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Review

Review on Current and Seawater Volume Transport through the Taiwan Strait

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Patterns and features of currents and seawater volume transports in the Taiwan Strait have been reviewed by examining the results from more than 150 research papers in recent decades. It is noted that there are diverse or even conflicting viewpoints on these subjects. Here both common and different opinions are summarized. This review paper covers the studies involving *in situ* measurements and numerical modeling of current velocity, analyses of hydrographic data, and classification of water masses. Generally speaking, there are three currents in the Taiwan Strait: the China Coastal Current along the Fujian coast in the western Taiwan Strait, the extension of the South China Sea Warm Current in the western and central Taiwan Strait, and the Kuroshio's branch or loop current intruding through the eastern Taiwan Strait. The current pattern in winter is quite different from that in summer, and the currents also exhibit differences between the upper and lower layers. The seawater volume transport through the Taiwan Strait is about 2.3 Sv northward in summer but about 0.8 Sv northward in winter. Both the current pattern and the seawater transport vary with local winds in the Taiwan Strait. This is particularly true in winter when the currents and the transport in the upper layer are significantly affected by strong northeasterly winds.

Keywords:
· Review,
· current pattern,
· seawater transport,
· Taiwan Strait,
· winter,
· summer.

1. Introduction

The Taiwan Strait, located between the South China Sea (SCS) and the East China Sea (ECS), is an important channel for seawater transport. It connects with the Luzon Strait on its southeastern side.

As shown in Fig. 1, the Taiwan Strait is characterized by variable bottom topography even though the depth is about 60 m for the most part. A shallow bank, i.e. the Taiwan Bank, is located in the southern Taiwan Strait with a depth of less than 30 m. In the southeastern Taiwan Strait, the deep Penghu Channel lies along the southwestern coast of Taiwan Island and the Pengbei Channel extends between the Penghu Islands and the Zhang-Yun Ridge (or Changyun Rise, Chang-yuen Ridge in some references) from the Penghu Channel.

The Taiwan Strait is in a subtropical monsoon regime. According to its climatological features, summer is usually from June to August, while winter is from December to February. Northeasterly winds prevail in the Taiwan Strait in winter; and the frequency of northeasterly winds reaches 58% with an average wind speed of 10.2 m s^{-1}. In summer, southwesterly and southerly winds dominate in the Taiwan Strait with a frequency of 45% and a mean speed of 5.1 m s^{-1} (Ke and Hu, 1991). Therefore, the wind-driven currents are mostly southwestward in winter but northeastward in summer, though their wind-driven properties have not been observed in detail. The difficulty in observing the wind-driven component is due

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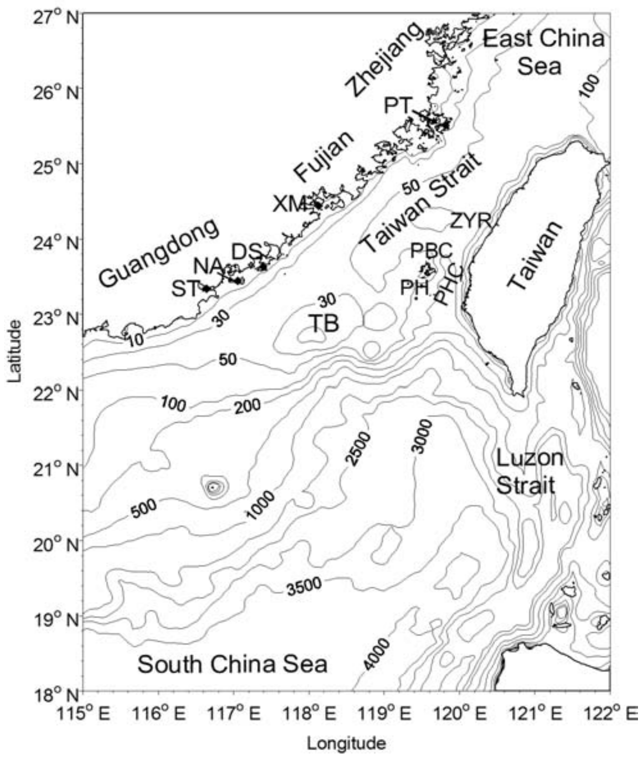

Fig. 1. Map of the Taiwan Strait and its adjacent seas, with depth contours in meters. PT, XM, DS, NA, ST, ZYR, PBC, PH, PHC and TB denote Pingtan, Xiamen, Dongshan, Nanao, Shantou, the Zhang-Yun Ridge, the Pengbei Channel, the Penghu Islands, the Penghu Channel and the Taiwan Bank, respectively.

to the fact that the currents are also strongly affected by other components from both the northern SCS and the Luzon Strait.

It has been accepted that the Taiwan Strait has several major currents, i.e. the China Coastal Current, the extension of the South China Sea Warm Current (SCSWC) (Guan, 1998, 2002; Guan and Fang, 2006) and the intrusion from the Kuroshio. Affected by monsoon winds, the currents demonstrate great seasonal variations. Especially, the China Coastal Current in the western Taiwan Strait is considered as the southwestward Zhemin Coastal Current in winter but the northeastward Yuedong Coastal Current in summer, which appears to be associated with the monsoon winds.

The study on the currents and seawater volume transports in the Taiwan Strait has been conducted for decades. Hu *et al*. (2000) and Hu *et al*. (2003) reviewed the SCS circulation and the Taiwan Strait upwelling, respectively. Wang (2000), Liu *et al*. (2002) and Xiao *et al*. (2002) described the hydrographic features in the Taiwan Strait. Su (2001, 2004), Wang G. H. *et al*. (2003), Su and Yuan (2005), Sun (2006) and Liu *et al*. (2008) summarized the circulation dynamics in the coastal oceans near China and in the SCS. Isobe (2008) reviewed the recent advances in ocean circulation research in the Yellow Sea and the ECS continental shelves. However, these papers did not elaborate sufficiently on the current patterns and seawater volume transport in the Taiwan Strait.

In summarizing more than 150 articles in this field, it is evident that there are several viewpoints on current patterns and seawater transport through the Taiwan Strait. The purpose of this paper is to provide a comprehensive summary of these studies. Sections 2 and 3 give reviews on the current patterns and seawater transport, respectively. And a summary with some discussions is given in Section 4.

2. Current Patterns in the Taiwan Strait

2.1 Early viewpoints on current patterns

Early studies on the current patterns in the Taiwan Strait were usually based on the following data sources: (1) the current charts published by the Japanese Hydrological Office in 1925; (2) the current vectors derived from ship drift; (3) the measured current data from the Chinese National Comprehensive Oceanographic Survey (1958–1960) (Guan and Chen, 1964); and (4) temperature and salinity distributions from a few oceanographic observation cruises. Moreover, these early studies were mostly associated with studying the current systems in the ECS (such as Japanese Hydrological Office, 1925; Uda, 1934; Nino and Emery, 1961; Chu, 1963, 1971; Guan and Chen, 1964; Nitani, 1972). As a typical early understanding of the currents in the Taiwan Strait, the monsoon system was regarded as the primary force causing the flow variations around Taiwan (Wyrtki, 1961).

An important study was conducted by Nitani (1972) who described the surface currents around Taiwan both in summer and in winter. It was indicated that a coastal current flows southwestward in winter but northeastward in summer in the western Taiwan Strait. In the eastern Taiwan Strait, the current flows northeastward in both summer and winter seasons. This was the early viewpoint on current patterns in the Taiwan Strait. Combining the charts from Nino and Emery (1961) and Nitani (1972), Jan *et al*. (2002) summarized the current patterns as shown in Fig. 2, specifying that the current in the western Taiwan Strait is the China Coastal Current (i.e. the Zhemin Coastal Current) in winter and the SCS surface current in summer. In contrast, the current in the eastern Taiwan Strait is the Kuroshio branch current.

As indicated in the following sub-sections, these early viewpoints on the current patterns were too simplified. For example, they did not represent currents in the central Taiwan Strait.

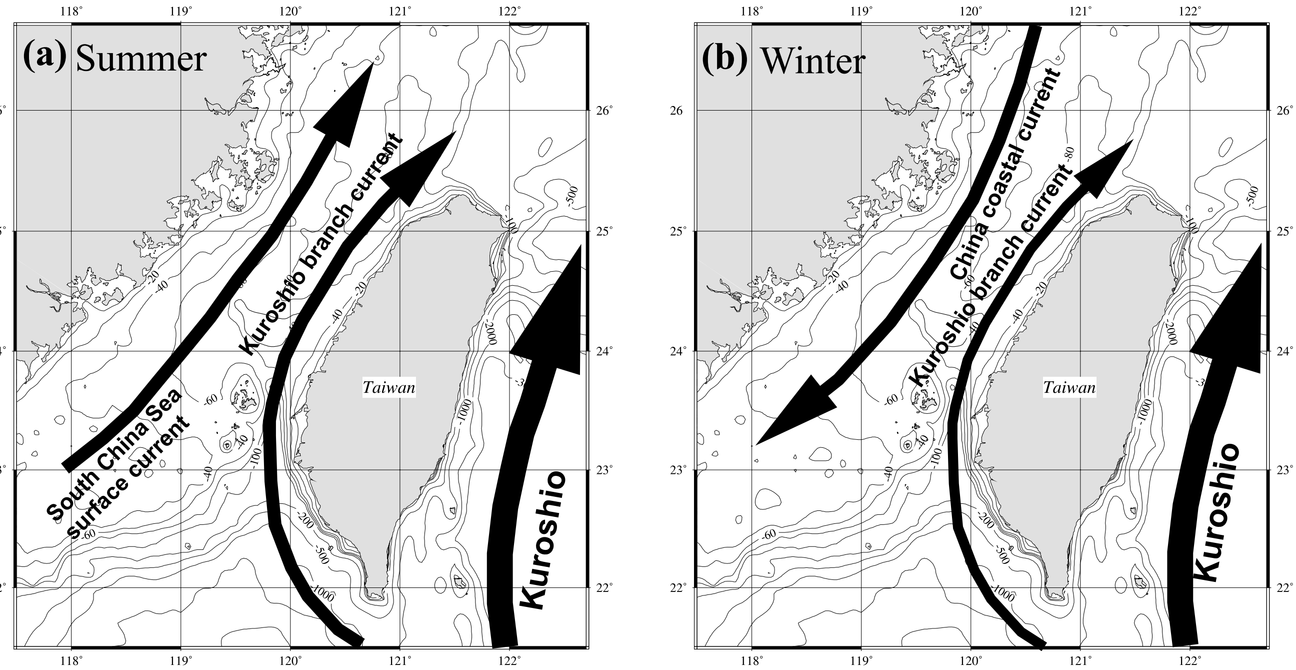

Fig. 2. Summarized early viewpoint of current patterns in the Taiwan Strait in (a) summer and (b) winter (cited from Jan *et al*., 2002 after Nino and Emery, 1961 and Nitani, 1972). In (b), the China Coastal Current may include the Zhemin Coastal Current.

2.2 *Modified viewpoints on current patterns in the 1980s*

In the 1980s, many hydrographic surveys were conducted in the Taiwan Strait by several oceanographic and fishery institutions in China (e.g., Fan, 1982; Qiu *et al*., 1985; Chuang, 1985, 1986; Wang and Weng, 1987; Weng *et al*., 1987, 1988; Xiao and Cai, 1988; Li and Li, 1989; Wang, 1989). The observational data from these surveys urged modifications to the earlier viewpoints on the current patterns in the Taiwan Strait.

At the beginning of the 1980s, Wu (1982a, 1982b, 1983) studied the currents in the Taiwan Strait. On constructing a current system in the China Seas, Guan (1986a) proposed a conceptual current pattern in the Taiwan Strait (Fig. 3), in which three currents appear in the Taiwan Strait in summer as well as in winter. One current flows southwestward in winter but northeastward in summer in the western Taiwan Strait. Another current was suggested to originate from the Kuroshio and flow northward in the eastern Taiwan Strait (Fan, 1982; Guan, 1985). Between both currents, a northeastward current exists in the central Taiwan Strait in summer and was supposed to appear in winter as well.

As revealed by Guan and Chen (1964) and Guan (1978a, b), there exists an SCSWC offshore of the Guangdong coast, which flows northeastward all the year round. It should be noted that the SCSWC flows against the prevailing northeasterly wind in winter. There also exists a northeastward current, the Taiwan Warm Current, in the southern ECS. As shown in Fig. 3(b), it is clearly indicated that these two warm currents connect with each other in the Taiwan Strait in summer. In contrast, there was not enough evidence to link these two currents in the central Taiwan Strait in winter (Fig. 3(a)) though such link had been hypothesized. Guan (1986b) argued with more evidence that the SCSWC extends northeastward and flows through the central Taiwan Strait even in winter. During the 1980s, several other studies (e.g., Ma, 1987; Su and Wang, 1987; Fang and Zhao, 1988) presented the possible mechanism for such a warm current system.

2.3 *Further modified viewpoints on current patterns in the 1990s*

A better understanding of the current patterns in the Taiwan Strait was given in the 1990s by intensive *in situ* current observations (e.g., Hong *et al*., 1991; Li and Liang, 1991; Fang *et al*., 1992; Weng *et al*., 1992, 1993; Wang and Chern, 1992, 1993; Chen and Tang, 1993; Huang *et al*., 1993; Fang, 1995; Xu *et al*., 1995; Wang, 1995; Xu and Su, 1997; Chen *et al*., 1999; Hu *et al*., 1999a, b, c) and numerical model studies (e.g., Li *et al*., 1993; Jan *et al*., 1994a, 1994b, 1998; Lu *et al*., 1997; Wang and Yuan, 1997a, b; Cai and Wang, 1997; Cai *et al*., 1998a, b).

Using the measured current data at several day-night

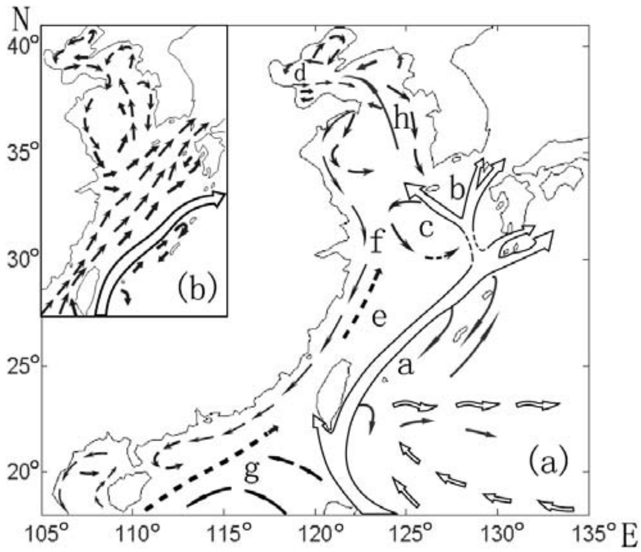

Fig. 3. Modified current patterns in the Taiwan Strait and its adjacent seas in (a) winter and (b) summer (redrawn after Guan, 1986a). In (a), **a** is the Kuroshio; **b**, the Tsushima Warm Current; **c**, the Huanghai Sea Warm Current; **d**, the Bohai Sea Circulation; **e**, the Taiwan Warm Current; **f**, the China Coastal Current; **g**, the SCS Warm Current; and **h**, the West Korea Coastal Current. The portion of the China Coastal Current along Zhejiang and Fujian coasts is the Zhemin Coastal Current.

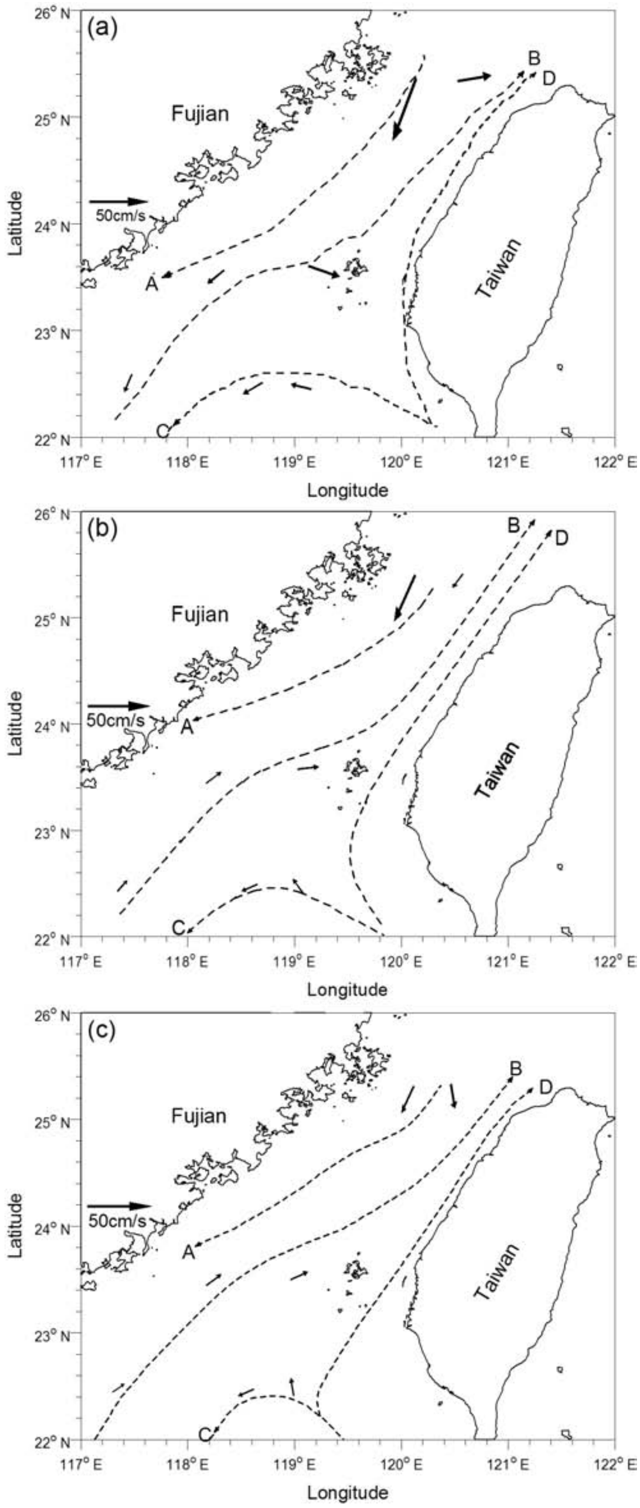

Fig. 4. Schematic wintertime current patterns in the Taiwan Strait (redrawn after Hu *et al*., 1990). (a) Surface layer, (b) intermediate layer, and (c) near-bottom layer. The vectors in the figures are from the *in situ* current measurements. The dashed long arrows denoted by **A**, **B**, **C** and **D** at the arrow-head are the schematic current patterns deduced from the measured currents.

anchored stations, Hu *et al*. (1990) proposed a schematic wintertime current pattern in the Taiwan Strait (Fig. 4). It was indicated that there is a coastal current flowing south-southwestward along the Fujian coast with a width of about 40 km and a mean speed of about 0.45 m s^{-1}. It is stronger in the north of the Taiwan Strait, and then becomes weaker as it heads south-southwestward (Fig. 4(a)). The coastal current, with low temperature and low salinity water, is originated from the Zhemin Coastal Current (one part of the China Coastal Current, see Fig. 3(a)) and was reported to reach the area near Dongshan (Zeng, 1986; Xiao and Cai, 1988; Guan, 1994), where the low temperature and low salinity water was still seen in the surface layer in winter. However, the Zhemin Coastal Current could not affect as far-away as the southwestern Taiwan Strait in the intermediate layer or near-bottom layer (Figs. 4(b) and (c)). The measured data also showed an upwind current flowing northeastward in the central Taiwan Strait (Fig. 4), with a relatively warmer and saltier water mass from the northern SCS. In the southern and southeastern areas of the Taiwan Strait, a current changes direction from northwestward in the southwest of Taiwan to southwestward in the south of Taiwan Bank (Fig. 4), which was regarded as the right flank of the SCS Branch of Kuroshio (SCSBK) (Qiu *et al*., 1985).

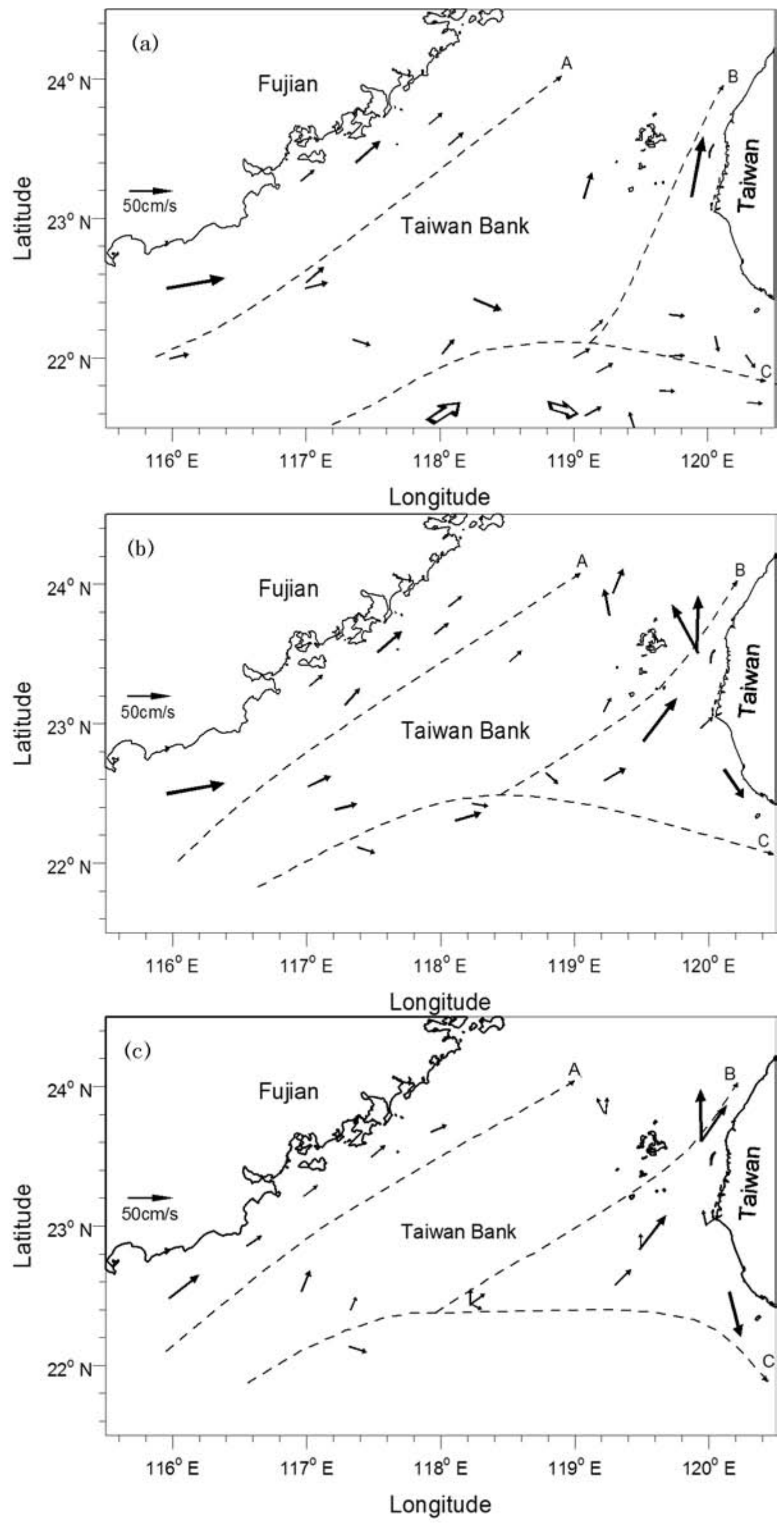

Fig. 5. Schematic summertime current patterns in the southern Taiwan Strait (redrawn after Hu and Liu, 1992). (a) Surface layer, (b) intermediate layer, and (c) near-bottom layer. The solid vectors are from the *in situ* current measurements; the dashed long arrows denoted by **A**, **B** and **C** at the arrow-head are the schematic current patterns deduced from the measured currents; and the double-arrows in (a) denote the flank of the Kuroshio's loop current in summer.

With more measurements, Hu and Fu (1991) summarized the wintertime current patterns in the southern Taiwan Strait. The currents in the surface, intermediate and near-bottom layers are similar to those in the southern part of Fig. 4. In the surface layer, there is a northeastward upwind current in the western and central Taiwan Strait with a speed of about 0.25 m s^{-1}. In the near-bottom layer, it flows northeastward (Wang and Weng, 1987; Weng *et al.*, 1990). This current was considered to be from the sea off Guangdong as an extension of the SCSWC. Qiu *et al.* (1985) and Guo *et al.* (1985) proposed that the SCSBK enters the northeastern SCS through the Luzon Strait in winter, forming a cyclonic meander with a width of about 130 km and a surface speed of about 1.0 m s^{-1}. Its right flank sweeps over the southern Taiwan Strait. While the SCSBK enters the northeastern SCS, the Kuroshio has another branch flowing northward along the western coast of Taiwan. *In situ* measurements (Fan and Yu, 1981; Wu, 1982a; Wang and Chern, 1988; Hu *et al.*, 1999a) and remote sensing observations (Chen, 1983; Xiu and Chen, 1987; Lin *et al.*, 1992) supported the idea that the Kuroshio may have one branch entering the eastern Taiwan Strait and its warmer and saltier water may reach 24~26°N.

Hu and Liu (1992) collected *in situ* current vectors in summer, and analyzed the summertime currents in the southern Taiwan Strait (Fig. 5). In the western sea area, there exists a northeastward current from the surface layer to near-bottom layer and flows all the way through the western Taiwan Strait. This current could be traced back to the SCSWC and was considered as the SCSWC's extension in the Taiwan Strait. This extension is affected by the Yuedong Coastal Current (Qiu *et al.*, 1985) on its inshore side so that it is sometimes characterized by high temperature and low salinity water in the surface layer. On the offshore side of this extension, another northeastward current flows side by side in the southwest of Taiwan Bank, which subsequently turns eastward while bifurcating into two branches in the southwest of Taiwan (Fig. 5). One of the branches flows out of the SCS through the northern Luzon Strait, and the other flows northward along the western coast of Taiwan. Qiu *et al.* (1984, 1985) and Li and Wu (1989) proposed that the Kuroshio intrudes the SCS in a loop form in summer, which means that the summertime SCSBK enters the SCS through the southern Luzon Strait as flowing westward, and then turns anticyclonically in the east of Dongsha Islands to flow through the northern Luzon Strait and back to the Kuroshio main path. It is clear that the left flank of the northern SCSBK loop could affect the southern Taiwan Strait in summer (Fig. 5).

These findings on current patterns focus on the southern Taiwan Strait, which indicates that the SCSBK affects the southern Taiwan Strait in different ways in winter and summer, and shows that the SCSWC extends to the Taiwan Strait both in winter and in summer (Figs. 4 and 5). In addition, Guan (1986a) suggested a combination of the SCSWC and the Taiwan Warm Current through the Taiwan Strait. Sun *et al.* (1996a) collected previous current charts (e.g., Institute of Marine Scientific and Technological Data and Information of SOA, 1978, 1982; Guan, 1986b; Chen, 1992) and sea-bed drifter observations (Zhang *et al.*, 1991), and indicated that northward and northeastward currents are dominated in the layer beneath 10 m in the Taiwan Strait and these currents merge with the Taiwan Warm Current after flowing out of the northern Taiwan Strait, but the surface currents in the Taiwan Strait are affected by local winds. Sun *et al.* (1996b) summarized the warm current system in the ECS and SCS and named it "the continental shelf warm currents in the East China Sea and South China Sea". This concept pictures the SCSWC as flowing through the Taiwan Strait in both summer and winter. However, some studies suggested a slightly more complicated current system in the northern Taiwan Strait, e.g., the Zhemin Coastal Current could have a branch intruding the central Taiwan Strait in winter (Weng *et al.*, 1988; Wang and Chern, 1989).

In the 1990s, several numerical model studies on the currents in the Taiwan Strait and its adjacent seas were conducted, focusing on mechanisms for these currents. Jan *et al.* (1994a, b) used a three-dimensional baroclinic ocean circulation model to study influences of the Changyuen Ridge and wind stress on the summertime currents in the Taiwan Strait. Using a barotropic numerical model, Cai and Wang (1997) studied the effects of wind stress and the Kuroshio on the circulation of the northeastern SCS and the Taiwan Strait. They indicated that the circulation in the Taiwan Strait is mainly affected by wind, bottom topography and the Kuroshio, and that the Kuroshio plays an important role in the formation of the SCSBK, the wintertime SCSWC and the Taiwan Warm Current. Cai *et al.* (1998a, b) further examined the roles of the Kuroshio, wind stress and bottom topography on the circulation in the Taiwan Strait through developing a barotropic and baroclinic coupled model. Wang and Yuan (1997a, b) used three-dimensional diagnostic models to compute the currents in the Taiwan Strait in summer. Jan *et al.* (1998) simulated the wintertime circulation in the Taiwan Strait. However, these models in the 1990s had relatively low spatial resolutions or small computational domains though they contributed to further advancement of understanding the mechanisms for the circulation in the Taiwan Strait.

2.4 *Recent progress in studying current patterns since 2000*

Recent progress in understanding the current patterns

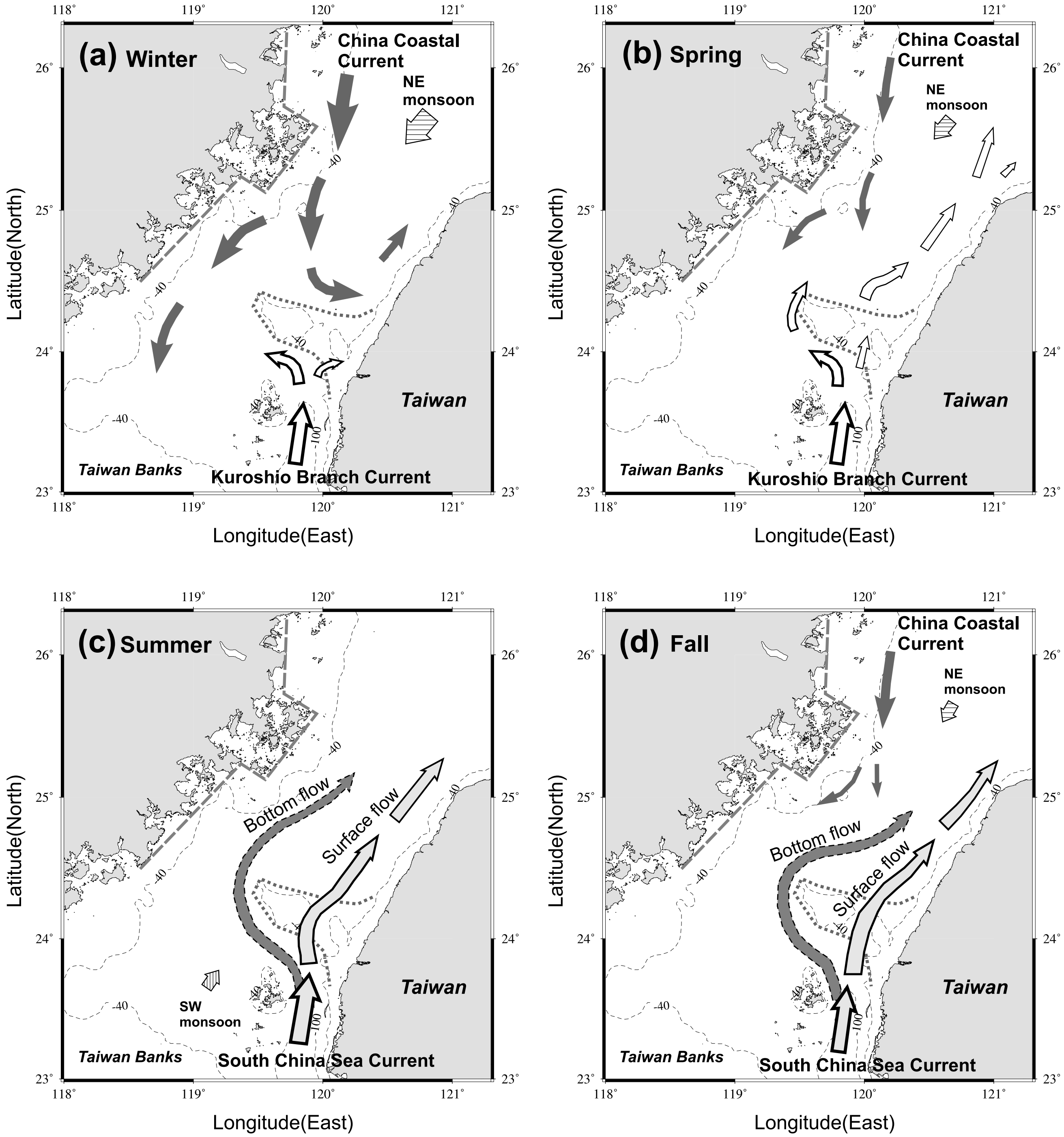

Fig. 6. Schematic charts showing the Taiwan Strait circulation in (a) winter, (b) spring, (c) summer and (d) fall (autumn). The thick and short-dashed line marks the outer edge of Changyun Rise (cited from Jan *et al*., 2002).

has been made with increasing observations using shipborne Acoustic Doppler Current Profiler (sb-ADCP), bottom mounted ADCP (bm-ADCP) and mooring systems in the Taiwan Strait (e.g., Tang *et al*., 2000; Lin *et al*., 2002, 2005; Liang *et al*., 2003; Wang *et al*., 2004), and several advanced numerical models in the Taiwan Strait and its adjacent seas (e.g., Chern and Wang, 2000; Chu and Li, 2000; Xue *et al*., 2001; Jan *et al*., 2002, 2010; Lo and Wang, 2002; Liang, 2002; Ren *et al*., 2002; Lu and Sha, 2003; Fang *et al*., 2003, 2005; Wu and Hsin, 2005;

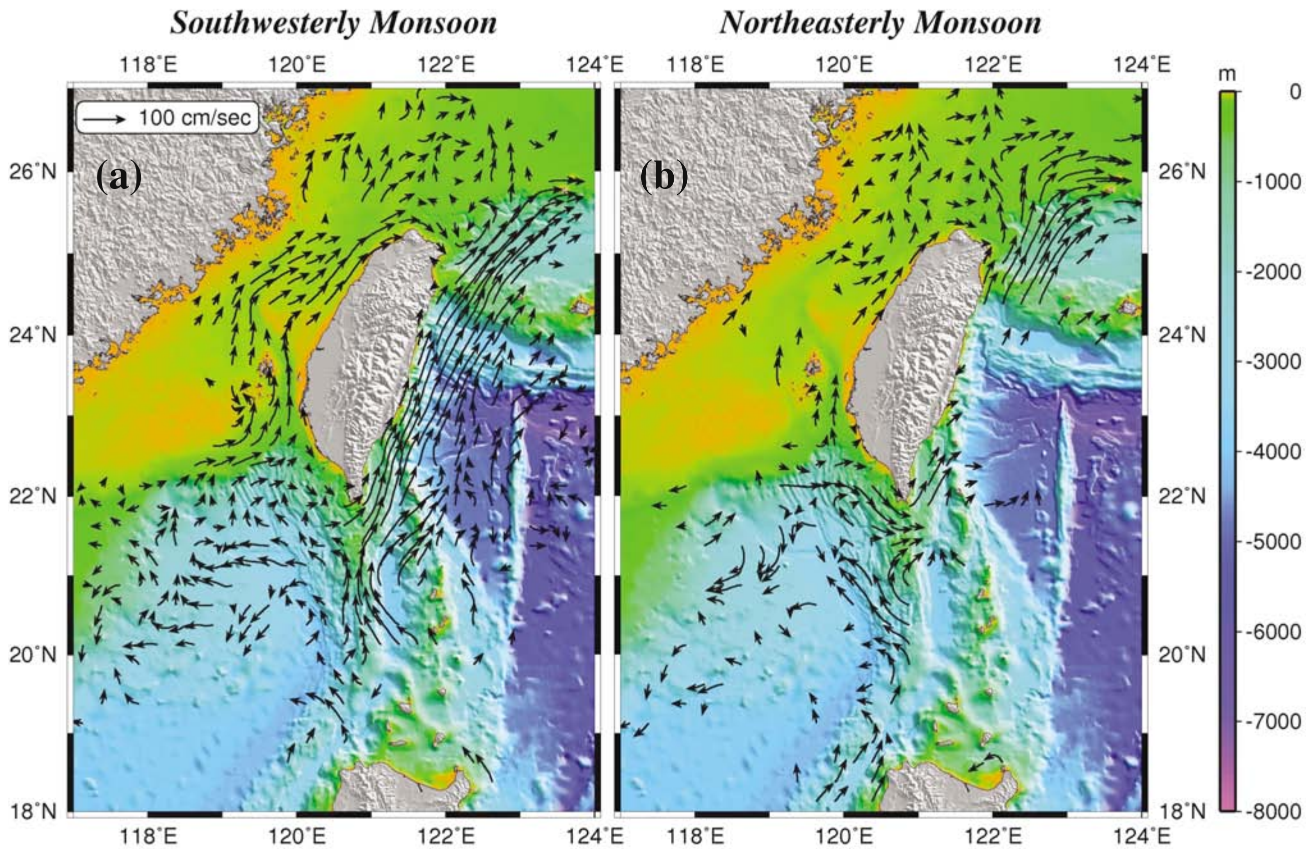

Fig. 7. Composite of sb-ADCP current velocity vectors at 30 m depth around Taiwan. (a) and (b) are for the southwesterly and northeasterly monsoon season, respectively (cited from Liang *et al*., 2003).

Jiang, 2007; Jiang *et al*., 2007; Wu *et al*., 2007). The oceanographers on the eastern side of the Taiwan Strait have made contributions to a further understanding of the current patterns through several big research projects such as TSNOW (Nowcast System for the Taiwan Strait) (Jan *et al*., 2001) and SWEET (Strait Watch on the Environment and Ecosystem with Telemetry) (Chen, 2004).

Using a numerical model and the data from hydrographic surveys and SST imagery, Jan *et al*. (2002) studied the seasonal variations of circulation in the Taiwan Strait (Fig. 6). They indicated that: in winter, the northward intrusion of the Kuroshio-sourced water in the eastern Taiwan Strait is blocked by the northeasterly monsoon, and the southward penetration of the China Coastal Current (i.e. the Zhemin Coastal Current in the Taiwan Strait) reaches its maximum, but a portion of it is deflected by the Chang-yuen Ridge and turns back northeastward (Fig. 6(a)). In spring, relaxation of the northeasterly monsoon unleashes the northward intrusion of the Kuroshio-sourced water, and the Zhemin Coastal Current retreats northward (Fig. 6(b)). With the aid of summer stratification and the southwesterly monsoon, the northward intrusion of the SCS Current in summer is relatively unimpeded by the Chang-yuen Ridge; only the near-bottom flow is deflected anti-cyclonically. The Zhemin Coastal Current does not enter the Taiwan Strait from the north in summer (Fig. 6(c)). The autumn (fall) pattern is similar to the summer one, except for the emergence of the Zhemin Coastal Current in the northwestern Taiwan Strait (Fig. 6(d)). Especially for the winter season, their results clearly showed that the Zhemin Coastal Current intrudes into the central Taiwan Strait, which was previously proposed by Wang and Chern (1989) and confirmed by He *et al*. (1999) and Hu *et al*. (1999a) using *in situ* current measurements and CTD data. Moreover, Jan *et al*. (2002) showed the Kuroshio's intrusion into the eastern Taiwan Strait, while branching northwestward through the Pengbei Channel. The circulation pattern around the Penghu Channel was verified later by some ADCP observations of Wang *et al*. (2004) and Lin *et al*. (2005). Wang *et al*. (2004) carried out a field survey with sb-ADCP across the Penghu Channel, the gate of Taiwan Strait, in May 1999, and observed a uniform northward current in the Penghu Channel with an average velocity of 0.73

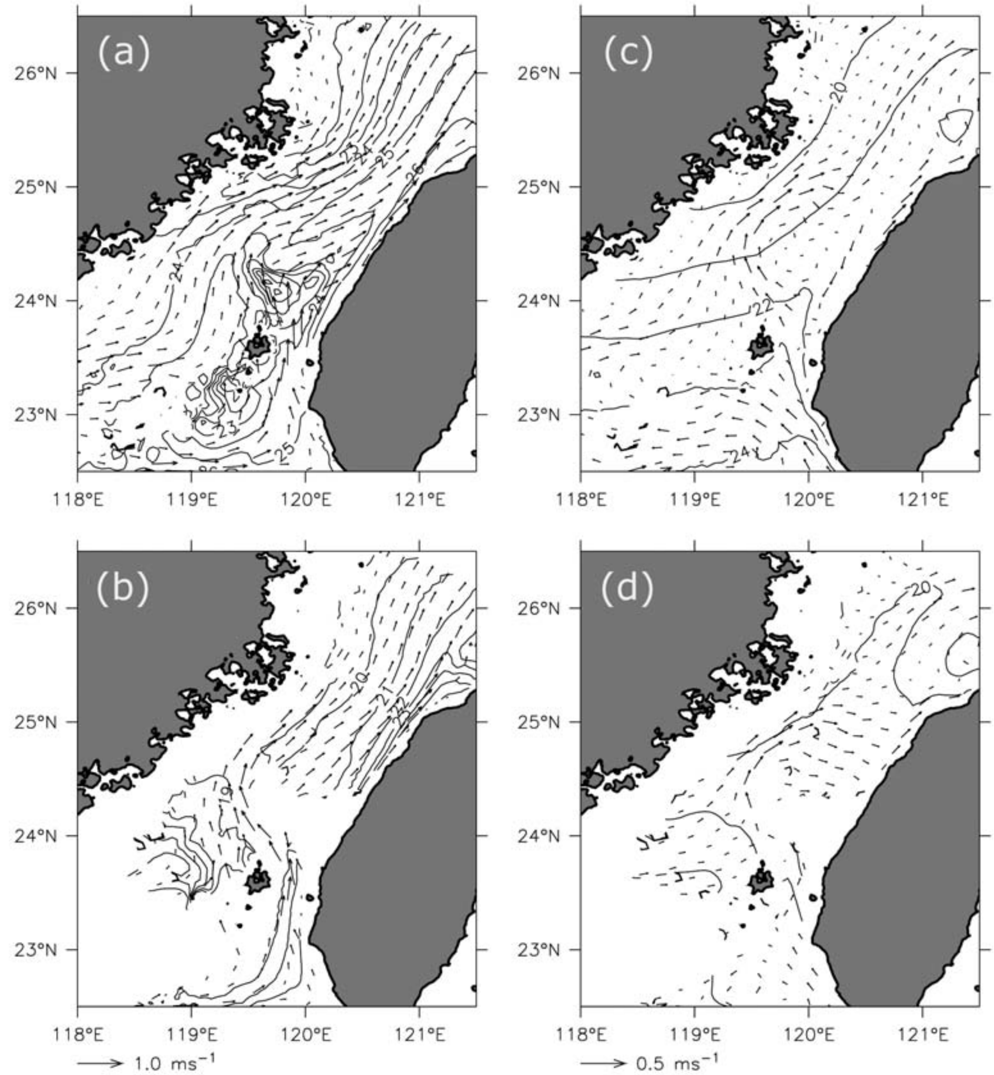

Fig. 8. Circulation and temperature distribution in the Taiwan Strait from a high resolution model (cited from Wu *et al*., 2007). (a) in summer at 20 m depth, (b) in summer at 50 m depth, (c) in winter at 20 m depth, and (d) in winter at 50 m depth. Time averaging for summer is over the period from June to August, while that for winter is over the period from October to February of the following year. Velocity scales are in m s^{-1}, and temperature contour interval is 1°C.

m s^{-1}. Evidently, the current patterns proposed by Jan *et al*. (2002) made good progress on the circulation study in the Taiwan Strait. However, since their model domain was limited to the major part of Taiwan Strait itself, the results did not well represent the current patterns in the southwestern Taiwan Strait, and neither was the influence of SCSWC considered in their model.

Using sb-ADCP data during 1991~2000, Liang *et al*. (2003) studied the upper-ocean (<300 m) currents around Taiwan. The composite current maps demonstrate that a branch of the Kuroshio intrudes steadily into the SCS. A part of the intruded Kuroshio flows out of the SCS through the northern Luzon Strait and merges with the main stream of the Kuroshio. Figure 7 depicts the current patterns in the 30 m layer of the Taiwan Strait and its adjacent seas during the southwesterly monsoon season (summer) and the northeasterly monsoon season (winter). It shows that the Kuroshio intrudes into the eastern Taiwan Strait and flows northward along the coast in both seasons, and that its branch flows northwestward through the Pengbei Channel. However, using satellite SST data and *in situ* data such as hydrographic and ^{18}O observations, Chen and Sheu (2006) argued that, in winter, the warm waters from the SCS and the Kuroshio's branch south of Taiwan would reach only the southern Taiwan Strait and not northward through the northern Taiwan Strait. Chen and Wang

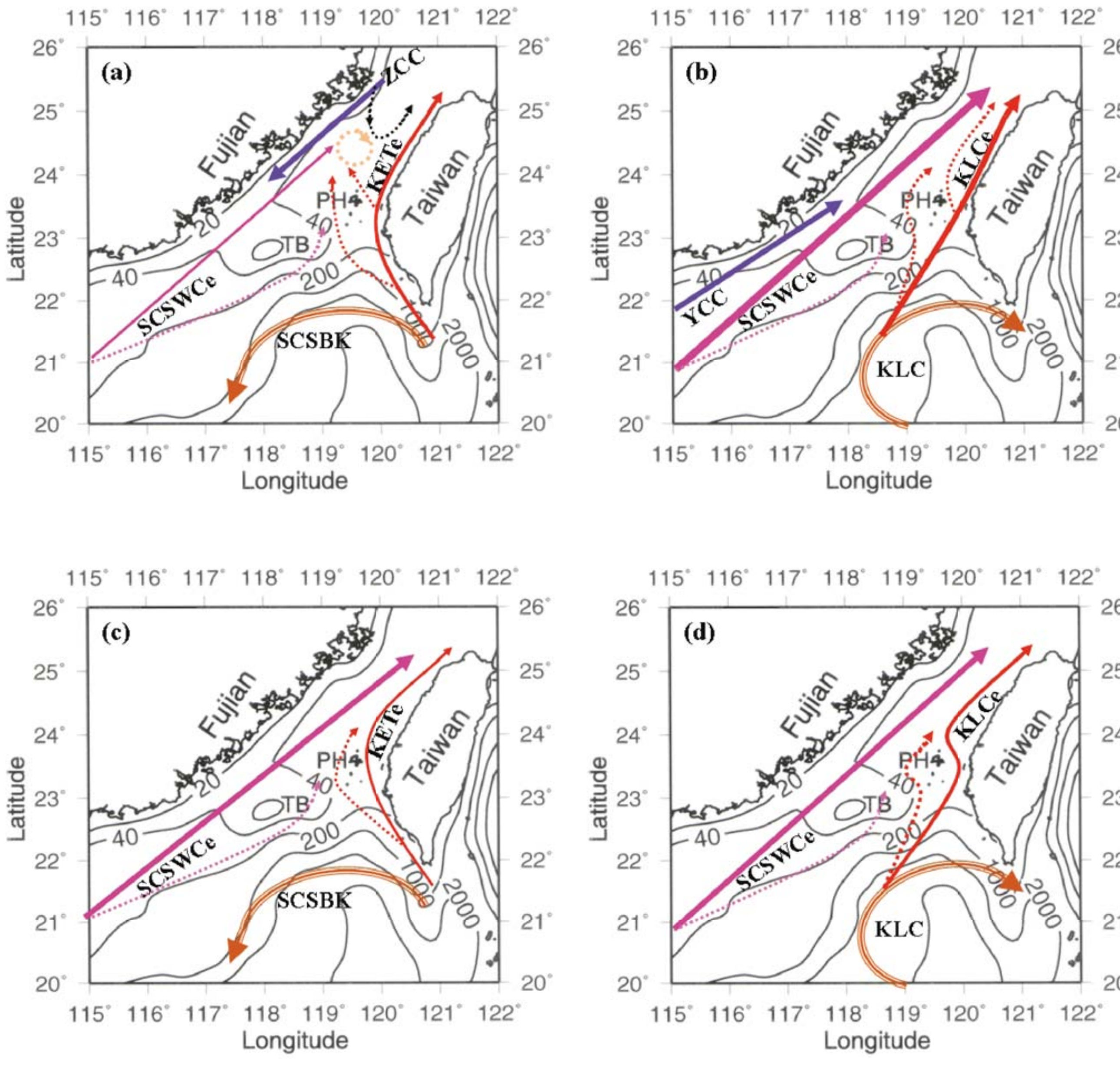

Fig. 9. Summarized current patterns in the Taiwan Strait. (a) In the upper layer in winter; (b) in the upper layer in summer; (c) in the lower layer in winter; and (d) in the lower layer in summer. In the figures, PH, TB, SCSWCe, SCSBK, ZCC, KETe, YCC, KLC and KLCe denote the Penghu Islands, the Taiwan Bank, the SCSWC's extension, the SCS Branch of Kuroshio, the Zhemin Coastal Current, the Kuroshio's Eastern Taiwan Strait's extension, the Yuedong Coastal Current, the Kuroshio's Loop Current, and the extension of Kuroshio's Loop Current, respectively.

(2006) presented observational evidence of occupation of the China coastal and Taiwan Strait waters in the western three-quarters of the northern Taiwan Strait. The remaining one-quarter is covered by the lower temperature and higher salinity Kuroshio subsurface waters, which circumvent the northern tip of Taiwan in summer. With relatively sparse observational data in the western and southwestern Taiwan Strait and during the northeasterly monsoon season due to rough sea conditions, it was difficult to depict the current patterns in more detail.

Wu *et al*. (2007) constructed a numerical model, with realistic bathymetry and fine-resolution of 3~10 km, to study the spatial and temporal variations of circulation in the Taiwan Strait. The model was forced by six-hourly wind stress at the sea surface and the open ocean boundary condition from a larger-scale East Asian Marginal Seas model. On seasonal time scales, the model showed that the northward current is the strongest, especially in the Penghu Channel in summer, consistent with the northward summer monsoon and pressure gradient force. The summertime northward current appears to be relatively unimpeded by the Changyun Rise and the current bifurcates slightly near the surface but not near the bottom (Figs. 8(a) and (b)); and a northeastward current flows through the western Taiwan Strait from the SCS. In the winter season (October to February, their definition), the northward current weakens in the eastern Taiwan Strait, with the current deflecting northwestward through the Pengbei Channel, as the northeasterly monsoon strengthens. The China Coastal Current (i.e. the Zhemin Coastal Current) flows downwind in the western Taiwan Strait and is partially blocked by the Changyun Rise, forcing a U-shaped flow pattern in the northern Taiwan Strait (Figs. 8(c) and (d)). Additionally, an anticyclonic eddy develops on the northern flank of the Changyun Rise (Fig. 8(c)). The wintertime current patterns presented by Wu *et al.* (2007) were supported by Lin *et al.* (2005) who used the measurements of bm-ADCPs deployed across the Taiwan Strait at the northern tip of the Pengbei Channel in winter.

Zhu *et al.* (2008) analyzed the long-term measurements from a pair of high-frequency radar systems installed on the southern Fujian coast and concluded that the surface currents in the southwestern Taiwan Strait are mainly composed of the monsoon-driven seasonally fluctuating alongshore current and the persisting northward surface background current with a speed of about 10 cm s^{-1} all the year round. Measurements from bm-ADCPs indicated that the alongshore currents are also northward below the surface Ekman layer, with speeds greater than 10 cm s^{-1} in summer and smaller than 5 cm s^{-1} in winter. Zhu *et al.* (2008) further confirmed a northward current in the lower layer, which could be the SCSWC's extension in the southwestern Taiwan Strait.

2.5 *Composite current patterns in the Taiwan Strait*

Figure 9 presents conceptual composite current patterns in the Taiwan Strait in winter and summer. There are three currents in the Taiwan Strait, differing between winter and summer, and between the upper and lower layers, as detailed in the four panels of Fig. 9.

In the upper layer of the western Taiwan Strait, the Zhemin Coastal Current (ZCC in Fig. 9(a)) flows southwestward in winter and the Yuedong Coastal Current (YCC in Fig. 9(b)) flows northeastward in summer. The Zhemin Coastal Current sometimes has a branch intruding southeastward to the central Taiwan Strait and likely turning in a "U" form northeastward (Fig. 9(a)) as is sometimes identifiable in satellite images (e.g., Li *et al.*, 2006; Chang *et al.*, 2009).

As shown in Figs. 9(a)–(d), the SCSWC's extension (SCSWCe in the panels) exits in the western and central Taiwan Strait, but it tends to be weaker or even disappears in the upper layer in winter. Besides this main path, the SCSWC's extension has a branch circumventing the Taiwan Bank to enter the central Taiwan Strait (dashed arrow bifurcating from SCSWCe in Figs. 9(a)–(d)).

The Kuroshio (i.e. the SCSBK) intrudes into the northern SCS in different ways in winter and summer, contributing to the great variability of currents in the southern and eastern Taiwan Strait. In winter, the SCSBK passes through the northern Luzon Strait and has a cyclonic meander in the northern SCS (SCSBK in Figs. 9(a) and (c)). Its branch heads northward along the western coast of Taiwan (KETe in Figs. 9(a) and (c)). In summer, the SCSBK passing through the southern Luzon Strait has an anti-cyclonic loop in the northern SCS (KLC in Figs. 9(b) and (d)). Before the KLC flows out of the SCS, it bifurcates into two branches, one of which flows northward along the western coast of Taiwan (KLCe in Figs. 9(b) and (d)). The KETe or the KLCe usually bifurcates into two or three branches around the Penghu Islands (dashed arrows in Figs. 9(a)–(d)). One of them flows northwestward through the Pengbei Channel in the upper layer both in winter and in summer (dashed arrow in Figs. 9(a) and (b)). In the lower layer, the intrusion water is deflected through the Penghu Channel and the Pengbei Channel (dashed arrows in Figs. 9(c) and (d)). In addition, there may exist an anti-cyclonic eddy in the upper layer of the central Taiwan Strait in winter (a dashed circle in Fig. 9(a)).

3. Seawater Volume Transport

3.1 *Wintertime and summertime seawater volume transports through the Taiwan Strait*

Using various sources of data, seawater volume transport through the Taiwan Strait was estimated by Fu *et al.* (1991). The data included measurements from 8 day-night anchored stations in December 1987 (Hu *et al.*, 1990) and 5 day-night anchored stations in June 1988 (Li and Liang, 1991), the Japanese current measurements during June–July 1938, and some other current data from Guan and Chen (1964), Guan (1978a, 1978b, 1985, 1986a, 1986b), Fan (1982), Chuang (1986) and Wang (1989).

In Fu *et al.* (1991), three zonal sections were defined for analyses of seawater volume transport in winter. As shown in Fig. 10(a), these sections have different current structures and seawater volume transport patterns. In the northern Taiwan Strait section, different currents (perpendicular to the section here) in either part of the section generate a southward transport of 1.02 Sv (1 Sv = 10^6 m^3s^{-1}) in the western part and a larger northward transport of 2.76 Sv in the eastern part. In the middle Taiwan

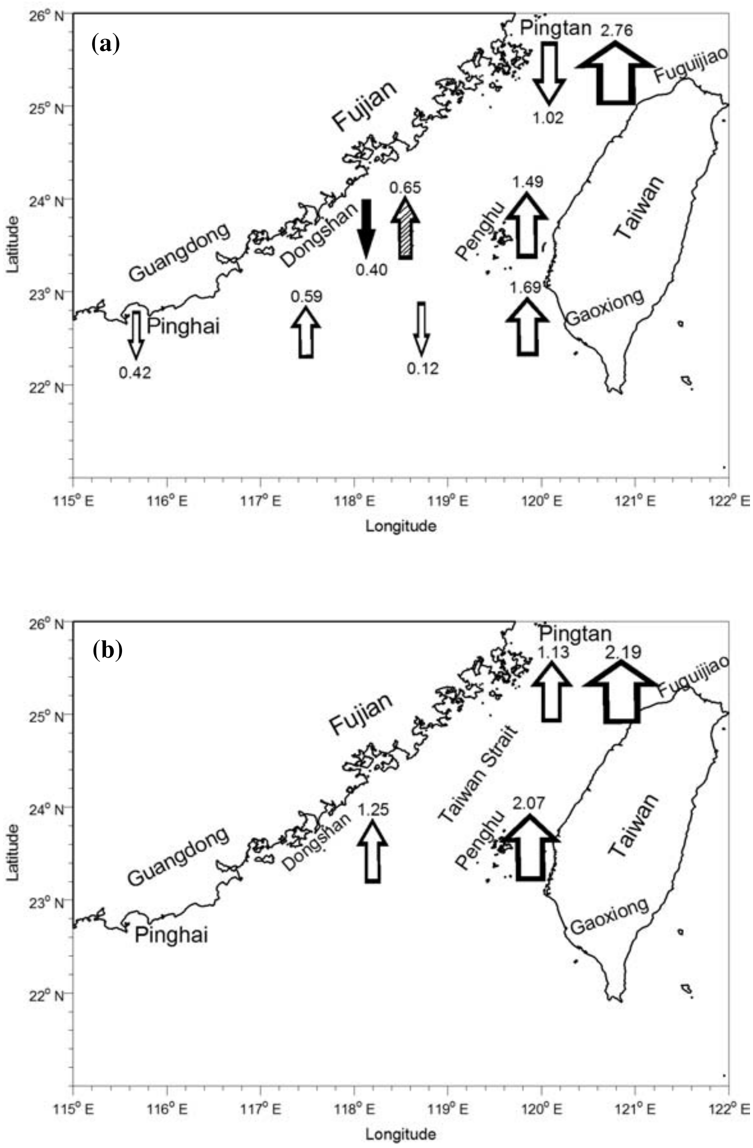

Fig. 10. Seawater volume transports (in Sv, 10^6 m^3s^{-1}) through 2~3 zonal sections in the Taiwan Strait in (a) winter and (b) summer (redrawn after Fu *et al*., 1991). The figure near the arrow-head is the volume transport in Sv. The open-arrow denotes the transport from surface layer to bottom layer, the solid-arrow in (a) the transport through the upper layer (0.40 Sv), and the shaded-arrow in (a) the transport through the lower layer (0.65 Sv).

Strait section, the current structure in the upper layer is opposite to that in the lower layer (Fig. 10(a)). In the western 2/3 part of the section, the upper layer has a southward transport of 0.40 Sv, and the lower layer a northward transport of 0.65 Sv. But in the eastern part, the current is northward in the upper and lower layers, with a transport of 1.49 Sv. The current, with alternating current directions, and the seawater volume transport are quite complicated in the southern Taiwan Strait section (Fig. 10(a)). The current is southward near the southern Fujian and eastern Guangdong coasts with a small transport of 0.42 Sv, but it is northward in the channel west of the Taiwan Bank with a transport of 0.59 Sv. In the eastern part of the section, Fu *et al*. (1991) speculated that the Kuroshio would branch into the Taiwan Strait through the Penghu Channel with a large northward transport of 1.69 Sv. Being affected by the right flank of SCSBK, the current would change direction in the south of Taiwan Bank to generate a southward transport of 0.12 Sv (Fig. 10(a)).

The pattern of seawater volume transport in summer (Fig. 10(b)) is simpler than that in winter (Fig. 10(a)). In the northern Taiwan Strait section, the northward transport is about 1.13 Sv through the western part and about 2.19 Sv through the eastern part. The transport through the eastern Taiwan Strait is about twice as that through the western Taiwan Strait. The same transport pattern is also seen in the middle Taiwan Strait section, where the northward transport is about 1.25 Sv through the western part and 2.07 Sv through the Penghu Channel (Fu *et al.*, 1991).

In summary, the currents in the central and northern parts of the Taiwan Strait normally flow northward with a net transport of 3.32 Sv in summer, and the transport is larger through the eastern Taiwan Strait than through its western part. In winter, both the Kuroshio intrusion water (1.69 Sv) and the SCS water (0.59 Sv) with high temperature and high salinity enter the southern section of Fig. 10(a). The ECS water (1.02 Sv) enters the Taiwan Strait from the northern section. About 0.40 Sv of the ECS water enters the SCS along the Fujian and Guangdong coasts in winter and the other 0.62 Sv ECS water is mixed with both the Kuroshio intrusion water and the SCS water in the northern Taiwan Strait. The net northward transport is 1.74 Sv in winter. However, this wintertime volume transport estimation may be too large because the *in situ* current data in the eastern Taiwan Strait were limited at the time of the study by Fu *et al.* (1991). In addition, the current data from December 1987 were measured under a particularly calm wind condition, not under the severe northeasterly winds that dominate there in winter. Under such a circumstance, the southward transport may be underestimated, which may have resulted in an overestimate of northward transport in winter.

3.2 *Comparison of the seawater volume transport studies in the Taiwan Strait*

Table 1 lists 29 studies on the seawater volume transport through the Taiwan Strait. These transport calculations were mostly based on numerical model simulations and *in situ* data, presenting estimates of the transport mostly for winter and summer. The results differ significantly from each other. The winter estimates are between –1.1 and 2.74 Sv northward, and the summer ones range from 0.5 to 3.4 Sv northward.

Wang Y. H. *et al.* (2003) studied the seawater transport in the Taiwan Strait using sb-ADCP measurements for 2.5 years (1999–2001). The annual mean transport through the Taiwan Strait is 1.8 Sv northward. They concluded that the transport (V, in Sv) is related to the along-strait wind speed (W, in m s^{-1}) by a simple regression, $V = 2.42 + 0.12W$. Using this empirical formula, the maximum seasonal transport (2.7 Sv) appears in summer while the minimum (0.9 Sv) appears in winter. Lin *et al.* (2005) calculated the seawater transport using current profiles at four cross-strait stations and concluded that the along-strait volume transport varied from –5 to 2 Sv with a mean value of 0.12 ± 0.33 Sv during the observational period from September to December. Lin *et al.* (2005) also presented a consistent transport estimate from sea level difference across the Taiwan Strait. Jan *et al.* (2006) studied the transport in the Taiwan Strait using long-term of strait-wide CTD (1985–2003) and sectional ADCP (1999–2001) data and indicated that the mean transport across the central strait was about 0.1 Sv southward during this period. Using the bm-ADCP data, Jan *et al.* (2006) showed that the monthly mean transports were 0.43 ± 1.05 Sv (October), 0.12 ± 0.78 Sv (November), –0.26 ± 0.75 Sv (December), –0.15 ± 0.56 Sv (January) and –0.07 ± 0.63 Sv (February), and the northward transports ranged from 1.16 to 2.34 Sv between March and August. Isobe (2008) used available published observations to estimate the transport (V, in Sv), suggesting a sinusoidal annual variation expressed as: $V = V_0 + V_1 \cos[2\pi(t - K)/T]$, where V_0, V_1 and K are 1.2 Sv, 1.3 Sv and 157 days (6 June), respectively, t is year-day, and T is 365.2422 days (i.e. 1 year). This approximation gave a transport of 2.5 Sv in June and –0.1 Sv in December.

Chai *et al.* (2001) used the numerical model results from an SCS circulation model (Xue *et al.*, 2001) to calculate the monthly mean seawater transport through the Taiwan Strait, and concluded that the annual mean along-strait seawater transport is 1.535 Sv northeastward, with a wintertime mean (from November to February in their paper) of 0.83 Sv, and a summertime mean (from May to September, their definition) of 2.19 Sv (maximum 2.35 Sv in July). Using a fine resolution model, Wu and Hsin (2005) showed that the northward volume transport would be the largest in summer while minimal southward volume transports would occur in autumn and winter. The general trend of volume transport is related to the seasonal reversal of monsoon winds. An annual average transport of 1.09 Sv northward was estimated, smaller than most of the published values based on sb-ADCP observations. They suggested that the sb-ADCP observations were biased toward estimates in summer and fair weather conditions since bad weather during the winter northeasterly monsoon often prevented seagoing observations.

Guo *et al.* (2005) used the AVISO's sea surface height anomaly data from satellite altimeter, the National Center for Environmental Prediction wind field data and the channel flow solution (Zhang and Qiao, 1993) to make diagnostic calculations of volume transport through the Taiwan Strait and its variations during 1993~2001 (see Table 2). It is shown from the calculated results that the annual mean volume transport through the Taiwan Strait ranged from 0.99 to 1.65 Sv during 1993~2001 with an average of 1.27 Sv and the seawater volume transport had a noticeable seasonal variation with the maximum mean

Table 1. Comparison of the seawater volume transports through the Taiwan Strait (unit: Sv).

Annual mean	Summer	Winter	Spring	Autumn	Through the Penghu Channel	Reference	Approach
	0.5~1.0	0.5	0.0	0.5		Wyrtki (1961)	Ship drift data
	3.32	1.74			Winter: 1.69 Summer: 2.07	Fu *et al*. (1991)	*In situ* current observations
2.0	Summer half year: 3.1	Winter half year: 1.0				Fang *et al*. (1991)	*In situ* current observations
	3.16	1.05				Zhao and Fang (1991)	*In situ* current observations
	3.32	1.74				Fu and Hu (1995)	*In situ* current observations
	1.0	−0.5				Chao *et al*. (1996)	Numerical modeling
	3.40	2.04				Cai and Wang (1997)	Numerical modeling
1.9	>3.0	<1.0				Guo (1999)	Numerical modeling
				0.8		Isobe (1999)	Numerical modeling
	August: 1.88 (along-strait)	2.74 (March)	2.74 (March)			Liu *et al*. (2000)	*In situ* current observations
1.535	2.19 (May–Sep.)	0.83 (Nov.–Feb.)	1.7	1.3		Chai *et al*. (2001)	Numerical modeling
1.15	2.1~2.9	0.0~0.6	1.5~2.4	−0.4~0.6		Fang *et al*. (2001)	Numerical modeling
2.0	2.5~3.1	1.5~1.8	2.0~2.5	0.9~1.7		Bao *et al*. (2002)	Numerical modeling
0.93	1.00~1.18	0.78~1.02	1.10~1.20	0.42~0.67		Cai *et al*. (2002)	Numerical modeling
1.8	2.7	0.9				Wang *et al*. (2002)	*In situ* current observations
	2.5	0.5				Liu (2003)	*In situ* current observations
				Oct.–Nov.: −5.0~2.0 Mean: 0.2		Ko *et al*. (2003)	Numerical modeling
1.8	2.7	0.9				Wang Y.H. *et al*. (2003)	*In situ* current observations
		2.74 (March)	2.74 (March)			Chen (2003)	*In situ* current observations
					Winter: −0.11~0.02 Spring: 0.56~1.10 Summer: 1.26~1.72 Autumn: 0.76 Annual mean: 0.86	Jan and Chao (2003)	*In situ* current observations
		0.14 (Oct.–Dec.)		0.14 (Oct.–Dec.)		Teague *et al*. (2003)	*In situ* current observations
0.42	1.9~2.2	−1.1~−0.8	0.2~1.5	−1.1~0.8		Yang *et al*. (2004)	Numerical modeling
					May: 1.6	Wang *et al*. (2004)	*In situ* current observations
1.09					Annual mean: 0.55	Wu and Hsin (2005)	Numerical modeling
1.27	2.27	1.17	1.59	0.46		Guo *et al*. (2005)	Satellite altimeter data
		0.12+/−0.33 (along-strait; Sep.–Dec.)		0.12+/−0.33 (along-strait; Sep.–Dec.)		Lin *et al*. (2005)	*In situ* current observations
	1.87~2.34	−0.26~−0.07	1.61~2.02	0.12~0.43		Jan *et al*. (2006)	*In situ* current observations
	2.5	−0.1				Isobe (2008)	*In situ* current observations*
2.3	3.1			1.5		Wang *et al*. (2009)	Numerical modeling

Note: 1) Positive/negative seawater volume transport is northward/southward for longitudinal transport or northeastward/southwestward for along-strait transport.
2) Summer, winter, spring and autumn are defined as June–August, December–February, March–May and September–November, respectively except those different definitions mentioned in the table.

*An estimate averaged using various current observations published previously.

Table 2. Diagnostic mean volume transport through the Taiwan Strait (unit: Sv) (from Guo *et al*., 2005).

Month	Year									
	1993	1994	1995	1996	1997	1998	1999	2000	2001	Mean
1	1.62	1.56	0.67	2.75	0.91	0.82	2.21	1.11	–0.73	1.21
2	0.93	1.24	1.35	2.62	–0.33	–0.68	2.45	1.53	0.29	1.04
3	0.27	0.92	1.99	2.25	0.82	–0.62	1.29	1.72	1.82	1.16
4	0.69	1.10	1.62	2.46	2.49	1.34	1.39	1.83	1.92	1.65
5	1.45	1.20	1.81	2.66	2.06	1.32	2.92	2.21	2.11	1.97
6	2.56	1.60	2.53	3.89	2.15	1.70	2.52	2.78	1.71	2.38
7	2.59	1.45	1.71	2.98	3.42	3.26	2.31	2.83	2.01	2.51
8	1.69	1.66	1.99	1.01	2.47	2.33	1.35	2.20	2.53	1.91
9	1.73	1.95	2.02	0.45	0.79	0.78	–0.88	0.60	0.58	0.89
10	0.65	0.99	0.57	–0.41	0.18	0.53	–0.82	–0.03	–0.52	0.13
11	0.39	0.60	0.35	–0.86	0.14	1.39	0.51	0.46	0.14	0.35
12	0.53	0.48	1.32	0.85	0.51	1.73	0.76	0.02	0.48	0.74
Mean	1.21	1.19	1.38	1.65	1.26	1.01	1.27	1.44	0.99	1.27

volume transport of 2.27 Sv in summer and the minimum one of 0.46 Sv in autumn. The mean volume transport was 1.17 Sv in winter and 1.59 Sv in spring. Maximum volume transport was in July (2.51 Sv) while the minimum was in October (0.13 Sv). Table 2 shows that the inter-annual variation of volume transport is smaller in summer and autumn, but quite large in winter. For example, the volume transport varies from –0.73 to 2.75 Sv in January, which suggests that the current is quite complicated in winter and may be associated with local wind conditions. However, after comparing the different contributions from the mean sea level slope and local wind, it is concluded from the results that the determining factor for the variations of volume transport through the Taiwan Strait is the north–south slope of sea level in the Taiwan Strait, and the secondary factor is local wind (Guo *et al*., 2005).

4. Summary and Discussion

The present review on current patterns and seawater volume transport in the Taiwan Strait is mostly based on more than 150 research papers using the *in situ* data and numerical modeling. The following conclusions are drawn:

(1) In winter, the Taiwan Strait is under the control of three currents: the Zhemin Coastal Current, the Kuroshio's intrusion in the eastern Taiwan Strait and the SCSWC's extension. The Zhemin Coastal Current flows southwestward in the upper layer along the Fujian coast, and extends as far as to near Dongshan while it sometimes intrudes into the central part of the strait from the sea area southeast of Pingtan. The Kuroshio intrudes the northern SCS through the Luzon Strait, then extends northward along the western Taiwan coast and branches northwestward through the Pengbei Channel. The SCSWC's extension flows northeastward against the prevailing wind both in the upper layer and in the lower layer. However, the wintertime currents in the Taiwan Strait are significantly affected by strong northeasterly winds in the upper layer.

(2) In summer, the entire Taiwan Strait is dominated by the northeastward currents both in the upper and lower layers. The SCSWC extends northeastward along the eastern and central parts of the Taiwan Strait. The Yuedong Coastal Current, with higher temperature, lower salinity and lower density in the upper layer, also flows northeastward along the eastern Guangdong and southern Fujian coasts. This coastal current may be pushed offshore due to the coastal upwelling along the southern Fujian coast and may sometimes bring the low salinity surface water from the Zhujiang River (or the Pearl River) (Hong *et al*., 2009; Gan *et al*., 2009). The Kuroshio intrusion water extends northward through the Penghu Channel as the Kuroshio takes a loop form near the Luzon Strait in summer.

However, the above-described general current patterns can be modulated or changed by the wind conditions and may have a correlation with the ENSO, which was discussed in several studies (Kuo and Ho, 2004; Hong *et al*., 2005; Shang *et al*., 2005). The current patterns in spring and autumn are less studied though a few studies did mention them.

(3) The transport through the Taiwan Strait is about 2.3 Sv (with standard deviation of 0.82 Sv) northward in summer and about 0.8 Sv (with standard deviation of 0.96 Sv) northward in winter. Here we computed the summertime and wintertime mean transports and their standard deviations using all the estimates (27 for summer and 29 for winter) listed in Table 1. The summertime transport is about the same as that calculated by Isobe (2008). For

the wintertime transport, Isobe (2008) used several published observations to get a transport formula, from which the wintertime mean transport is about 0.5 Sv if averaging the transports for December, January and February. So our result differs only slightly from Isobe (2008)'s even in winter. The seawater volume transport varies in accordance with the local wind conditions in the Taiwan Strait and may even become southward during the typhoon period (Zhang *et al*., 2009; Chang *et al*., 2010).

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