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Review

Since the MH370 aircraft went off the radar on March 8, 2014, at 103 E, 6.7 N, it would seem obvious that a search for debris would focus on this spot in the South China Sea, taking into account the seasonal circulation, as described in Hu et al. 2000. No evidence has been found that the authorities realized the surface drift direction would be to the south.

A Review on the Currents in the South China Sea: Seasonal Circulation, South China Sea Warm Current and Kuroshio Intrusion

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Researches on the currents in the South China Sea (SCS) and the interaction between the SCS and its adjacent seas are reviewed. Overall seasonal circulation in the SCS is cyclonic in winter and anticyclonic in summer with a few stable eddies. The seasonal circulation is mostly driven by monsoon winds, and is related to water exchange between the SCS and the East China Sea through the Taiwan Strait, and between the SCS and the Kuroshio through the Luzon Strait. Seasonal characteristics of the South China Sea Warm Current in the northern SCS and the Kuroshio intrusion to the SCS are summarized in terms of the interaction between the SCS and its adjacent seas.

Keywords:
· South China Sea,
· seasonal circulation,
· South China Sea Warm Current,
· Kuroshio intrusion,
· review.

1. Introduction

The South China Sea (SCS) with a maximum depth deeper than 5000 m is the largest marginal sea in the Southeast Asia (Fig. 1). It is generally regarded to range from the equator to 23°N and from 99°E to 121°E, and to join the Pacific Ocean through the Luzon Strait (or named as the Bashi Strait or the Bashi Channel by some literatures) between the Taiwan Island and the Luzon Island. The central deep basin is bordered by two broad shelves shallower than 200 m in the northwestern and southwestern SCS.

The SCS is situated in the monsoon regime. The annual cycle of wind stress fields (Hellerman and Rosenstein, 1983) shows that northeastly winds prevail over the whole region with an average magnitude of 9 m/s in winter. In contrast, weaker southwestly winds of about 6 m/s dominate over most parts of the SCS and the direction changes to more southerly in the northern SCS (NSCS) in summer.

Driving debris south.

The seasonal circulation pattern in the SCS and its adjacent seas has been investigated by several researchers such as Dale (1956), Wyrtki (1961), Xu *et al.* (1982), Pohlmann (1987), Li *et al.* (1992a), Mao *et al.* (1992), Zhang *et al.* (1994), Shaw and Chao (1994), Zhang, M. Y. *et al.* (1995), Chao *et al.* (1996), Takano *et al.* (1998), Wu *et al.* (1998) and Chu *et al.* (1999a). They have pointed out that the seasonal SCS circulation is mostly affected by the monsoon winds and that the NSCS circulation is also related to water exchanges between the SCS and the East China Sea (ECS) through the Taiwan Strait and between the SCS and the Kuroshio through the Luzon Strait. However, since the observational data were quite limited in the SCS, most of these researches were still qualitative, though some numerical models (i.e. Shaw and Chao, 1994; Takano *et al.*, 1998) presented some relatively quantitative results while mostly focused on the circulation pattern.

In the present paper, Section 2 reviews the studies on the overall seasonal SCS circulation pattern using climatological hydrographic data or some specific hydrographic observations (see Subsection 2.1), a few satellite observations (Subsection 2.2) and several numerical models (Subsection 2.3). We review studies on the

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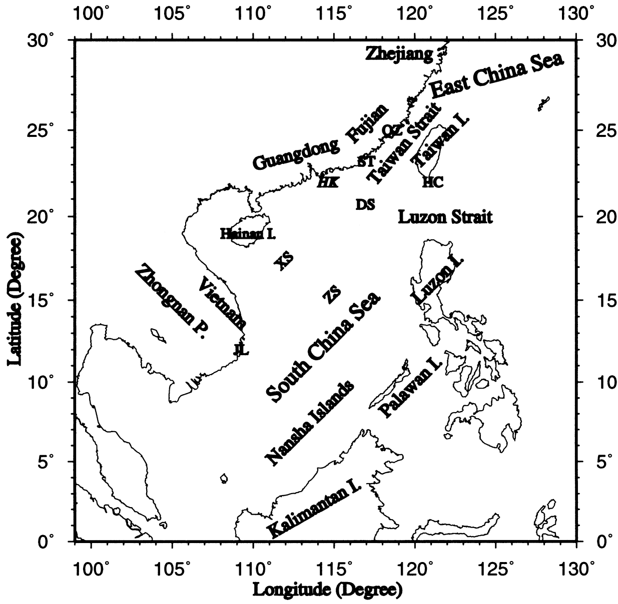

Fig. 1. The map of the South China Sea and its adjacent seas. DS, HC, HK, JL, QZ, ST, XS and ZS in the figure represent the Dongsha Islands, Heng Chun, Hong Kong, the Jinlan Bay, Quanzhou, Shantou, the Xisha Islands and the Zhongsha Islands, respectively.

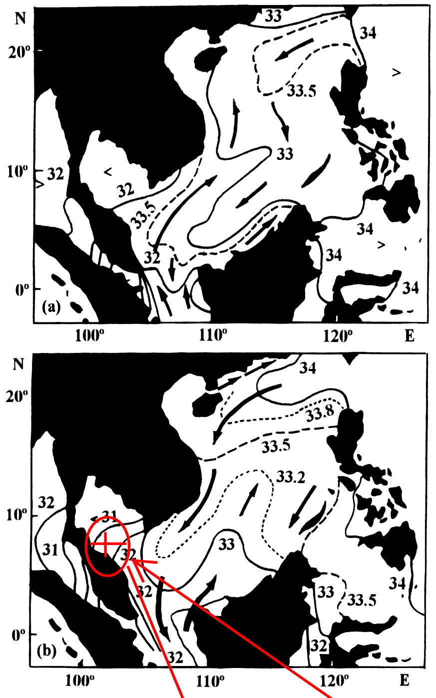

Fig. 2. Sea surface salinity in the SCS. Arrows indicate the inferred direction of currents. (a) August and (b) February. From Tomczak and Godfrey (1994).

Debris from the crash goes south.

South China Sea Warm Current (SCSWC) in the NSCS in Section 3. Specifically, Subsection 3.1 describes some observational evidences of the SCSWC, Subsection 3.2 mentions about the extension of the SCSWC in the Taiwan Strait and Subsection 3.3 discusses the mechanism for the SCSWC formation. The Kuroshio intrusion to the SCS is reviewed in Section 4, in which Subsection 4.1 presents some viewpoints on the Kuroshio intrusion, Subsection 4.2 deals with the water exchange in the Luzon Strait and Subsection 4.3 explains the Kuroshio intrusion into the Taiwan Strait. The summary and discussion are given in Section 5.

2. Overall Seasonal Circulation in the SCS

2.1 *Circulation patterns investigated by the hydrographic observations*

The previous studies on the SCS circulation were mostly based on the observational data. These limited results reveal some important features of the circulation.

Some typical surface current charts were produced by the Hydrographic Office of the U.S. Navy (1945), Dale (1956) and Wyrtki (1961) before 1970’s. These results were mainly deduced from ship drift data and prevailing wind data. With the analysis of ship drift data, Dale (1956) presented several charts of the surface currents in the SCS. Wyrtki (1961) further pointed out that since the entire SCS is under the influence of monsoon system, the surface currents undergo a seasonal reversal of direction in the absence of major oceanic inflow. This is particularly true for the surface currents on the shelves which are easily forced by pressure gradients established through coastal sea level set-up. Both Dale (1956)’s and Wyrtki (1961)’s results, often quoted as the typical SCS surface circulation pattern, have taken the monsoon winds as the main cause for the surface circulation. Based on Wyrtki (1961)’s result and salinity distribution, Tomczak and Godfrey (1994) summarized the surface circulation patterns as shown in Fig. 2. Obviously, the southwest monsoon pushes the shelf water northward so as to result in some compensatory southward movements over the deep basin in the eastern SCS, while the northeast monsoon reverses the flowing direction and a strong boundary current is thus developed along the Vietnam coast.

In order to carry out more intensive analysis on the climatological distributions of seasonal SCS circulation, Xu *et al.* (1982) adopted the historical observational data during 1921–1970. The results indicate a seasonally-averaged circulation pattern in the entire SCS and have often been referred as a representative SCS circulation pattern by the subsequent literatures. General features of circulation pattern introduced by this study are close to those of Dale (1956) and Wyrtki (1961), but they newly pointed

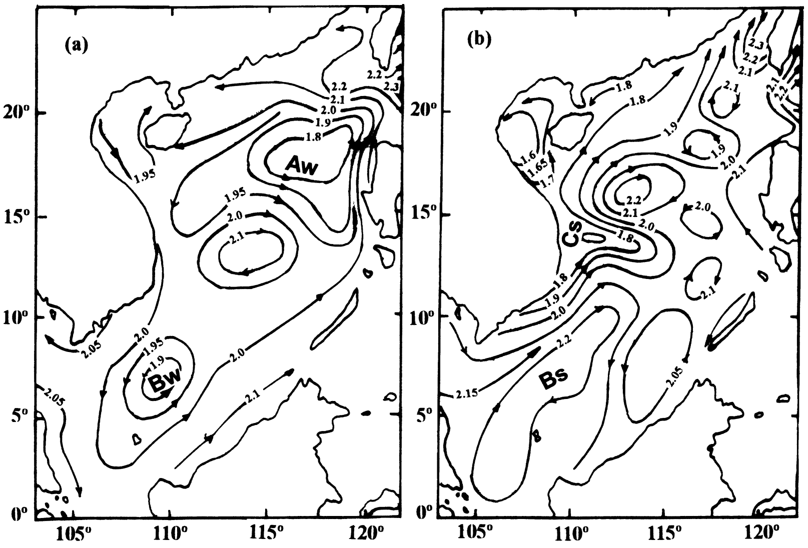

Fig. 3. The dynamic height (0/1200 db, dyn·m) and surface geostrophic current fields in the SCS. Aw, Bw, Bs and Cs in the figure indicate the eddies described in the text. (a) Winter and (b) summer. After Xu *et al.* (1982).

out some eddies in the SCS. As shown in Fig. 3, Xu *et al.* (1982) concluded that the general SCS surface circulation is cyclonic in winter but anticyclonic in summer. Besides the winter cyclonic circulation pattern, two cyclonic eddies are located near the western coast of the Luzon Island (named as "Eddy Aw" hereafter, also implying the location and direction of the eddy) and in the southeast of the Zhongnan Peninsula (called "Eddy Bw" afterward). In summer, two anticyclonic eddies appear in the southeast of the Zhongnan Peninsula (called "Eddy Bs") and between the Xisha Islands and the Zhongsha Islands. Meanwhile, a cyclonic eddy (hereafter referred to "Eddy Cs"), which may be induced by the local summertime upwelling, exists in the east of the Vietnam coast and forces the main circulation to meander in summer. Yu and Liu (1993), and Rong (1994) also presented the similar winter and summer SCS circulation patterns, especially the existences of the above-stated eddies were furthermore demonstrated in their surface geostrophic current fields. Moreover, these circulation patterns and some related major eddies (Eddy Aw, Bw, Bs and Cs) were further confirmed by Zhou *et al.* (1995) who used the Levitus (1982)'s climatological data set to diagnose annual and seasonal surface elevation and geostrophic surface circulation of the SCS.

Although the climatological patterns of seasonal circulation in the entire SCS have been described by the above-cited investigations, some of the following researches have been focused only on the NSCS or the southern SCS (SSCS). In early 1970's, Williamson (1970), Chan (1970), Watts (1971, 1973), and Uda and Nakao (1974) mostly regarded the NSCS surface circulation as wind-driven current. The northeastward current prevails in the NSCS during southwest monsoon period while the southwestward current dominates during northeast monsoon period.

Moreover, several comprehensive investigations were conducted in specific periods in the NSCS from late 1970's to increase knowledge on the NSCS circulation. Accordingly, Qiu *et al.* (1985) constructed the winter and summer NSCS circulation patterns as illustrated in Fig. 4. It is evident that a year-around northeastward current, regarded as the SCSWC, flows with the speed of about 25~50 cm/s along the open sea off Guangdong. And a strong year-around westward current, with the speed of about 30~50 cm/s, flows in the southern side of the SCSWC and is considered to originate from the Kuroshio, i.e. the SCS Branch of Kuroshio (SCSBK). In addition, a cyclonic eddy, with the horizontal scale of about 180 km, exists in the southwest of the Dongsha Islands throughout year. Obviously, these results further modify the NSCS circulation patterns.

In recent years, researchers have paid more attention to the SSCS circulation pattern. However, the basic features and the seasonal variation of the SSCS circulation are not yet well understood. Fang (1997) described the spatial structures of summertime SSCS circulation according to the distribution of geopotential anomaly derived from CTD data in September 1994 and pointed out that a large scale wind-driven anticyclonic circulation exists in the upper layer (0~150 m). Then, Fang *et al.* (1997) summarized that there are four major currents in the upper layer (0~400 m) of the SSCS: the Nansha Western Coastal Current (NWCC), the Nansha Eastern

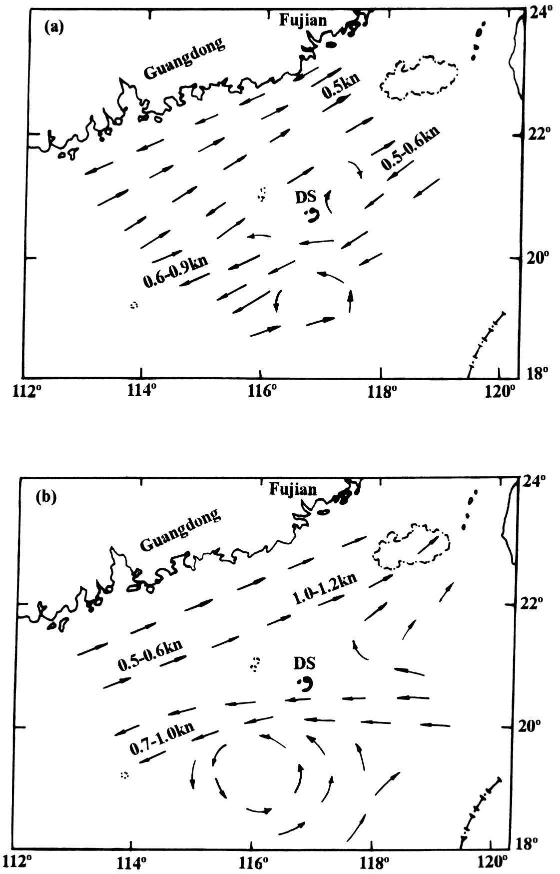

Fig. 4. Circulation pattern in the northeastern SCS. 1 kn is about 51 cm/s. DS means the Dongsha Islands. (a) Winter and (b) summer. After Qiu *et al.* (1985).

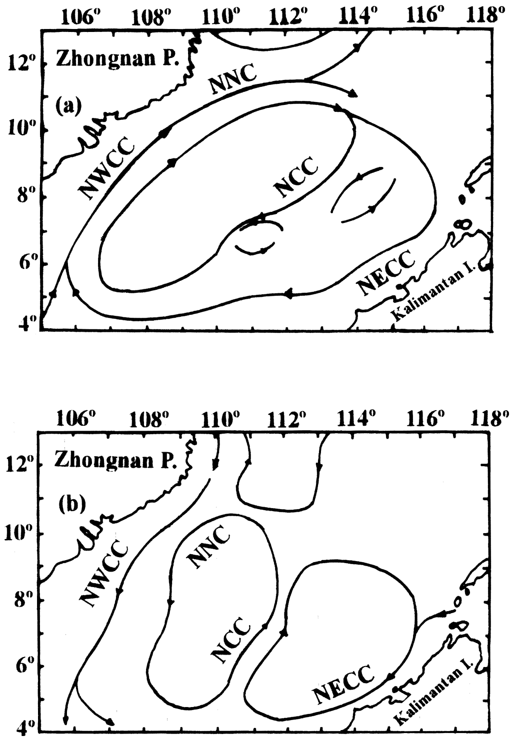

Fig. 5. Schematic diagram of the upper layer circulation pattern in the SSCS. (a) Southwest monsoon period and (b) northeast monsoon period. NWCC, NECC, NCC and NNC represent Nansha Western Coastal Current, Nansha Eastern Coastal Current, Nansha Counter-wind Current and North Nansha Current, respectively. Redrawn after Fang *et al.* (1997).

Coastal Current (NECC), the North Nansha Current (NNC) and the Nansha Counter-wind Current (NCC). As shown in Fig. 5, these four currents except NECC indicate quite different patterns in the respective monsoon (southwest or northeast monsoon) period, and suggest a strong influence of monsoon winds on the SSCS circulation. The NWCC flows northward along the southeastern coast of the Zhongnan Peninsula and then turns eastward to form the NNC at about 11°N, while an anticyclonic eddy (Eddy Bs) exists during the southwest monsoon period. However, the NWCC flows southward during the northeast monsoon period, being accompanied by a cyclonic eddy (Eddy Bw) and another anticyclonic eddy (near the northwestern coast of the Kalimantan Island). Fang and Fang (1998) pointed out that the anticyclonic Eddy Bs develops in May–June and grows up in August, centering around (9°N, 112°E) with the horizontal scale of 400 km and vertical scale of 400 m, and the cyclonic Eddy Bw stays near 112°E in an elliptic shape during the northeast monsoon period.

2.2 Circulation patterns derived from the satellite observations

The satellite observations provide a possible way to investigate the circulation pattern. Chen (1983) used some sea surface temperature (SST) satellite images not covered by cloud to study temporal distribution of surface offshore currents in the NSCS. However, there are quite a few studies on the SCS circulation using the satellite altimeter data since recent work by Yanagi *et al.* (1997) and Li *et al.* (1999) on eliminating tidal aliasing from the altimeter measurement.

Soong *et al.* (1995) detected a large, cyclonic, cold-core eddy in the NSCS in January 1994 using the TOPEX/POSEIDON (T/P) altimeter data. The measurements of sea surface height (SSH) reveal some characteristic levels of the eddy activity. A satellite positioned surface-drifting buoy further confirmed that this eddy has a horizontal scale of about 500 km. Meanwhile, the SST data from the Advanced Very High Resolution Radiometer (AVHRR) aboard the NOAA satellite also provide an additional support demonstrating the eddy with a cold core with temperature of 16.5°C, about 0.5~1.5°C lower than its surroundings. This cold eddy might be the same as the cyclonic Eddy Aw indicated by Xu *et al*. (1982) (see Subsection 2.1 and Fig. 3(a)). Its presence was further confirmed by hydrographic observation and numerical simulation (Shaw *et al*., 1996).

Recently, Mao *et al*. (1999) analyzed the geostrophic current in the SCS from Geosat altimeter observation and reported that the general SCS surface circulation is anticyclonic in summer but cyclonic in winter. Shaw *et al*. (1999) also examined the sea surface elevation in the SCS using the T/P altimeter data from 1992 to 1995 and suggested that the wind stress curl is the main driving force of the circulation in the deep basin of the SCS except near the Luzon Strait. The variation of the circulation in the central part of the basin is associated with the wind stress curl. Wu *et al*. (1999) and Wang, D. X. *et al*. (2000) respectively assimilated the T/P altimeter data into the SCS numerical model and observed results in good accordance with the previous ones. Morimoto *et al*. (2000) also revealed the temporal and spatial variations of the SCS surface circulation with the use of the T/P altimeter data from December 1992 to October 1997.

2.3 *Circulation patterns obtained by the numerical experiments*

Many numerical models have been developed to simulate the SCS seasonal mean or monthly averaged currents. Wang (1985) developed a numerical model to simulate a steady state of the SCS surface current fields. Zeng *et al*. (1989, 1992), Su and Liu (1992), Li *et al*. (1992a, 1992b, 1994), Liu and Su (1993) used two-dimensional numerical models to calculate the monthly or seasonal mean SCS circulation, which provide some satisfactory results of the depth mean circulation. For example, Li *et al*. (1992a) used a barotropic two-dimensional ocean model to calculate the upper layer (0~200 m) monthly mean circulation and suggested that the Pacific Ocean water enters into the SCS through the Luzon Strait in January and can still maintain a weaker depth mean speed in July. They also confirmed that both Eddy Aw and Eddy Bw are cyclonic in January, but Eddy Bs is anticyclonic while Eddy Cs is cyclonic in July. In addition, Liu and Su (1992) adopted a reduced gravity numerical model to study the SCS circulation and discussed the current structure near the Luzon Strait.

As summarized by Wang *et al*. (1994), some multilayer or three-dimensional numerical models for studying the SCS circulation have been developed since the late 1980's. Pohlmann (1987) applied a prognostic baroclinic three-dimensional circulation model developed by Backhaus (1985) to simulate the SCS circulations during the winter and summer monsoons; the grid size of this 12-layer model is about 50 km in the horizontal, but the simulation time is only 15 days. Mao *et al*. (1992) used the same three-dimensional model to simulate the seasonal mean SCS circulation; this 15-layer model is different from Pohlmann (1987)'s in details such as salinity and temperature fields and boundary conditions. Zhang *et al*. (1994) developed a three-dimensional nonlinear diagnostic model to simulate the seasonal current field in the sea areas deeper than 200 m based on the seasonally-average temperature, salinity and wind stress in the SCS; the model is with 14 layers and with the reference plane at 1200 m. Shaw and Chao (1994) applied a three-dimensional primitive equation model with a free surface to simulate the monthly SCS circulation; the model has a resolution of 0.4° in the horizontal and 21 layers in the vertical, and is integrated for three years with the climatological forcing and with the consideration of Kuroshio near the Luzon Strait. Zhang, M. Y. *et al*. (1995) used a three-dimensional circulation model for the SCS and the adjacent western Pacific Ocean with the σ-coordinate system in the vertical direction and the Alternating Direction Explicit (ADE) method. These numerical results manifest that the surface circulation has evident seasonal variations due to the seasonal reversal of monsoon winds. It is basically cyclonic in winter and anticyclonic in summer. Specifically, Shaw and Chao (1994)'s simulation demonstrate that the current is generated by the Ekman drift at the top layer centered at 2.5 m depth, which is westward in winter but eastward in summer. At the surface layer centered at 50 m depth, the current flow into the SCS through the Luzon Strait reaches its maximum speed in the southeast of Vietnam and then changes its direction to northeastward off the coasts of the Kalimantan Island and the Palawan Island in December, but a strong northeastward boundary current in the southeast of Vietnam leaves the Vietnam coast between 11°N and 14°N and diffuses northeastward in August. In addition, these numerical results also demonstrate the existence of some small-to-meso-scale eddies (Eddy Aw, Bw, Bs and Cs) at the upper layers, e.g. at the 30 m depth or 50 m depth, of the SCS.

In recent years, Chao *et al*. (1996), Wang *et al*. (1996, 1997), Camerlengo and Demmler (1997), Takano *et al*. (1998), Wu *et al*. (1998), Cai and Wang (1999), Qian *et al*. (1999), Zhang and Qian (1999), Ly and Luong (1997, 1999), Chu *et al*. (1999a, b) and Yang *et al*. (2000) also executed some numerical studies on the SCS circulation, consequently these numerical results provided further understandings of the SCS circulation pattern. Especially, Wu *et al*. (1998) used a three-dimensional numerical model to simulate the SCS current variability for 1992–1995. The model is driven by daily wind and daily SST fields derived from the NCEP/NCAR 40-year reanalysis project. The four-year model outputs were analyzed using Empirical Orthogonal Functions (EOF) suggesting that the seasonal and inter-annual variations of the SCS circulation could be described in two velocity modes. The first mode associated with a southern gyre shows symmetric seasonal reversal, which is cyclonic in winter but anticyclonic in summer with little year-to-year variation. The second mode, which contributes to a northern gyre off Vietnam, is responsible for the asymmetric seasonal and inter-annual variations. In general, both southern and northern cyclonic gyres combine into a strong basin-wide cyclonic gyre in winter, while a cyclonic northern gyre connects with an anticyclonic southern gyre so as to form a dipole with a jet leaving the coast of Vietnam in summer. These circulation features were also indicated by Chao *et al*. (1996) who applied a three-dimensional, climatology-driven circulation model to calculate the SCS circulation and pointed out that the winter and summer patterns are not symmetric; the northward jet along the western boundary in summer leaves Vietnam coast at 13°N, while the southward current in winter follows the western boundary throughout. They were also indicated by Takano *et al*. (1998) who simulated the annual cycle of the SCS circulation with a rigid-lid, three-dimensional prognostic model and indicated that a large cyclonic gyre persists throughout a year in the northern half of the SCS, but the circulation in the southern half is predominantly cyclonic in winter and anticyclonic in summer. Another new simulation of the seasonal SCS circulation was carried out by Chu *et al*. (1999a) who applied the Princeton Ocean Model (POM) with 20-km horizontal resolution and 23 sigma levels conforming to a realistic bottom topography. A 16-month control run was performed using climatological monthly mean wind stresses, restoring-type surface salt and heat, and observational oceanic inflow/outflow at the open boundaries. The simulation is reasonable when compared to the observations. Sensitivity experiments suggested that the seasonal SCS circulation patterns are determined and forced by wind, while the lateral boundary forcing plays a secondary role in determining the magnitude of the circulation velocities.

3. South China Sea Warm Current (SCSWC) in the Northern SCS

The SCSWC has been drawn attention to for decades because it has a counter-wind property in winter and it plays an important role on the water exchange between the SCS and the ECS.

3.1 Observational evidences of the SCSWC

By using hydrographic data obtained during the Chinese National Comprehensive Oceanographic Survey (1958–1960), Guan and Chen (1964) discovered a northeastward counter-wind current in the near shore region off Shantou (marked by ST in Fig. 1) and another counter-wind current in the coastal area northeast of the Hainan Island. Both of them are considered to be connected with each other and are known as the “South China Sea Warm Current (SCSWC)”. The discovery of the SCSWC has modified the traditional circulation pattern in the NSCS. Since then, many observations (Guan, 1978a, 1978b, 1981, 1985a) have provided evidences to demonstrate that the SCSWC is a strong, narrow and band-like northeastward current persisting throughout winter in the open sea off Guangdong.

Afterwards, Guo *et al*. (1985) and Qiu *et al*. (1985) pointed out that the main stream of the SCSWC is located near the Dongsha Islands with the weaker surface speed of about 58 cm/s (relative speed) during 1981–1982. They confirmed that the current direction of the SCSWC is about the same vertically, i.e. it is basically between N and NE for 7-days of direct current measurements at each layer of a mooring buoy station off Shantou (see Table 1). Moreover, it is indicated that the current is spatially and temporally unstable and variable, with its width of about 27 km/130 km in the west/northeast of the Dongsha Islands.

3.2 Extension of the SCSWC in the Taiwan Strait

Guan (1986a) indicated that the wintertime counter-wind currents both in the SCS and in the ECS, as discov-

Table 1. Mean residual current direction at the station off Shantou in February 1982 (Qiu *et al*., 1985).

Layer (m)	Observational date							
	Feb. 20–27	Feb. 20–21	Feb. 21–22	Feb. 22–23	Feb. 23–24	Feb. 24–25	Feb. 25–26	Feb. 26–27
10	N	NE	NNW	N	ENE	NW	N	NE
50	NNE	NNE	N	N	NNE	NNE	N	ENE
100	N	NNW	N	N	NNE	NNE	NNW	NE
200	NNE	NNE	NNE	NNE	NNE	NNE	NNE	ENE
300	NE	NE	ENE	ENE	ENE	NE	NE	ENE
500	NE	NE	NE	NE	NNE	NE	NNE	NE
800	N	NE	SSE	N	ENE	S	N	NW

ered by Guan and Chen (1964), may be connected through the Taiwan Strait. Figure 6 illustrates the synoptic current vectors derived from ship drift observations in 1910–1920 and from current measurements in 1959–1982, indicating that a counter-wind current really flows northeastward along the coasts of the eastern Guangdong and the western Taiwan Strait. In addition, the geostrophic current distributions also suggest that the SCSWC extends northeastward at least to the offshore areas of Shantou and Quanzhou (marked by QZ in Fig. 1). However, it is deduced that this current can be covered up by the drift current and disappears at the surface layer when the northeastly wind strengthens.

Su and Wang (1987) analyzed historical hydrographic data and pointed out that the SCSWC exists year-around along the shelf break off the Guangdong coast and the northward current in the Taiwan Strait seems to be the SCSWC extension. In addition, Hu *et al*. (1990) revealed that the SCSWC extension flows to NE or ENE direction against the prevailing wind in the Taiwan Strait in winter. And the SCSWC extends northeastward through the southern Taiwan Strait in summer (Hu and Liu, 1992).

3.3 *Mechanism for the SCSWC formation*

Mechanism for the SCSWC formation has been studied using numerical models since late 1980's. Ma (1987) conducted barotropic numerical experiments and showed that a part of the westward current through the Luzon Strait is deflected by the continental slope and forms the SCSWC. The reflection of the incident Rossby waves by the continental slope is found to be significant in the intensification of the SCSWC. Su and Wang (1987), Li *et al*. (1993) and Cai and Wang (1997) used some other numerical models and concluded that the Kuroshio's intrusion plays an important role on the SCSWC formation.

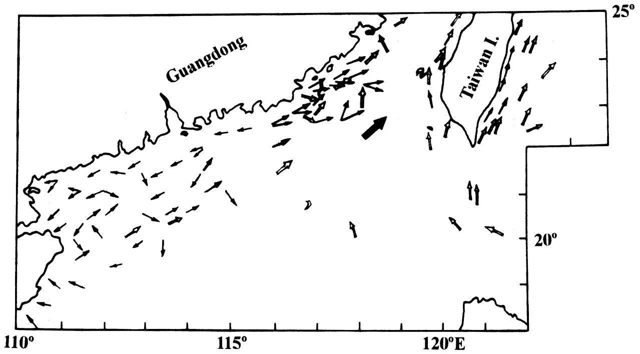

Fig. 6. Observational results of the current in winter off the southeast coast of China. Open arrows show the current vectors derived from ship drift data, thick arrows show the northeastward and eastward current vectors from day-night anchored or mooring buoy stations, and fine arrows show the southwestward and westward current vectors from day-night anchored stations. After Guan (1986a).

Fang and Zhao (1988) regarded sea surface slopes as the main force for intruding the northeastward flowing SCSWC off the southeast China coast. The sea surface inclination along the southeast coast of China is assumed to be associated with the high sea surface elevation in the western tropical Pacific Ocean and relatively low elevation in the northwestern Pacific Ocean. Li *et al.* (1992a) used a barotropic numerical model to study the SCSWC and described that a northeastward current starts from the region off the eastern Hainan Island, passes through the Taiwan Strait and finally reaches the Japan Sea both in January and in July. They considered that the sea surface slope in the direction of the current and across the current from southeast to northwest is probably one of the major forces driving the current. Moreover, Guan (1993)'s hypothesis, Li *et al*. (1993)'s simulation and Fang (1995)'s analysis also supported the viewpoint that the sea surface slope is a significant factor for the SCSWC formation.

Chao *et al*. (1995) presented a new idea that the wind relaxation is a possible cause of the SCSWC. From December to April, the wind relaxation invariably triggers a northeastward current of which the location and alongshore span are comparable to that of the observed warm current. This current is driven by the pressure gradient along the SCS northwestern boundary where the sea level is high in the southwest but low in the northeast. The sea level gradient is built up by the monsoon-driven southwestward coastal current along the northwestern boundary and, after wind relaxes, triggers a return current.

By simplifying the primitive equations, Yuan and Deng (1996) proposed the diagnostic equations for the monsoon counter-wind current in the NSCS. Then, Yuan and Deng (1997a, 1997b, 1998) further made some numerical experiments and suggested that the winter wind stress and continental slope are determinants for the formation of the winter counter-wind current. During the winter monsoon, the prevailing wind drives the Kuroshio water into the SCS through the Luzon Strait, and speeds up the formation and strengthens the winter counter-wind current.

Obviously, it has not reached an agreement on the mechanism for the SCSWC formation. However it is suggested that the Kuroshio intrusion, sea surface slope and wind stress are some important influence factors.

4. Kuroshio Intrusion to the SCS

4.1 *Some viewpoints on the Kuroshio intrusion through the Luzon Strait*

The Kuroshio strongly affects the hydrographic feature and circulation pattern in the NSCS, though it still remains not clear as to how the Kuroshio intrudes the NSCS through the Luzon Strait. Therefore, there exist a few viewpoints as reviewed below.

4.1.1 *"Direct branch" viewpoint*

Most researchers pay attentions to whether or not there is a direct branch into the NSCS from the Kuroshio. It has been regarded by some previous researchers, such as Dale (1956), Chan (1970), Williamson (1970) and Nitani (1972), that some of the Kuroshio water might enter the SCS at the surface layer under the influence of the winter monsoon. Some researchers (i.e. Chan, 1970; Chu, 1971; Guan, 1978c) thought that the Kuroshio could also enter the SCS or inflow the Taiwan Strait through the Luzon Strait in summer. Furthermore, Qiu *et al.* (1984) definitely indicated a westward current in the southern side of the SCSWC in summer by analyzing observational data in the northeastern SCS during 1976–1982. Both vertical current distribution and dynamic height further suggest that this westward current is a direct branch from the Kuroshio and is named as the SCSBK. It is about 55–110 km at the surface layer in late spring and in summer with relatively wider/narrower in the southeast/southwest of the Dongsha Islands. Guo *et al.* (1985) indicated a southwestward current in the right side of the SCSWC in winter and regarded it as originating from the Kuroshio. The maximum speed of this current reaches 144 cm/s at the surface layer and the width is greater than 130 km. Moreover, Pu *et al.* (1992, 1993) observed that the Kuroshio branches into the northeastern SCS through the Luzon Strait during 5 cruises in late 1980's because most of current measurements indicated a northwestward current in the Luzon Strait (see Fig. 7). The intrusion can also be observed in some recent analytical results (Wang and Chern, 1996; Qu *et al.*, 2000), numerical results (e.g. Fang *et al.*, 1996; Metzger and Hurlburt, 1996; Li, R. F. *et al.*, 1996; Chern and Wang, 1998; Liu *et al.*, 2000) and satellite images (Farris and Wimbush, 1996).

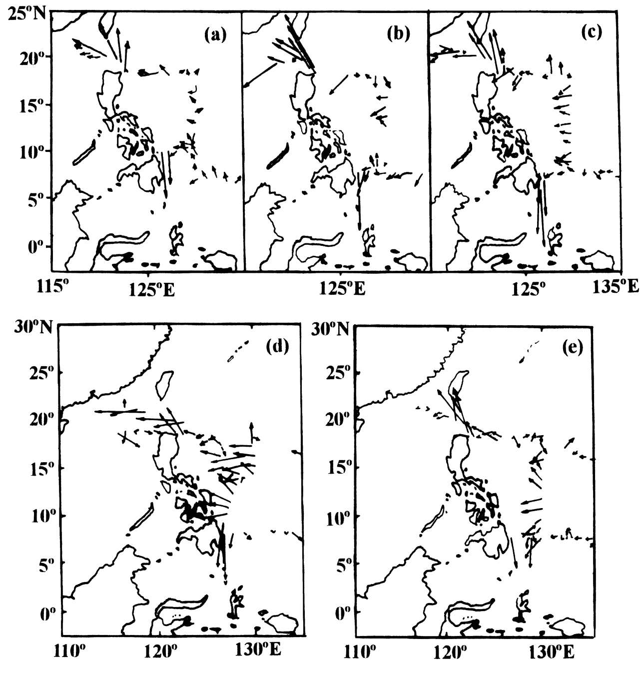

Fig. 7. The vector distribution of average currents in the layer between 175–225 m. ADCP measurements conducted in (a) November 1986, (b) September 1987, (c) April 1988, (d) October 1988, and (e) June 1989. Redrawn after Pu *et al.* (1992).

Furthermore, some observations suggest that there is no intrusion in late spring, partial intrusion in late summer and the maximum intrusion in winter. Nitani (1972) presented three examples that there existed intrusion as far as 118°E in February 1967, no intrusion in May 1959 and partial intrusion to 119°E in August–September 1942. The T-S diagrams in the Luzon Strait indicated intrusion in December 1980 and April 1981 (Fan and Yu, 1981), no intrusion in June 1982 (Fan, 1982) and partial intrusion in August 1980 (Fan and Yu, 1981; Fan, 1984) and August 1981 (Fan, 1982). Shaw (1991) mentioned that there is no intrusion water in summer except for the presence of a meandering Kuroshio front in the Luzon Strait, but the Philippine Sea (east of the Luzon Island) water is located along the entire continental margin south of China in October–January, suggesting an intrusion path along the continental slope. Shaw and Chao (1994) indicated that the Kuroshio's branch with the warm and salty water enters the SCS through the Luzon Strait from October to February, but the westward flow virtually vanishes in summer. Zhang *et al.* (1994) also suggested that the winter monsoon induces the Kuroshio to branch into the SCS with the surface current speed of about 40 cm/s near the Luzon Strait, but the Kuroshio has no apparent intrusion into the SCS in summer because it is blocked by the northeastward current in the NSCS. More recent CTD observations confirmed that the Kuroshio had no direct branch intruding the SCS during the survey period of March 1992, as mentioned by Xu *et al.* (1995) that part of the Kuroshio water has been brought into the SCS when it flows through the Luzon Strait, but it only expands westwards to the vicinity of 120°E.

4.1.2 *"Loop" viewpoint*

Li and Wu (1989) referred the surface dynamic height distribution near the Luzon Strait in the summer of 1966 (Nitani, 1970, 1972) and applied some other observational data to investigate the Kuroshio's intrusion into the northeastern SCS, and pointed out that the Kuroshio often enters the SCS through the Luzon Strait in the form of "loop". This began a new viewpoint about the Kuroshio's intrusion to the NSCS, which has often been quoted by the subsequent literatures. Zhang, F. *et al.* (1995) applied a three-dimensional nonlinear diagnostic model to simulate the currents near the Luzon Strait and showed that the Kuroshio branches into the SCS as a "loop", which stretches westward to 118°E at least at the surface layer in the summers of 1965 and 1966.

The "loop" viewpoint can be confirmed by the dynamic calculation from the CTD data obtained in March 1992 and some ADCP data at the upper layers. Huang and Zheng (1995) considered that the Kuroshio enters the SCS through the middle and southern sections of the Luzon Strait and then splits into three parts at the 100 m depth in the west of the Luzon Strait. The first part flows out of the SCS in a "loop" form through the northern section of the Luzon Strait, the second extends westward off the continental shelf in the north of the Dongsha Islands, and the third forms a cyclonic circulation near the southern Luzon Strait.

Liu *et al*. (1996) analyzed the hydrographic data in the Luzon Strait and the NSCS since 1990 and some satellite-derived SST images, and concluded that there is a persistent bending of the Kuroshio's path westward into and eastward out of the SCS. The Kuroshio enters the SCS through the southern and central section of the Luzon Strait and returns to the Pacific Ocean through the northern section. It has a large range in winter but a relatively small range in summer. Farris and Wimbush (1996) noted that the Ekman transport of the northeast winds can push the Kuroshio surface water westward and induce a loop current in the Luzon Strait. Li, W. *et al*. (1996) and Li and Liu (1997) also indicated that the northward flowing western boundary current, such as Kuroshio, can deform at a gap in the western boundary and form an anticyclone loop current as the gap becomes sufficiently wide.

4.1.3 *"Extend" viewpoint*

Hu *et al*. (1999a) used the CTD data investigated at about 330 stations in the northeastern SCS and their adjacent seas in August–September 1994 to discuss the possibility of the Kuroshio's intrusion to the NSCS. The results show that: as the main stream of the Kuroshio passes by the northern Luzon Strait during the survey period, the Kuroshio's western edge, i.e. the "Kuroshio-influenced water" with some hydrological features of the Kuroshio, might flow through the Luzon Strait, and then extend to the NSCS in two ways. One looks like a branch extending to the sea areas near both the Dongsha Islands and the southern Taiwan Strait and then rejoining the main stream of the Kuroshio, and another flows in a "loop" form passing by the Luzon Strait. This viewpoint is a further modification and generalization of both "direct branch" viewpoint and "loop" viewpoint. It emphasizes that the Kuroshio intrudes the NSCS in the way of extending when it passes through the Luzon Strait and the Kuroshio itself has no direct branch into the NSCS during the survey period.

4.1.4 *"Ring" viewpoint*

Li, L. *et al*. (1997, 1998) reported that a closed current ring of probable Kuroshio origin was observed near the slope of the Chinese continent in the NSCS in September 1994. The ring with a scale of 150 km was a warm-core, anticyclone centered at about (21°N, 117.5°E) just off the continental slope. Near surface current speeds of about 1 m/s were estimated from ADCP measurements and from geostrophic calculations. T-S diagrams show that the water characteristics inside the ring are different from those of the SCS and suggest an origin from the Kuroshio.

Based on the analysis of a long time-series of SSH output from the high-resolution Parallel Ocean Climate Model, a permanent Kuroshio loop taking the shape as a tongue in the SSH distribution is also inferred by Li, W. *et al*. (1998) in the Luzon Strait. It extends westward as far as 118°E from the western Pacific Ocean through the Luzon Strait. During January–July 1995, a complete process of a ring detached from the Kuroshio is seen to move southwestward in the NSCS in the SSH distribution. Obviously, the "ring" viewpoint is another further modification of the "loop" viewpoint.

4.2 *Water exchange in the Luzon Strait*

Huang (1983) suggested that both eastward and westward currents are alternated spatially in the Luzon Strait and the maximum westward net transport (0–1200 db) occurs in winter, the medium in spring and the minimum in summer. By analyzing the oceanographic data during September 1985, Guo and Fang (1988) indicated that the Kuroshio has a westward net volume transport of 11 Sv (referred to the 1200 db plane) in the Luzon Strait, which contributes to the Kuroshio's westward branch that splits from Kuroshio's main path near 21°N and goes westward through 120°E into the SCS at the speed of about 80 cm/s.

Shaw and Chao (1994) pointed out that the water exchange between the SCS and the Pacific Ocean is mostly concentrated on the upper 300 m of the water column in the Luzon Strait. The surface current is toward the Pacific Ocean across the entire strait in August, but there is a weak outflow/inflow on the north/south side of the strait below 300 m. The geostrophic contours also show that the northeastward current from Vietnam to the Luzon Island prevents the Kuroshio water from entering the SCS in summer. In winter, the flow is into the SCS in the surface layer, while the flow below the surface current is toward the Pacific Ocean on both north and south side of the strait. Apparently, they also suggested a great/small westward net transport through the Luzon Strait in winter/summer.

4.3 *Intrusion into the Taiwan Strait*

It has been believed for a long time that water movement along the western coast of the Taiwan Island is northward throughout a year (e.g. Fan, 1982; Wu, 1982; Guan, 1985b, 1986b) and is fed by a branch from the Kuroshio. For example, Huang and Huang (1983) quantitatively differentiated water mass in the Luzon Strait and specifically showed that the Kuroshio split one branch in the south of the Taiwan Island and entered the Taiwan Strait in July 1967, though the axis of the Kuroshio's main stream is variable in the Luzon Strait. Shaw (1992) suggested that the warm and salty water from Kuroshio might enter the Taiwan Strait along its eastern coast in spring but is replaced by the fresher SCS water in summer. Pu *et al.* (1993) and Zhang *et al.* (1994) also indicated that part of the Kuroshio's branch might flow northward into the Taiwan Strait. Cai *et al.* (1998a, b) demonstrated by numerical experiments that most of Kuroshio water heads for the southern shore of the Taiwan Island initially in the direction of incident angle from the east of the Luzon Island and then flows northward along the eastern coast of Taiwan Strait.

Some other observations such as Wang and Chern (1988) have indicated that the northward current along the western coast of the Taiwan Island is interrupted by the northeast monsoon, which holds the warm tropical Kuroshio water back behind a front. The front is broken during periods of weak winds when large parcels of the Kuroshio water manage to escape through the Taiwan Strait into the ECS. Therefore, a net northward supply of water still appears in winter, but it occurs sporadically rather than continuously and is related to the strength of the northeast monsoon. However, Shaw (1989) pointed out that the intrusion is probably not due to the monsoon wind, instead the instability of the Kuroshio front and the inertial force in the Kuroshio are the possible mechanisms for the intrusion.

5. Summary and Discussion on the Currents in the SCS

Based on some previous researches (e.g. Dale, 1956; Wyrtki, 1961; Qiu *et al.*, 1984, 1985; Guo *et al.*, 1985), Huang *et al.* (1994) summarized that the prevailing winter/summer monsoon results in a cyclonic/anticyclonic circulation at the surface layer of the SCS. Yang and Liu (1998) further concluded that the solar radiation, the monsoon wind and the SCS topography could be considered as the main influencing factors for the SCS circulation. Among them, the monsoon wind is the most important factor for the formation, maintenance and seasonal variation of the whole SCS circulation. Recently, Fang *et al.* (1998) reviewed the progresses on the understanding of the upper layer SCS circulation since the works of Dale (1956) and Wyrtki (1961). The schematic diagrams of the SCS circulation patterns (Fig. 8) demonstrate that the NSCS circulation is jointly driven by both monsoon winds and Kuroshio intrusion through the Luzon Strait, which consists of the SCSBK, the Northwest Luzon Cyclonic Gyre, the Northwest Luzon Cyclonic Eddy, the Northwest Luzon Coastal Current, the SCSWC and the Guangdong Coastal Current. But the SSCS circulation is mainly controlled by the monsoon winds. The SCS Southern Cyclonic Gyre occupies most of the SSCS in winter while the SCS Southern Anti-Cyclonic Gyre exists in summer. The circulation in the central SCS is governed by monsoon winds and interaction between the circulation systems in the NSCS and the SSCS.

As reviewed above, there has reached the agreement on some principal features of the seasonal SCS circulation pattern, regardless of using the hydrographic observational data, numerical model computations or satellite data. Tables 2 and 3 compare some major circulation fea-

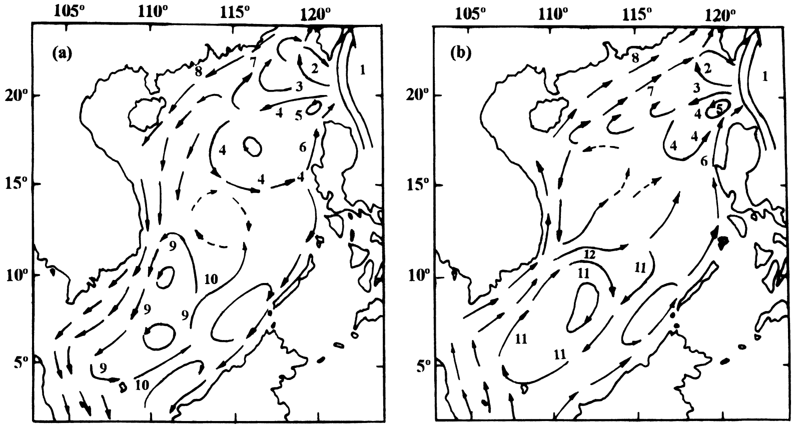

Fig. 8. Schematic diagram of the SCS circulation patterns (a) Winter and (b) summer. Note: 1. Kuroshio, 2. Loop current, 3. SCSBK, 4. NW Luzon Cyclonic Gyre, 5. NW Luzon Cyclonic Eddy, 6. NW Luzon Coastal Current, 7. SCSWC, 8. Guangdong Coastal Current, 9. SCS Southern Cyclonic Gyre, 10. Natuna Offshelf Current, 11. SCS Southern Anticyclonic Gyre, 12. SE Vietnam Offshore Current. After Fang *et al.* (1998).

tures derived from some representative researches in winter and in summer, respectively. The sign "○" in the tables means that authors indicated the existence of the circulation feature and the sign "×" denotes that authors did not mention it. It is evident from comparisons that the following circulation features are confirmed by almost all researches: the overall SCS circulation pattern (cyclonic/anticyclonic in winter/summer), the eddy in the southeast of the Zhongnan Peninsula (cyclonic/anticyclonic in winter/summer, corresponding to "Eddy Bw" and "Eddy Bs", respectively), the wintertime cyclonic eddy ("Eddy Aw") in the west of the Luzon Island, and the summertime cyclonic eddy (Eddy Cs) in the east of Vietnam coast. From these available results, the overall SCS circulation patterns are summarized as follows:

(1) At the top layer (approximately 0~5 m), the SCS current is considered as the Ekman drift that is in accordance with the local wind direction. As shown in Fig. 9(a), the wind direction (an open arrow) is northeastly in winter, so the current (solid arrows) is westward at the top layer. The wind and the Ekman drift reverse in summer (Fig. 9(b)).

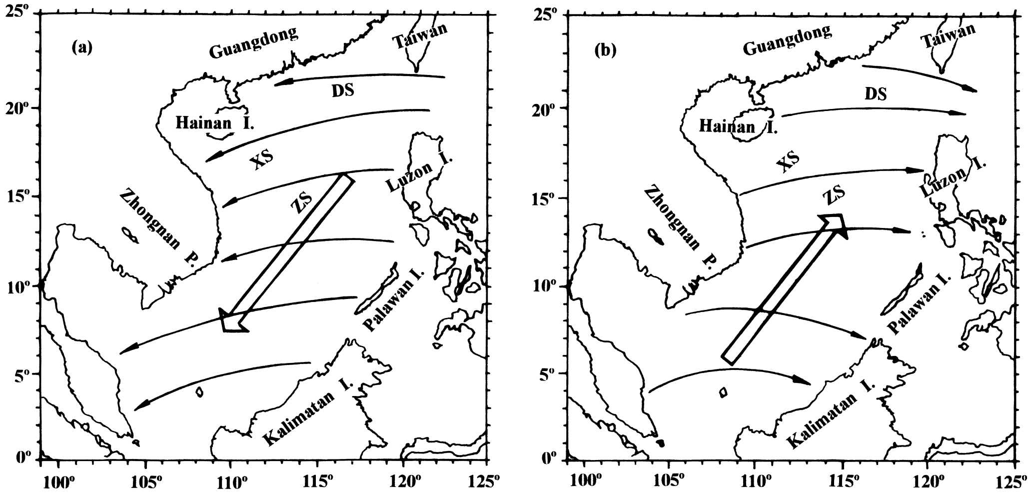

Fig. 9. Overall seasonal circulation pattern at the top layer of the SCS summarized from the previous studies. Solid arrows show the circulation pattern, and open arrow shows the monsoon wind direction. (a) Winter and (b) summer.

Table 2. Comparisons of the major circulation features in winter.

	Cyclonic circulation in SCS	Cyclonic eddy W of Luzon I.	Cyclonic eddy SE of Zhongnan P.
Wyrtki (1961)	○	×	×[1]
Xu *et al*. (1982)	○	○	○
Pohlmann (1987)	○	×[2]	×[3]
Li *et al*. (1992a)	○	○	○
Mao *et al*. (1992)	○	×	○
Shaw and Chao (1994)	○	×[4]	×[5]
Zhang *et al*. (1994)	○	○	○
Zhou *et al*. (1995)	○	○	○
Chao *et al*. (1996)	○	○	×[6]
Wu *et al*. (1998)	○	×	○

[1] The current changes its direction in this area.
[2] There is a cold eddy at the 60 m depth of this area.
[3] There is a cyclonic eddy at 20–30 m depth of this area.
[4] There is a cyclonic circulation at 50 m depth of this area.
[5] There is a cyclonic circulation at 50 m depth of this area.
[6] There is a cyclonic circulation at 150 m depth of this area.

(2) As for the upper layer (0~200 m) mean circulation, it is cyclonic in winter but anticyclonic in summer (Fig. 10). In addition, two cyclonic eddies (Eddy Aw and Eddy Bw) exist in winter in the west of the Luzon Island and southeast of the Zhongnan Peninsula, respectively. And an anticyclonic eddy (Eddy Bs) appears in the southeast of the Zhongnan Peninsula while another cyclonic eddy (Eddy Cs) in the east of Vietnam coast in summer.

(3) It has been suggested that there exists an anticyclonic eddy (shown in short dash line in Fig. 10(a)) in the northwest of the Kalimantan Island in winter and a cyclonic eddy (shown in short dash line in Fig. 10(b)) in the northwest of the Luzon Island in summer. However, this needs further confirmation in future.

Obviously, the overall seasonal circulation is mostly driven by the monsoon wind. However, the NSCS circulation pattern may be modified if the local current structures such as the SCSWC, the Kuroshio intrusion and some small-scale local eddies are taken into consideration. Huang *et al.* (1992) pointed out three major currents at the upper layers of the NSCS, namely the Guangdong Coastal Current, the SCSWC and the SCSBK. Specifically, two main components of the NSCS circulation pattern are summarized as follows:

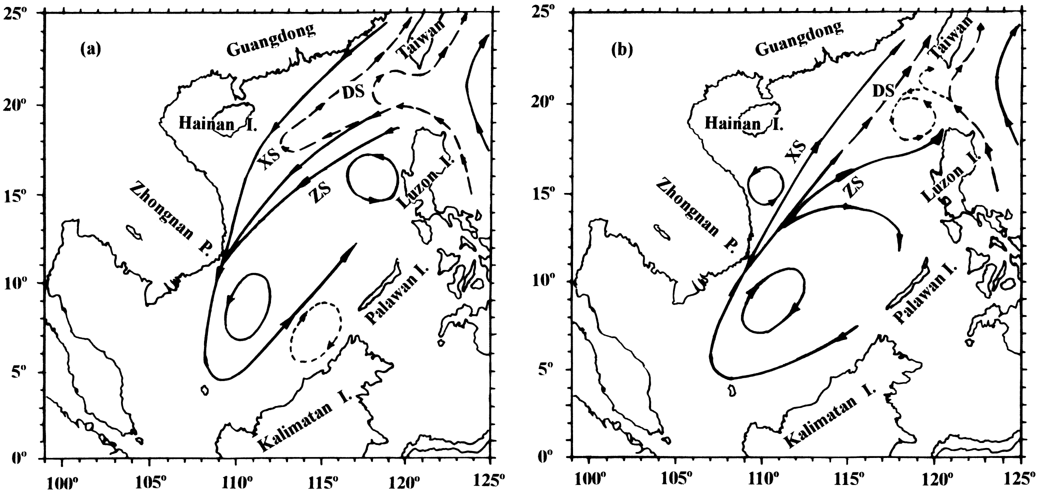

Fig. 10. Overall upper layer mean circulation pattern in the SCS summarized from the previous studies. The long dash arrows schematically illustrate the SCSWC and the Kuroshio intrusion. The short dash arrows mean the unstable intrusion and the eddies in need of further confirmation. (a) Winter and (b) summer.

Table 3. Comparisons of the major circulation features in summer.

	Anticyclonic circulation in SCS	Anticyclonic eddy SE of Zhongnan P.	Cyclonic eddy E of Vietnam coast
Wyrtki (1961)	○	×1)	×
Xu *et al.* (1982)	○	○	○
Pohlmann (1987)	○	×2)	○
Li *et al.* (1992a)	○	○	○
Mao *et al.* (1992)	○	○	○
Shaw and Chao (1994)	○	×3)	○
Zhang *et al.* (1994)	○	○	○
Zhou *et al.* (1995)	○	○	○
Chao *et al.* (1996)	○	×4)	○
Wu *et al.* (1998)	○	○	○

1)The current changes its direction in this area.
2)There is an anticyclonic eddy at 20–30 m depth of this area.
3)There is an anticyclonic circulation at 50 m depth of this area.
4)There is an anticyclonic circulation at the mid-depth of this area.

(1) There exists a northeastward current, the SCSWC, in the deep water off Guangdong Province. The schematic pictures of this current are shown in the long dash lines near the Dongsha Islands in Fig. 10. The current, probably originated from the southeast of the Hainan Island, flows northeastward along the continental slope off the southern Guangdong and extends to the Taiwan Strait. Moreover, the current exists throughout a year and has a property of counter-wind in winter, but it is a spatially and temporally unstable current because of its variable speed (about 25~60 cm/s), width (about 27~130 km) and axis. However, there is no agreement on the formation mechanism for this current, though the Kuroshio intrusion, sea surface slope and wind stress may be some important driving forces. Therefore, a reasonable and generally accepted conclusion of the SCSWC formation mechanism is upon to the further efforts of scientists, as also hoped by Guan (1998).

(2) As for the seasonal pattern of the Kuroshio intrusion process, it is regarded that the Kuroshio has a branch intruding into the NSCS in winter, but it sometimes intrudes to the NSCS in summer, mostly in the form of “loop” or “extend”. In winter, a southwestward current, which is considered to origin from the Kuroshio, flows into the SCS through the Luzon Strait and can at least reach the sea near the Dongsha Islands (Fig. 10(a)). Meanwhile, Fig. 10(b) demonstrates a schematic intrusion path of the Kuroshio in summer, which suggests that the Kuroshio intrudes the NSCS in a “loop” form (shown in long dash lines near the Luzon Strait) when it passes by the Luzon Strait while there are two unstable offshoots (shown in short dash lines near the Luzon Strait) extending towards the southeast of the Dongsha Islands and the southwest of the Taiwan Island, respectively.

(3) There may exist some small-scale local eddies in the NSCS, e.g. the eddies near the Dongsha Islands (Qiu *et al*., 1985; Guan, 1997) and the Luzon Strait. However, it still remains disputable because these eddies are deduced from some specific observational data in a short period. It is suggested that some more comprehensive investigations are needed to give further confirmation as to the possible existence, stability, mechanism and feature of these local eddies.

As for the SCS circulation pattern in spring or in autumn, the general agreement has not been reached because of data limitation. Several researches (e.g. Xu *et al*., 1982; Zhang *et al*., 1994) indicate that the circulation pattern in either spring or autumn is much more complicated than that in winter or summer.

Finally, it is worth mentioning that the recent observational data (Huang *et al*., 1997) indicated another westward current in the sea north of the Dongsha Islands in August 1992, which is different from the SCSBK indicated by some previous researches such as Qiu *et al*. (1984, 1985) and Zhong (1990). The σ_t distribution and ADCP data also confirmed the existence of this westward current and suggested the current to be narrow, weak and unstable. Fang *et al*. (2000) reported an abrupt strong current over the continental slope of the NSCS. Evidently, these recent findings reflect that the NSCS circulation is complicated. Moreover, recent researches (Cai and Su, 1995; Guan, 1997; Chu *et al*., 1997a, 1997b, 1998a, 1998b; Hu *et al*., 1999b; Su *et al*., 1999; Wang, L. P. *et al*., 2000; and etc.) also demonstrate some preliminary features of the multi-eddy structures in the SCS, and some other researches (Wang, 1986; Wang and Chern, 1987a, b; Chen and Wang, 1998) even focused on circulation or eddies at the intermediate or deep layer of the SCS. However, there has not reached an agreement as to the existence and formation mechanism for these current structures, which awaits for furthermore studies in the near future.

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Fig. 2 from "A Review on the Currents in the South China Sea: Seasonal Circulation, South China Sea Warm Current and Kuroshio Intrusion", JIANYU HU, HIROSHI KAWAMURA, HUASHENG HONG and YIQUAN QI, Journal of Oceanography, Vol. 56, pp. 607 to 624, 2000, is Commented by Carl H. Gibson, Journal of Cosmology (25) pp 13310-13338. Winter monsoon winds power currents to the south near the crash site at speeds ~ 0.5 kn, or ~ 12 miles/day. This explains why no debris has been found in the Gulf of Thailand to the north, since floating items like the floating flaperon, found June 30, 2015, on Reunion Island 3000 miles away, would move south. It is impossible for debris from the Australian search area to arrive at Reunion Island this soon, with a much larger distance ~ 6000 miles, and weaker currents. Most debris from the questionable Australian site, termed "Rogue Pilots", would be trapped in the center of the gyre, like all the floating garbage in the North Pacific gyre. The flaperon must have passed through the Sunda Strait between Sumatra and Java. The search for debris of MH370 should have concentrated on the Sunda Strait and its many islands, not on the coast of Australia and waters off Perth. See the attached figures, from the Journal of Cosmology, Vol. 25.

It is important to cosmology, as well as to stratified turbulence mixing and diffusion theory in natural fluids such as the ocean, atmosphere and stars, to establish that MH 370 crashed due to catastrophic equatorial icing, rather than meaningless and costly "Rogue Pilot" speculations. It validates the HGD cosmology description of the big bang, the MECO description of active galactic nuclii, and the many other astrophysical descriptions of self-gravitational turbulent transport by BZTMA mixing chimneys using the Gibson (1962 etc.) claims that turbulence must always be defined by the inertial vortex force, and always cascades from small scales to large following the Kolmogorov-Batchelor scenario. Tragic crashes like MH370 and AF447 punish ignorance of the extreme intermittency of turbulence at equatorial latitudes (Baker and Gibson 1987) where supercooled water vapor at the sea surface can suddenly become deadly icing at aircraft cruising altitudes. CHG

~1x7 foot Boeing 777 wing flaperon found on island July 30, 2015

Currents in March 2014 should carry debris south across the Equator into the trade wind drift toward Reunion Island, as shown by the dotted line below.

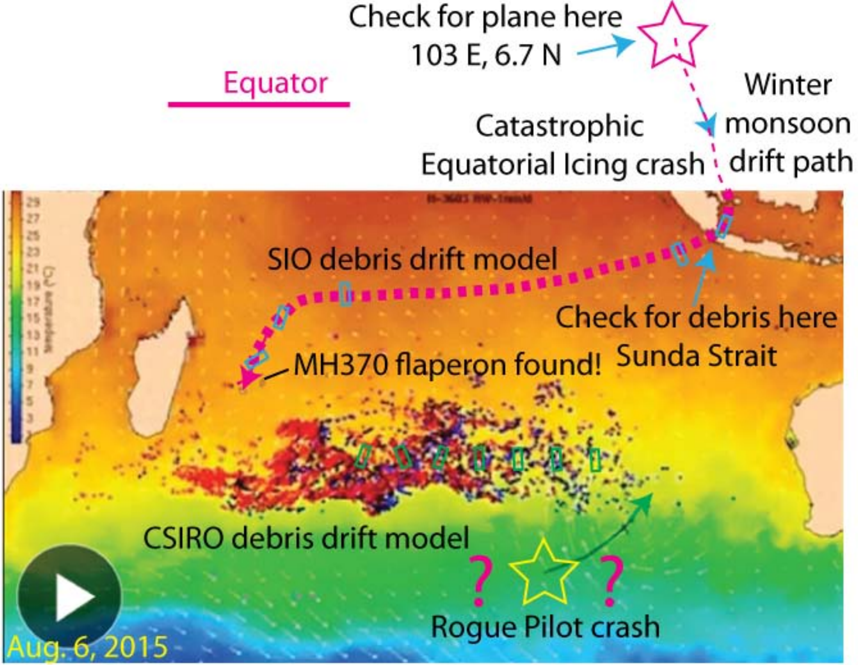
Catastrophic Equatorial Icing event probably caused the crash.

Wing section discovery suggests crash of MH37O was here

Wing section discovery

Rogue pilot crash location

See journalofcosmology.com, Volumes 21-25, Carl H. Gibson



MH370 Hunt: Debris Drift Consistent With Ocean Modeling *(1:21)*

An Australian research lab's modelling of ocean currents shows that debris could have drifted to Reunion Island from the suspected crash zone of Malaysia Airlines flight 370 off Western Australia. Photo: CSIRO

The frequency of CEI events is increasing (2009 Jun, 2014 Mar, 2014 Dec)

The water is hotter and the winds are stronger (global warming)