed that the winter currents in the strait (from November to next February) are highly variable interannually, in which the southward longshore component in the winter of 2007/2008 is considerably stronger than that of the other winters.

The current profiles from the bottom-mounted ADCPs in the west side of the Taiwan Strait also show similar results. And, the hydrographic measurements during the same period suggest that a large-scale southward intrusion of the Zhe-Min coastal water during the winter of 2007/2008 is the direct cause of the interannual differences. There is evidence that invasion of the Zhe-Min coastal water had caused significant changes of stratification and that its effect might have reached the entire water column and resulted in a weaker northward undercurrent.

It is suggested that the energetic East Asian monsoon caused by La Niña during the winter of 2007/2008 is the main reason for the observed interannual variation of circulation in the research area.

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