Review

Chinese Science Bulletin

Progress of Projects Supported by NSFC
Oceanology

April 2013 Vol.58 No.11: 1205–1215
doi: 10.1007/s11434-012-5663-4

Progress of regional oceanography study associated with western boundary current in the South China Sea

WANG DongXiao[1], LIU QinYan[1*], XIE Qiang[1,2], HE ZhiGang[3], ZHUANG Wei[1], SHU YeQiang[1], XIAO XianJun[4], HONG Bo[5], WU XiangYu[6] & SUI DanDan[1]

[1] *State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China;*
[2] *Sanya Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences, Sanya 572028, China;*
[3] *College of Ocean and Earth Sciences, Xiamen University, Xiamen 361005, China;*
[4] *National Climate Center, Chinese Meteorological Administration, Beijing 100081, China;*
[5] *Virginia Institute of Marine Science, College of William and Mary, Virginia, VA23186, USA;*
[6] *National Marine Environmental Forecasting Center, State Oceanic Administration, Beijing 100081, China*

Received September 4, 2012; accepted November 29, 2012; published online January 31, 2013

Recent progress of physical oceanography in the South China Sea (SCS) associated with the western boundary current (WBC) and eddies is reviewed in this paper. It includes Argo observations of the WBC, eddy detection in the WBC based on satellite images, cross-continental shelf exchange in the WBC, eddy-current interaction, interannual variability of the WBC, air-sea interaction, the SCS throughflow (SCSTF), among others. The WBC in the SCS is strong, and its structure, variability and dynamic processes on seasonal and interannual time scales are yet to be fully understood. In this paper, we summarize progresses on the variability of the WBC, eddy-current interaction, air-sea interaction, and the SCSTF achieved in the past few years. Firstly, using the drifting buoy observations, we point out that the WBC becomes stronger and narrower after it reaches the central Vietnam coast. The possible mechanisms influencing the ocean circulation in the northern SCS are discussed, and the dynamic mechanisms that induce the countercurrent in the region of northern branch of WBC in winter are also studied quantitatively using momentum balance. The geostropic component of the WBC was diagnosed using the ship observation along 18°N, and we found that the WBC changed significantly on interannual time scale. Secondly, using the ship observations, two anti-cyclonic eddies in the winter of 2003/2004 in the northern SCS, and three anti-cyclonic eddies in the summer of 2007 along 18°N were studied. The results show that the two anti-cyclonic eddies can propagate southwestward along the continental shelf at the speed of first Rossby wave (~0.1 m s^{-1}) in winter, and the interaction between the three anti-cyclonic eddies in summer and the WBC in the SCS is preliminarily revealed. Eddies on the continental shelf of northern SCS propagated southeastward with a maximum speed of 0.09 m s^{-1}, and those to the east of Vietnam coast had the largest kinetic energy, both of which imply strong interaction between eddy activity and WBC in the SCS. Thirdly, strong intraseasonal variability (ISV) of sea surface temperature (SST) near the WBC regions was found, and the ISV signal of SST in winter weakens the ISV signal of latent heat flux by 20%. Fourthly, the long-term change of SCSTF volume transport and its connection with the ocean circulation in the Pacific were discussed.

South China Sea, western boundary current, eddy, eddy-current interaction, intraseasonal variability, South China Sea thoughflow

Citation: Wang D X, Liu Q Y, Xie Q, et al. Progress of regional oceanography study associated with western boundary current in the South China Sea. Chin Sci Bull, 2013, 58: 1205–1215, doi: 10.1007/s11434-012-5663-4

The South China Sea (SCS), the largest marginal sea in the western Pacific Ocean, is a unique semi-enclosed ocean basin located in the tropical and subtropical oceans of Southeast Asia. It covers a vast area of about 3.5 million km^2, with an east-west span of 99°–123°E and a north-south span of 0°–23°N. Its northwest boundary is close to the

*Corresponding author (email: qyliu66@scsio.ac.cn)

Asian continent, while its northeast, southeast, and southwest boundaries are surrounded by islands. The SCS joints the East China Sea through the Taiwan Strait to the north, and is connected to the western Pacific through the Luzon Strait. It also connects with the Karimata Strait in the south, and with the Java Seas and Indian Ocean through the Malacca Strait and Andaman Sea; and it connects with the Sulu Sea through the Bashi Channel. The Luzon Strait, the only deep water channel connecting the SCS with the Pacific Ocean, has a sill depth of about 2400 m, which is far deeper than the other channels around the SCS. The bottom topography of the SCS is complex: the maximum depth of the SCS is approximately 5400 m, with an average depth of 1200 m; the northeast-southwest diamond-shaped basin with depth over 1000 m accounts for about half of the total basin; the rest of the SCS area is mostly shallower than 100 m; from the shallow to the deep central basin there is a steep terrain. The dynamic characteristics of SCS are similar with the oceans, but a large number of islands, shoals, and gulfs, as well as the complex shoreline, which will affect the dynamic characteristics of the interior circulation in the SCS, making the interior temperature-salinity distribution, eddies, and the meridional circulation of the SCS different from the characteristics of an open ocean.

The SCS is situated in the tropical and subtropical region. The SCS climate is dominated by the monsoons: the powerful East Asian monsoon in winter and the southwest monsoon in summer (also known as the SCS summer monsoon [1]). The wind-driven circulation is the main component of the general circulation in the SCS [1,2]. Wyrtki also noted that there is a western boundary current (WBC) in the SCS [1]. The SCS has basically a cyclonic gyre in winter and an anti-cyclonic gyre in summer, as a result of the seasonally reversing monsoon [3]. Xu et al. [4] confirmed that there exist sub-basin-scale gyre characteristics under the large-scale circulation pattern. The results based on several historical observation datasets confirm the above seasonal circulation structure in the SCS. Before 2006, the oceanographic research of the SCS is mostly based on early observations and analyses; after that, quantitative numerical calculations and simulations of the SCS circulation became more common [5,6]. As new observations increase, particularly the ocean remote sensing data widely used in recent years [7], studies of vertical structure, transport and variability of the SCS circulation become possible. However, the observations and research of the SCS WBC (SCSWBC) have only just started, which consists of the SCS Warm Current (SCSWC) [8] and the Vietnam Coastal Current (VCC) [9,10]. We use the remote sensing information and moored buoy observations in the SCS to perform synthesis study on the SCSWBC in the present stage, which is important for understanding the relationship among the SCSWBC of unique tropical deepwater, the formation, maintenance and change of the Vietnam coast eddy, the SCS winter/summer monsoon-driven circulations, and the large-scale planetary waves. Fang et al. [11] reviewed the dynamic characteristics of the SCSWBC associated with offshore current, double structure, upwelling, and cold filament, but hardly touched the eddy characteristics of the SCSWBC and the interaction between the SCSWBC and eddies. This article mainly describes the characteristics of the SCSWBC from its structure and variability, the associated eddies, their interaction, the regional air-sea interaction, to the SCS throughflow.

1 Structure and variability of the SCSWBC

The studies on the SCSWBC are limited. In 1961, Wyrtki [1] pointed out for the first time that there is a western intensification in the SCS. Using satellite altimeter data, Li et al. [7] noted in 1999 that the SCSWBC is mainly part of the SCS circulation, and that the strongest flow is always located in the southeast coast of the Sino-Indian Peninsula, which is southward in winter and northward in summer and whose velocity can reach 1 m s^{-1}. Wang et al. [12] described the relationship between the dynamic field and the thermal field of the upper-ocean circulation in the SCS in terms of seasonal cycle, and indicated that the intensity of the SCSWBC is related to the monsoons in the SCS. Liu et al. [13] calculated the basin-scale Sverdrup transport in the SCS by neglecting the bottom topographic effect, and explored the impact of wind stress on the seasonal circulations in the SCS. The thermocline change caused by the wind stress curl can adjust the ocean state to the quasi-steady Sverdrup balance; it finally establishes the seasonal-mean large-scale circulation and the corresponding strong SCSWBC [14]. Zhai et al. [15] used numerical experiments to study the dynamics of barotropic circulation caused by summer and winter monsoons. Their results showed that the water that flows through the Luzon Strait into the SCS has an important contribution to the boundary current on the northern slope and the SCSWBC. Moreover, the β effect is crucial to the western intensification of circulation and the intrusion via the Luzon Strait. Liu et al. [13] pointed out that the Sverdrup theory cannot reflect the upwelling off the coast of Vietnam, and it can only be used to estimate the contribution of the net vertical mean transport caused by wind stress curl in the interior SCS. The other effects in the SCSWBC region, such as baroclinicity, terrain, and flow, and buoyancy flux impact are all ignored, which leads to the difference between the idealized circulation characters and the reality.

1.1 Observation

The SCSWBC is the focus of some studies through hydrological observations and altermeter data [7,16–20], and can be reproduced by ocean models [21–24]. There are limitations in these studies, however, so the full picture of the SCSWBC is yet to be seen. For example, altimeter data over shallow shelf is not accurate enough to calculate the flow field. The strengthening of the SCSWBC cannot be obtained correctly using the dynamic height field calculated by the historical hydrological data due to excessive smoothing [25], although the data from a single cruise can reveal such a feature [26]. The seasonal pictures of the SCSWBC in spring, summer, and autumn of 1998 are given through diagnostic calculations based on three SCS cruise data [17], but notable differences induced by strong El Niño in 1998 are present, which can be confirmed by geostrophic flow and Ekman pumping in the cruise data [27].

The paths and patterns of SCSWBC do not so clear when it comes to its variability due to sparse observations. Many drifters have been released in the SCS in winter in the recent years, providing more observational data of the SCSWBC. Recently, drifting buoys have been widely used to measure the surface current using Lagrangian description, which can provide the flow field when there are enough data samples. Using 2003–2006 satellite-tracked surface drifting buoy data, He and Wang [28] studied the surface characters, including path, pattern, and variation of the SCSWBC in winter (Figure 1). They pointed out that the SCSWBC flows southwestward originated from the northern SCS, becomes narrow, and strengthens after reaching to Vietnam coast. The winter SCSWBC includes the southward flow (the northern branch) originated from the Kuroshio intrusion and the westward flow (the southern branch) originated from the eastern boundary near 18°N. In December, the southern branch flows clockwise to the middle of Vietnam coast, or flows southwestward over the continental shelf of northern SCS after having joined with the northern branch. The intensity of winter WBC exceeds 1.4 m s^{-1}, and the location of the maximum velocity appeared at 10°N in 2004, nearly two degrees to the south than that in 2003 and 2005 [29].

1.2 Model results of the SCSWBC

It is difficult to obtain a complete picture of the SCS circulation, due to large spatial and temporal variation and sparse observations. Therefore, it is necessary to study its dynamic processes using ocean modeling. Yang et al. [30] discussed the temporal-spatial structure and formation mechanisms of ocean circulation in the SCS using Princeton Ocean Model (POM), including the SCSWBC. Their results show that the temporal variation of the SCSWBC, especially that of the VCC, is determined by the wind forcing over the interior SCS. Buoyancy forcing can strengthen (weaken) the summer (winter) SCSWBC. The Kuroshio Loop Current is crucial to the SCS circulation north of 18°N, and ultimately determines the SCSWC in winter [30]. The result of VCC controlled by wind forcing is confirmed by Cai et al. [31]. The wind stress is crucial for the generation of the SCSWBC [13,14], while buoyancy forcing and surface heat flux play a minor role in the variability of the SCSWBC [30,32]. Meanwhile, the vorticity transport by the nonlinear effect of the WBC is crucial for the generation of the dipole structure off central Vietnam, which has an anti-cyclonic eddy south of the eastward jet and a cyclonic eddy north of it [33]. In addition, the interaction between wind-driven coastal current and shelf topography plays a crucial role in controlling the separation of the coastal jet in the southwest of SCS [34]. The SCSWBC is tightly connected with the circulation in the northern SCS. The circulation in the northern SCS is mainly controlled by the monsoons, and the local wind forcing over the straits pushes the water exchanges between the SCS and East China Sea and between the SCS and the Pacific. Numerical simulations show that topography [35] and local wind forcing [5,36] play important roles in the formation of upwelling events in the northern SCS.

Hong and Wang [37] studied the circulation in the northern SCS using POM. They investigated the effects of surface wind forcing, Kuroshio intrusion, and bottom topography on the circulation in the northern SCS. Their model results show that a branch of the Kuroshio in the upper layer can intrude into the SCS and have direct influence on the

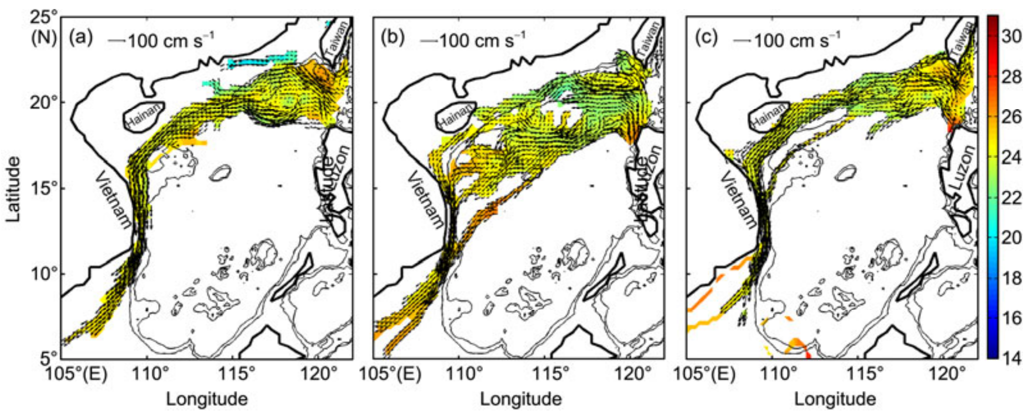

Figure 1 Velocity (unit: cm s^{-1}) and SST (unit: °C) observed by drifting buoys in Decembers of 2003 (a), 2004 (b) and 2005 (c). The two contours denote the 200, and 1000 m isobaths, respectively. Modified from [28].

circulation over the continental shelf break in the northern SCS. The lateral forcing through the Luzon Strait and Taiwan Strait can induce southwestward slope current and northeastward SCSWC in the northern SCS. Wind forcing is the primary factor that induces the seasonal variation of SCS circulation. Without the blocking by the plateau around the Dongsha Islands, the intruded Kuroshio tends to extend northwestward and influences the variation of the total circulation system in the SCS. Wang et al. [38] studied the interaction between continental slope and continent shelf currents and the mechanisms of the winter countercurrent in the northern SCS using the POM. Their results show that the onshore pressure gradient in the outer shelf plays an important role in the momentum balance in the upper layer. Their analyses of momentum budget show that the high pressure belt between the SCSWC and continental slope current is induced by the strong stratification caused by the Kuroshio intrusion and the onshore-veered slope current (Figure 2). The joint effect of baroclinicity and relief (JEBAR), that is due to the baroclinic-bathymetric interaction and the conservation of potential vorticity, is the dominant forcing of the cross-shelf transport over the shelf break area.

1.3 Interannual variability of the SCSWBC

In the early 20th century, there was a great deal of ocean hydrological research abroad. In contrast, the studies of SCSWBC's interannual and interdecadal variability are limited, due to the lack of observational data. Fang et al. [39] investigated the interannual variation of upper-layer circulation in the SCS using satellite altimeter data, and pointed out that there is a significant interannual interaction between the SCSWBC and eddies off southern Vietnam. The interannual variation of circulation off Vietnam can affect the basin-scale gyre intensity [40]. Based on the China Ocean Re-Analysis (CORA) dataset, Xing et al. [41] analyzed the seasonal character of the circulation in the SCS and its variability during El Niño events. Their results show that the two have a close relationship. In the El Niño year's summer,

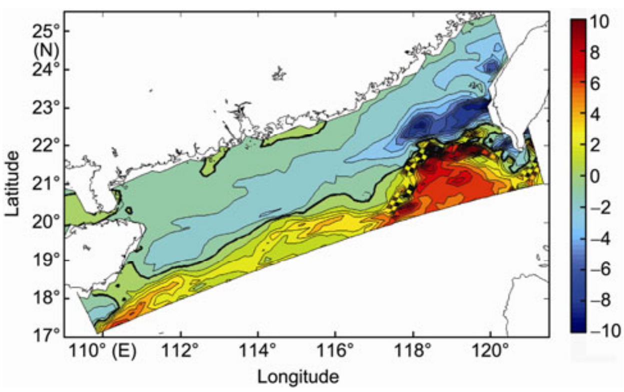

Figure 2 Cross-shelf density gradient in winter. The bold black lines represent the zero contours. The contour interval is 1×10^{-8} m s^{-1}. Modified from [38].

the cyclonic circulation in the northern SCS and the anticyclone circulation in the southern SCS are enhanced; the intensity of the whole cyclonic circulation system becomes weakened in winter and the following summer. That is to say the WBC is enhanced in the summer when El Niño occurs. According to the study of Yang and Wu [42], the weakening trend of cyclonic circulation in winter may be related to a weak Asian monsoon in winter. As for the strengthening trend of the circulation in summer, it may have a relationship with the increase in the Luzon Strait transport (LST).

Based on the hydrological datasets of northern SCS open cruises and satellite altimeter data, the 18°N section's geostrophic flow in the SCS was calculated by Ge et al. [43]. Its cross-section temperature, salinity and density characters show that the isotherm and isopycnal of 18°N cross-section appeared to be high in the west and low in the east, both at surface and sub-surface. The tilt was most notable in 2008 and clear in the years of 2006 and 2007, which indicates the eddy activities may be active there. The spatial variation of geostrophic flow's direction along the 18°N section is closely related to meso-scale eddy activity. From 2005 to 2007, the geostrophic volume, and heat and salt transports shallower than 1000 m were all southward and showed an interannual variation, indicating that the interaction of SCSWBC and eddies played a very important role in interannual variation of southward transports.

2 Eddies associated with the SCSWBC

2.1 Cross-shelf water exchange in the source region of the SCSWBC

Influenced by the monsoon, the Kuroshio intrusion and complex topography, a large amount of eddies are generated in the SCS, especially the anti-cyclonic warm eddies in the northern SCS [44–46]. However, these eddies are seldom captured by *in-situ* observations. Satellite altimetry data shows that the region off Vietnam, which is one of the energetic regions in the SCS, has large eddy kinetic energy (EKE) [47]. The structure, generation and dissipation mechanisms of the cold eddies in the northern SCS were mainly discussed based on mooring and altimetry data in the literature. Li et al. [48] showed the existence of an anti-cyclonic warm eddy in the northern SCS using in-situ conductivity-temperature-depth (CTD) data, and the Argos drifter rotated around the eddy for four cycles after leaving the Luzon Island in winter 1993. There are different theories for variation mechanism of the eddies in the northern SCS; e.g. the anti-cyclonic eddies (AEs) shed from the Kuroshio branch [48–50], which intrudes into the SCS and changes the local circulation, and those due to the instability of the Kuroshio, which results in the shedding and westward moving of AEs [51,52]. However, some other studies pointed out that not all observations supported the view of water intrusion associated with the Kuroshio branch, and thus the Kuroshio water is not the main reason for the formation of the AEs [53]. Yuan et al. [52] pointed out that the shedding of AEs from the Kuroshio occurred most frequently in winter, and the eddy shedding is influenced by the Kuroshio transport [54].

Some studies noted the AEs could move westward into the SCS after shedding from the Kuroshio [55,56], but few discussed its interaction with the SCSWBC. Wang et al. [57] studied the generation and development of two AEs in the northern SCS in the 2003/2004 winter. Their results showed that Drifter No. 22918 tracked an AE in the northern SCS during December 4–23, 2003, and that Drifter No. 22517 tracked two different warm eddies in the same region during January 28 to April 14, 2004 (Figure 3). Both eddies moved southwestward along the continental shelf in the northern SCS after their generations, and their moving speeds are similar to that of the first baroclinic Rossby wave. Nan et al. [58] revealed the generation and dissipation processes and activities of three AEs around 18°N (Figure 4). Their results showed that the life spans of the three AEs were 147, 168 and 210 days, respectively (Figure 4(a)), and that the background circulation was anti-cyclonic (Figure 4(b)). Studies of the interaction between the SCSWBC and the three AEs showed that the SCSWBC flew northward during April to August, and when the SCSWBC and its east branch increased in strength, AE1 (that is ACE1 in Figure 4(a)) and AE2 (that is ACE2 in Figure 4(a)) strengthened simultaneously. Their generation and development were related to the instability of the SCSWBC. The continual appearance of AEs in the northwestern SCS influenced the precipitation through the atmospheric boundary layer [59].

2.2 Interaction between SCSWBC and eddies

There are distinct differences among the seasonal circulations in the upper SCS: there are cyclonic circulation in winter and anti-cyclonic in the south in summer [1,2]. There are a large number of meso-scale eddies associated with these circulations. The nonlinear vorticity advection of the SCSWBC is of vital importance for the dipole mode (an anticyclonic eddy south of the eastward jet off central Vietnam and a cyclonic eddy north of it) in summer [33]. The

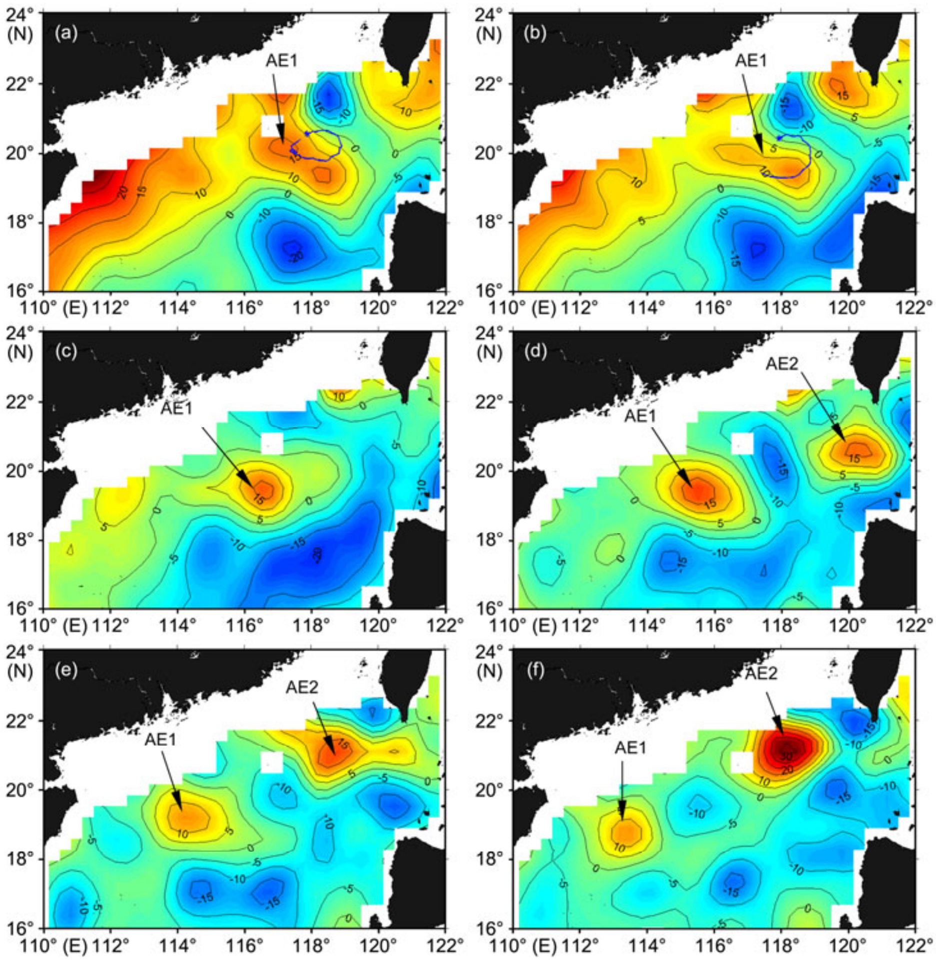

Figure 3 Snapshot of sea-level anomaly (SLA, unit: cm). Buoy 22918's trajectory (blue lines, with blue asterisk represents its initial position). (a) From December 4–15, 2003, superposed on the SLA field of December 10, 2003; and (b) from December 16–23, 2003, superposed on the SLA field of December 17, 2003. SLA field on (c) January 7, 2004; (d) January 21, 2004; (e) February 4, 2004; and (f) February 18, 2004. Modified from [57].

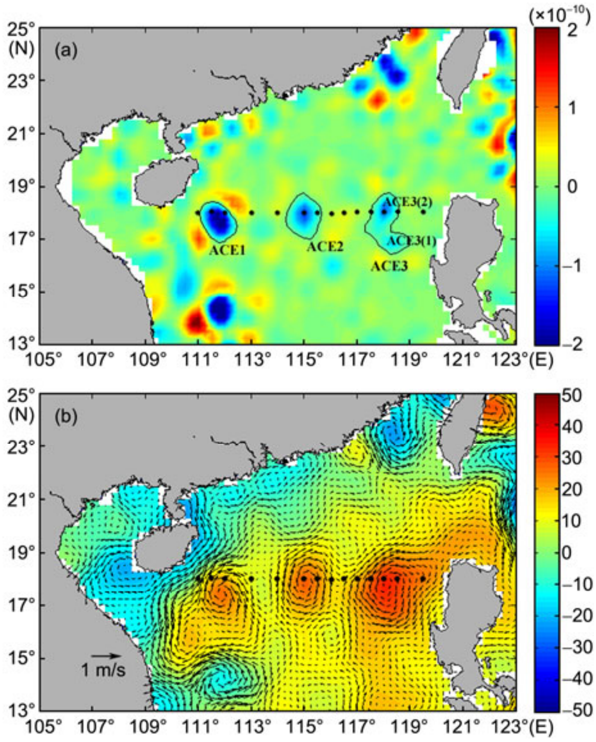

Figure 4 (a) The three anti-cyclonic eddies in the satellite map of Okubo-Weiss parameter (unit: s^{-2}) on August 22, 2007. Black dots denote eddy core's locations. (b) The SLA (unit: cm) and corresponding surface geostrophic currents (unit: m s^{-1}) on August 22, 2007. Modified from [58].

monsoon influences the sea surface height (SSH) through baroclinic Rossby waves [14,60], and the characteristics of the meso-scale eddies could be indentified through the change of SSH anomaly [61,62]. Two regions of strong meso-scale eddies exist in the SCS: one along the SCSWBC, and the other across the central SCS from southwest to northeast [58]. Sometimes, the circulation in the northern SCS is mainly influenced by the Kuroshio intrusion [63,64], and most of the meso-scale eddies are formed by the Kuroshio intrusion [48–52]. The sub-surface temperature is affected by the westward propagation of eddies, and shows obvious intra-seasonal variation [65]. Besides, the circulation south of Taiwan Island also shows significant intra-seasonal variation [66]. There is typical upwelling in summer along the coastal region off Vietnam, which shows obvious intra-seasonal and interannual variations [67,68]. In July–August, the AEs associated with upwelling spread southeastward, and transport cold coastal water to the interior SCS [67]. The southward spreading of the chlorophyll bloom caused by the upwelling has an intra-seasonal oscillation of 30–60 d [69]. The variation of thermocline depth in the central SCS is influenced by eddies, and is negatively correlated with the change of SSH [70]. By analyzing the cruise observation in the upper SCS, it was found that there is very strong meso-scale variation of the circulation around the Natuna Islands [71]. The meso-scale eddies with larger energy usually sustained for a longer time, and penetrated to a deeper depth [72].

By using the temperature and salinity data of Generalized Digital Environment Model (GDEM), Wang et al. [73] analyzed the deep circulation in the SCS, and pointed out that the cyclonic deep circulation is mainly influenced by the topography in the Luzon Strait. Hu et al. [74] analyzed the three-dimensional characteristics of eddies along the SCSWBC in September 2007 using the current and temperature observation data. The authors pointed out that the formation of the cyclonic eddy north of the Vietnam offshore jet is related to the recirculation caused by the baroclinic instability of the jet. In addition, the evolution of this cyclonic eddy is closely related to the AE south of the offshore jet.

Chen et al. [75] pointed out that the cyclonic and AEs have different seasonal characteristics: more cyclonic eddies are formed in winter, while more anti-cyclonic eddies are formed in summer. The cyclonic eddies with minimum (maximum) radius and lifetimes appear in summer (winter), and the lifetime of the AEs is longer than that of the cyclonic eddies. The Eddy Kinetic Energy (EKE) (Figure 5) is much larger in Z1 and Z4 regions than in Z2 and Z3 regions, and the maximum EKEs in Z1 and Z4 appear in winter and summer, respectively. Over the continental shelf of the northern SCS, the eddies propagate southwestward, and the speed is the largest of the whole SCS [75], probably due to the SCSWBC. This is different from the common characteristic that the propagating speed is larger in the lower latitude. There are many eddies in the Vietnam coastal region. The quasi-stationary eddies move about locally and strongly interacts with the SCSWBC [76]. Other studies show that there is energy transfer between the SCSWBC and eddies through baroclinic instabilities [77]. The Xisha region is the assembly area for the extinction of eddies. And owing to the complex topography, there are interactions among eddy, the WBC, and topography. Related research is in progress.

3 Air-sea interaction

The change of sea surface temperature (SST) is the most important reason to study the air-sea interaction. Existing research has shown that, although the SCS has a climatological warm pool structure [78,79], its SST has significant interannual variation [80], and the interannual variability of the basin-wide SST is different in winter and summer [81]. Through the atmospheric and ocean circulations [82,83], the El Niño and Southern Oscillation (ENSO) signal can affect the oceanic variability in the SCS. The change of mixed layer depth (MLD) is also an important factor that impacts the SST [84], and in turn SST can impact the atmospheric circulation. The interannual variability of SST in the SCS has a distinct bimodal structure: the El Niño-related warming in February and August in the following year, and the mean meridional geostrophic heat advection of the SCS are the main factors that lead to the second warming in August [85].

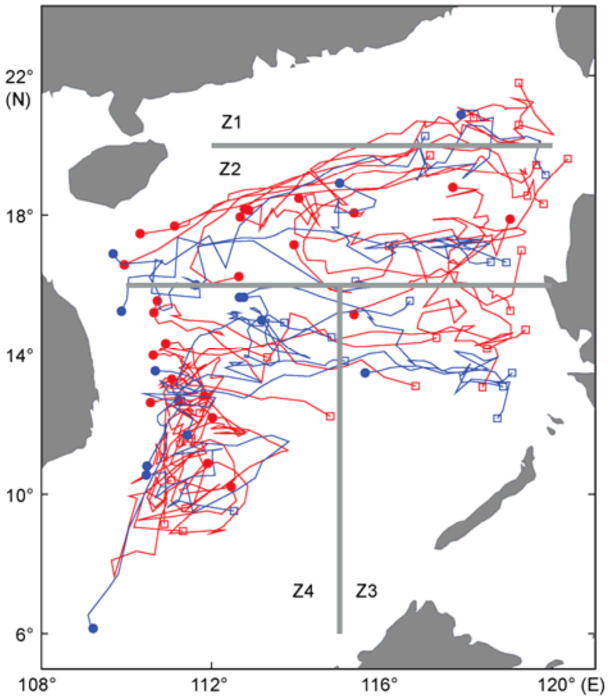

Figure 5 Tracks of long-lived eddies, with squares and circles representing the genesis and dissipation positions of the eddies, respectively. Red and blue lines represent AEs and cyclonic eddies tracks, respectively. Modified from [75].

Most previous studies suggested that the interannual variability of SST in the SCS is closely related to the wind change, and little research concerned the SCSWBC influence on the SST. Xie et al. [67] demonstrated that the development of cold filament associated with Vietnam offshore jet disrupts the summer warming of the SCS and causes a pronounced semi-annual cycle in local SST. The blocking of Annan Mountains to the southwest monsoon and the wind stress curl induced by the wind jet on the south edge of the mountain range are the main factors that cause the summer upwelling off Vietnam coast and the blocking of the summer SST warming in the SCS. The impact of topography on the SCS summer climate characteristics was further validated by a model [86]. There exists a summer cold tongue in the temperature structure associated with the SCSWBC; in addition, there is still a significant cold tongue in the same region in winter, and the generation of the winter cold tongue is related to the southward cold advection by the SCSWBC [87]. Xie et al. [88] found that the 30–60 day intraseasonal oscillation of SST associated with the SCSWBC was under the influence of the Vietnam coastal upwelling [67,68], and this intraseasonal oscillation amplitude was obviously more significant near Vietnam coast than in any other regions. The analysis of moored buoy data found that there was also a significant period of 40–70 day intraseasonal oscillation in the subsurface near the SCSWBC region [89]. Zhuang et al. [90] noted that there existed a weak seasonal signal between 100- and 200-m isobaths in the SCSWBC, which separated the strong intraseasonal signals of shallow and deep waters. We suspect that the intraseasonal variability (ISV) of the WBC cannot be significant in the WBC region because the WBC is a relatively stable and strong flow, but the WBC originated from the Luzon Strait and in Vietnam jet area, due to different dynamic factors and eddies can cause relatively strong ISV signals in these regions. The diluted water off southern Vietnam affects the distribution of barrier layer in the WBC region, and the ISV in winter SST causes the ISV signal of the latent heat flux to weaken by 20%, which has certain impact on the local air-sea interaction [91].

4 Implication of the SCS throughflow (SCSTF)

As a main passage of water and heat transports between the Pacific and Indian oceans, the Indonesian throughflow (ITF) plays an important role in the global thermohaline circulation. The influences of the SCS on the ITF have been studied more and more recently, with the development of regional ocean modeling. The traditional ITF is about the water entering the Indian Ocean from the Pacific Ocean through the Makassar and Maluku straits. The Pacific water through the Luzon Strait (inflow to the SCS) and through the Karimata Strait (outflow from the SCS) and its role were neglected previously. The heating from the atmosphere will induce cold ocean heat advection between warmer temperature in southern SCS and colder temperature through the Luzon Strait, which plays an important role connecting tropical Pacific and Indian oceans. The Pacific water entering the SCS through the Luzon Strait can flow southward along the western boundary, and will re-enter into the Pacific as a surface current in the Makassar Strait after flowing out of the SCS through the Karimata Strait, which plays an important role to the heat transport of the ITF on the interannual time scale [92]. This circulation branch in the SCS connecting the Pacific and Indian oceans, which originates from the western Philippine Seas toward the Indonesian Seas through the SCS, as well as through the Karimata and Mindoro straits, is named as the SCSTF [93].

The ocean circulation in the SCS plays an important role in modulating the ITF variability climatologically, and that the Sunda Shelf and Java Sea may be the major passages of the SCS water crossing the equator to join the water exchange between the Pacific and Indian oceans [94]. The north branch of the North Equatorial Current (NEC) will enter the Indonesian Seas after flowing through the Luzon Strait into the SCS and flowing out of the SCS through the Karimata Strait [95]. The SCS branch of the Pacific-to-Indian Ocean throughflow in winter, is confirmed by drifter buoys [96] and numerical modeling results [24,97]. The net outflow from the SCS plays an important role in the net transport of the ITF, and 25% of the net heat transport from the Pacific Ocean to the Indian Ocean is through the

SCSTF [98], and the role of the SCSTF has been confirmed by the subsurface salinity structure in the interior SCS [97,99]. The SCS should gain net heat flux from the atmosphere just to balance the cold ocean advection, which is caused by the relatively colder water into the SCS via the Luzon Strait and warmer water out of the SCS in the south; so the SCS contributes to the meridional circulation of the North Pacific Ocean as a heat capacitor [100,101]. Numerical results show that the SCSTF can further affect the low-latitude western boundary of the Pacific, besides providing heat transfer through the Makassar Strait [102,103]. The SCSTF may play an active role in regulating SST patterns and modulating conditions of the Indo-Pacific warm pool, thus having important implications for climate variability [104].

The variability of SCSTF is mainly controlled by the equatorial Pacific wind stress on the interannual time scale [93]. The SCSTF increased and the ITF decreased after the 1976/77 climate shift [105], which is similar with their variations on interannual time scales [106]. After the climate shift, the NEC decreased, the Kuroshio east of the Luzon Strait increased, and the Mindoro Current decreased. The abnormal cyclonic ocean circulation in the origin of the ITF, associated with the weakening of the NEC and South Equatorial Current (SEC) after 1975 was unfavorable for the Pacific water entering the Indian Ocean directly [105] (Figure 6). When the SCSTF is stronger, the ocean circulation is cyclonic in the northern SCS and anti-cyclonic in the southern SCS. A heat budget analysis shows that the advection caused by the SCSTF is also important during 1982/1983 and 1997/1998 El Niño events, which is not consistent with some previous studies [100]. The roles played by the SCSTF in setting up thermal structure and dynamics process need to be investigated further using more datasets and better numerical models.

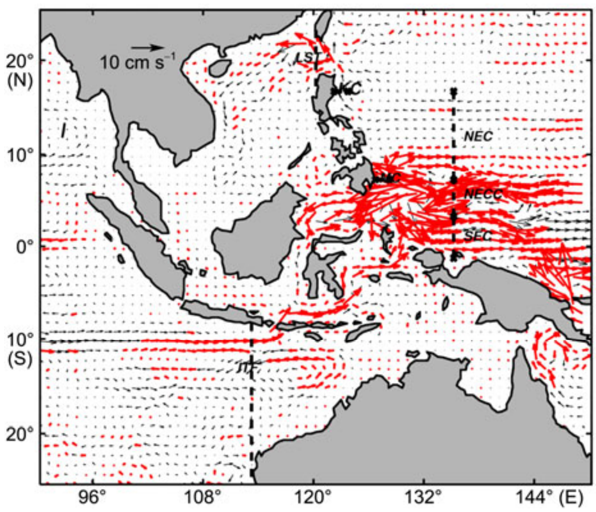

Figure 6 Ocean circulation difference (1976–2001 minus 1958–1975) averaged in the upper 465 m (unit: cm s^{-1}). The red vectors indicate significant differences with a confidence level of 95%.

The mass transport of the SCSTF is weak, but its importance to the climate variability cannot be omitted due to the significant modulation on ITF heat transport, and will also affect the major currents in the tropical southeastern Indian Ocean. Suppose the SCS provides salinity to the water mass of the Indonesian Seas, and then the role of the SCS and its connection of the Indo-Pacific would be strengthened to become important to the air-sea interaction of ocean and climate systems. The ITF variability through its three main passages was discussed by Du and Qu [107] in detail, and the role of the SCS as a semi-closed basin on the dynamic process of large-scale circulation was also given. The ITF is an important component of the current system, as the major connection between the Pacific and Indian oceans. The ITF can supply warm water from the Pacific into the SEC between 14°S and the Java Sea, so the thermal structure of eastern Indian Ocean is tightly connected with the ocean circulation. The ocean circulation will further affect the upwelling in the eastern Indian Ocean, and the changes in SST will feedback to the atmosphere by local air-sea coupled process. Some progresses of the SCSTF study has been obtained, but its connection with Maritime Continent system and its role on East-Asian monsoon system need be investigated further.

5 Summary

In this paper, we discuss the variability of the SCSWBC, interaction between eddy and SCSWBC, air-sea interaction, and the SCSTF. Figure 7 summarizes some of the new results. Although we have gained new knowledge of the characteristics of SCS currents, in particular the SCSWBC, our understanding of the physical oceanography of the SCS is still limited. Some unresolved problems are listed as follows.

(1) Observations. Since 2004, the South China Sea Institute of Oceanology (SCSIO) has led one northern SCS (NSCS) open cruise each year, which covers about 60 stations during each cruise. Funded by the National Natural Science Foundation of China in 2010, the multi-disciplinary NSCS open cruise is now executed under the ship-sharing policy. During the NSCS open cruise, the long-term observation section of 18°N is included in the Climate Variability and Predictability (CLIVAR) International Climate and marine planning framework (www.wcrp-amy.org and http://eprints.soton.ac.uk/41826/), which promotes the Indo-Pacific warm pool and SCS to become one of the key research areas of the "Asian Monsoon Years". The moorings have been placed in the SCSWBC area between Xisha and Hainan since 2007. The weather monitoring units built on Yongxing Island provide the marine hydrological and meteorological real-time remote observations. Although the existing systems in the SCS include the field observations and continuous observations, only part of the air-sea interface buoy relies on islands and offshore General Packet Radio Service

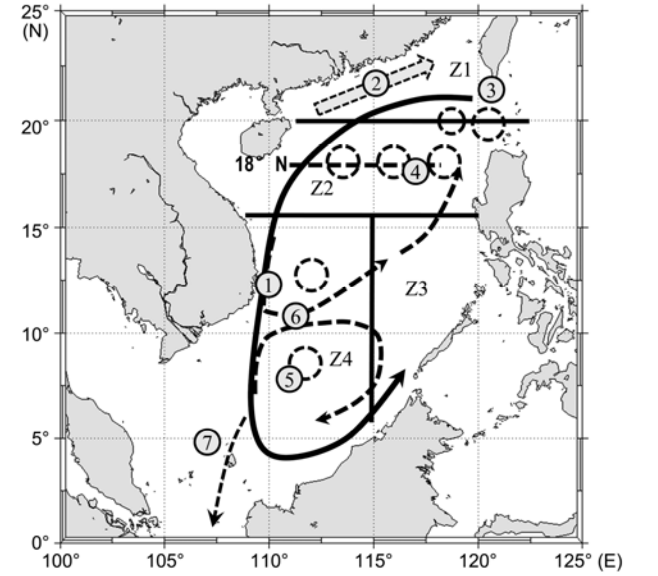

Figure 7 A diagram for the main results reviewed in this paper. 1, Observation: the location of the Vietnam coastal current with fast velocity and narrowest width is 12°N; 2, the mechanism of the SCSWC: JEBAR and PV conservation are the main forcing for the continental slope current climbing and deflection; 3, the speed of the warm eddies propagation is similar to the first Rossby wave phase velocity; 4, warm eddy activity is related to the SCSWBC; 5, eddy propagates fastest in Z1, and EKE is the largest in Z4; 6, SST in the east of SCSWBC area shows a strong intraseasonal oscillation, which will reduce the latent-heat intraseasonal oscillation by 20% in winter; 7, the implication of SCSTF.

(GPRS) signals with real-time communication capabilities, and the rest of the far-reaching sea observation system does not have real-time data transmission capability. It cannot provide real-time services for environmental forecasting due to lack of quality of transferring data in real-time. Some mooring observation arrays have been built in the WBC area around the Xisha Islands; however, the observation arrays in the upstream and downstream are lacking. The observation system should be improved further, for aiming at the Vietnam offshore flow, the possible existence of the SCSWBC branch to the east of the Dongsha Islands.

(2) Numerical simulations. It is difficult to simulate the warm eddy shed from the Kuroshio and to obtain similar results as those from satellite altimeter, without data assimilation in regional ocean models. The same difficulties exist in the Hybrid Coordinate Ocean Model (HYCOM) without assimilation, which is the only available fine-resolution simulation output we had. The meso-scale eddies originated from the interior SCS and WBC with stable seasonal variability (such as the Luzon cold eddy, Wan-an Bank eddy) can be roughly reproduced, although some differences between the simulation and the T/P altimeter data still exist in terms of strength and fine structure. The vertical structure of eddies is still unknown, due to the lack of observations.

(3) Urgent scientific issues. In addition to volume transport and sources of the SCSWBC, other issues, such as the mechanism of the interaction between the WBC and meso-scale eddies, the deep WBC structure, and the predictability of the SCS current and the lead time for the prediction, are also challenging. "Go Deep-Sea" is the world's trend, so is China's. Physical oceanographers should broaden their views and research fields. The related studies of the WBC and meso-scale eddies should be interdisciplinary, such as the application of fluid dynamics in the ocean dynamics, acoustics, ocean thermal processes, and biogeochemical cycles.

This work was supported by the National Basic Research Program of China (2011CB403504), the Knowledge Innovation Program of the Chinese Academy of Sciences (KZCX2-EW-Y040), and the National Natural Science Foundation of China (40830851). The three anonymous reviewers provided helpful suggestions on the manuscript.

1 Wyrki K. Physical oceanography of the Southeast Asian waters. NAGA Report, 1961, 2: 195
2 Dale W. Wind and drift current in the South China Sea. Malays J Trop Geogr, 1956, 8: 1–31
3 Hu J Y, Kawamura H, Hong H S, et al. A review on the currents in the South China Sea: Seasonal circulation, South China Sea warm current and Kuroshio intrusion. J Oceanogr, 2000, 56: 607–624
4 Xu X Z, Zhang Q, Chen H C. The general descriptions of the horizontal circulation in the South China Sea (in Chinese). In: Proceeding of the 1980 Symposium on Hydrology and Meteorology of the Chinese Society for Oceanology and Limnology. Beijing: Science Press, 1982. 137–145
5 Xue H J, Chai F, Xu D Y, et al. Characteristics and seasonal variation of the coastal currents in the South China Sea (in Chinese). In: Xue H J, Chai F, Xu J P, eds. Oceanography in China—Current Numerical Calculation and Mesoscale Features Research in South China Sea. Beijing: Ocean Press, 2001. 64–75
6 Fang G H, Wei Z X, Huang Q Z, et al. Volume, heat and salt transports between the southern South China Sea and its adjacent waters and their contribution to the Indonesian throughflow (in Chinese). Oceanol Limnol Sin, 2002, 33: 296–302
7 Li L, Wu R S, Guo X G. Seasonal circulation in the South China Sea-a TOPEX/POSEIDON satellite altimetry study (in Chinese). Acta Oceanol Sin, 2000, 6: 13–26
8 Guan B X. Winter Counter-Wind Current off the Southeastern China Coast (in Chinese). Qingdao: China Ocean University Press, 2002. 41–133
9 Shaw P T, Chao S Y. Surface circulation in the South China Sea. Deep-Sea Res I, 1994, 41: 1663–1683
10 Chu P C, Chen Y, Lu S. Wind-driven South China Sea deep basin warm-core/cool-core eddies. J Oceanogr, 1998, 54: 347–360
11 Fang G H, Wang G, Fang Y, et al. A review on the South China Sea western boundary current. Acta Oceanol Sin, 2012, 31: 1–10
12 Wang W Q, Wang D X, Shi P. Annual and interannual variations of large-scale dynamic in South China Sea (in Chinese). J Trop Oceanogr, 2006, 20: 61–68
13 Liu Q Y, Yang H J, Liu Z Y. Seasonal features of the Sverdrup circulation in the South China Sea. Prog Nat Sci, 2000, 10: 1035–1039
14 Liu Z Y, Yang H J, Liu Q Y. Regional dynamics of seasonal variability in the South China Sea. J Phys Oceanogr, 2001, 31: 272–284
15 Zhai L, Fang G H, Wang K. Numerical study on the dynamics of wind driven barotropic circulation in the South China Sea (in Chinese). Oceanol Limnol Sin, 2004, 35: 289–298
16 Hwang C W, Chen S A. Circulations and eddies over the South China Sea derived from TOPEX/Poseidon altimetry. J Geophy Res, 2000, 105: 23943–23965
17 Liao G H, Yuan Y C, Xu X H. The three dimensional structure of the circulation in the South China Sea during the winter of 1998 (in Chi-

nese). Acta Oceanol Sin, 2005, 27: 8–17
18 Liu Y G, Yuan Y C, Su J L, et al. Circulation in the South China Sea in summer of 1998. Chin Sci Bull, 2000, 45: 1648–1655
19 Morimoto A, Yoshimoto K, Yanagi T. Characteristics of sea surface circulation and eddy field in the South China Sea revealed by satellite altimetric data. J Oceanogr, 2000, 56: 331–344
20 Xu J D, Li L, Guo X G, et al. Multi-eddy features of the South China Sea circulation around onset of summer monsoon in 1998 (in Chinese). J Trop Oceanogr, 2001, 20: 44–51
21 Chern C S, Wang J. Numerical study of the upper-layer circulation in the South China Sea. J Oceanogr, 2003, 59: 11–24
22 Fang G H, Susanto D, Qiao F L, et al. A note on the South China Sea shallow interocean circulation. Adv Atmos Sci, 2005, 22: 946–954
23 Yang B, Zhao J P, Cao Y, et al. Study of regional ocean circulation numerical model and simulation of the South China Sea circulation and water transport through straits (in Chinese). Adv Mar Sci, 2004, 22: 405–416
24 Yu Z J, Shen S, McCreary J, et al. South China Sea throughflow as evidenced by satellite images and numerical experiments. Geophys Res Lett, 2007, 34: L01601
25 Su J L. Overview of the South China Sea circulation and its dynamics (in Chinese). Acta Oceanol Sin, 2005, 27: 1–8
26 Liu Y G, Yuan Y C, Su J L, et al. South China Sea circulation during the summer of 1998 (in Chinese). Chin Sci Bull (Chin Ver), 2000, 45: 1252–1259
27 Li L. Advance in observational studies of upper layer circulations of the South China Sea (in Chinese). J Oceanogr Taiwan Strait, 2002, 21: 114–125
28 He Z G, Wang D X. Surface pattern of the South China Sea western boundary current in winter. Adv Geosci, 2007, 12: 1–8
29 He Z G, Sui D D. Remote sensing and validation of the South China Sea western boundary current in December 2003, 2004 and 2005. In: Proceeding of Second IITA International Conference on Geoscience and Remote Sensing, 2010, 515–518
30 Yang H J, Liu Q Y, Liu Z Y, et al. A general circulation model study of the dynamics of the upper ocean circulation of the South China Sea. J Geophys Res, 2002, 107: 14pp
31 Cai S Q, Long X M, Wang S A. A model study of the summer southeast Vietnam offshore current in the southern South China Sea. Cont Shelf Res, 2007, 27: 2357–2372
32 Chu P C, Edmons N L, Fan C. Dynamical mechanisms for the South China Sea seasonal circulation and thermohaline variabilities. J Phys Oceanogr, 1999, 29: 2971–2989
33 Wang G H, Chen D J, Su J L. Generation and life cycle of the dipole in the South China Sea summer circulation. J Geophys Res, 2006, 111: C06002
34 Gan J P, Qu T D. Coastal jet separation and associated flow variability in the southwest South China Sea. Deep-Sea Res I, 2008, 55: 1–19
35 Gan J P, Li L, Wang D X, et al. Interaction of a river plume with coastal upwelling in the northeastern South China Sea. Cont Shelf Res, 2009, 29: 728–740
36 Jing Z Y, Qi Y Y, Hua Z L, et al. Numerical study on the summer upwelling system in the northern continental shelf of the South China Sea. Cont Shelf Res, 2009, 29: 467–478
37 Hong B, Wang D X. Sensitivity study of the seasonal mean circulation in the northern South China Sea. Adv Atmos Sci, 2008, 25: 824–840
38 Wang D X, Hong B, Gan J P, et al. Numerical investigation on propulsion of the counter-wind current in the northern South China Sea in winter. Deep-Sea Res I, 2010, 57: 1206–1221
39 Fang W D, Guo J J, Shi P, et al. Low frequency variability of South China Sea surface circulation from 11 years of satellite altimeter data. Geophys Res Lett, 2006, 33: L22612
40 Wu C, Chang C W J. Interannual variability of the South China Sea in a data assimilation model. Geophys Res Lett, 2005, 32: L17611
41 Xing Y S, Cheng G S, Shu Y Q, et al. Anomalous characteristics of the ocean circulation in South China Sea during the El Niño events (in Chinese). Oceanol Limnol Sin, 2012, 43: 201–210
42 Yang H Y, Wu L X. Trends of upper-layer circulation in the South China Sea during 1959–2008. J Geophys Res, 2012, 107: 14
43 Ge L L, Cheng X H, Qi Y Q, et al. Upper-layer geostrophic volume, heat and salt transports across 18°N in the South China Sea (in Chinese). J Trop Oceanogr, 2012, 31: 10–17
44 He Z G, Wang D X, Hu J Y. Features of eddy kinetic energy and variations of upper circulation in the South China Sea. Acta Oceanol Sin, 2002, 21: 305–314
45 Wang L, Koblinsky C J, Howden S. Mesoscale variability in the South China Sea from the TOPEX/Poseidon altimetry data. Deep-Sea Res I, 2000, 47: 681–708
46 Wang G H, Su J L, Chu C. Mesoscale eddies in the South China Sea observed with altimeter data. Geophys Res Lett, 2003, 30: 2121
47 Shaw P T, Chao S Y, Fu L L. Sea surface height variations in the South China Sea from satellite altimetry. Oceanol Acta, 1999, 22: 1–17
48 Li L, Nowlin W D, Su J L. Anti-cyclonic rings from the Kuroshio in the South China Sea. Deep-Sea Res I, 1998, 45: 1469–1482
49 Li Y C, Li L, Lin M S, et al. Observation of memsoscale eddy fields in the sea southwest of Taiwan by TOPEX/Poseidon altimeter data (in Chinese). Acta Oceanol Sin, 2002, 24: 163–170
50 Su J Z, Lu J, Hou Y J, et al. Analysis of satellite-tracked drifting buoys in the South China Sea (in Chinese). Oceanol Limnol Sin, 2002, 33: 121–127
51 Yuan D L, Han W Q, Hu D X. Surface Kuroshio path in the Luzon Strait area derived from satellite remote sensing data. J Geophys Res, 2006, 111: C11007
52 Yuan D L, Han W Q, Hu D X. Anti-cyclonic eddies northwest of Luzon in summer-fall observed by satellite altimeters. Geophys Res Lett, 2007, 34: L13610
53 Su J L. Overview of the South China Sea circulation and its influence on the coastal physical oceanography outside the Pearl River Estuary. Deep-Sea Res, 2004, 24: 1745–1760
54 Jia Y L, Liu Q Y, Liu W T. Primary studies of the mechanism of eddy shedding from the Kuroshio bend in Luzon Strait. J Oceanogr, 2005, 61: 1017–1027
55 Metzger E J, Hurlburt H E. The nondeterministic nature of Kuroshio penetration and eddy shedding in the South China Sea. J Phys Oceanogr, 2001, 31: 1712–1732
56 Jia Y L, Liu Q Y. Eddy shedding from the Kuroshio bend at Luzon Strait. J Oceanogr, 2004, 60: 1063–1069
57 Wang D X, Xu H Z, Lin J, et al. Anti-cyclonic eddies in the northeastern South China Sea during winter 2003/2004. J Oceanogr, 2008, 64: 925–935
58 Nan F, He Z G, Zhou H, et al. Three long-lived anti-cyclonic eddies in the northern South China Sea. J Geophys Res, 2011, 116: C05002
59 Zhang Y. A preliminary observation research of the warm eddy in the western and the warm water in the southern of South China Sea in spring (in Chinese). Dissertation for the Master's Degree. Guangzhou: South China Sea Institute of Oceanology Chinese Academy of Sciences, 2011
60 Gan J P, Li H, Curchitser E N, et al. Modeling South China Sea circulation: Response to seasonal forcing regimes. J Geophys Res, 2006, 111: C06034
61 Shaw P T, Chao S Y, Fu L. Sea surface height variations in the South China Sea from satellite altimetry. Oceanol Acta, 1999, 22: 1–17
62 Ho C R, Zheng Q, Soong Y S, et al. Seasonal variability of sea surface height in the South China Sea observed with TOPEX/Poseidon altimeter data. J Geophys Res, 2000, 105: 13981–13990
63 Shaw P T. Seasonal variation of the intrusion of the Philippine Sea water into the South China Sea. J Geophys Res, 1991, 96: 821–827
64 Qu T D. Upper-layer circulation in the South China Sea. J Phys Oceanogr, 2000, 30: 1450–1460
65 Wu C R, Chiang T L. Mesoscale eddies in the northern South China Sea. Deep Sea Res II, 2007, 54: 1575–1588
66 Wu C R, Chang C W J. Interannual variability of the South China Sea in a data assimilation model. Geophys Res Lett, 2005, 32: L17611
67 Xie S P, Xie Q, Wang D X, et al. Summer upwelling in the South China Sea and its role in regional climate variations. J Geophys Res, 2003, 108: 3261

68 Xie S P, Chang C H, Xie Q, et al. Intraseasonal variability in the summer South China Sea: Wind jet, cold filament, and recirculations. J Geophys Res, 2007,112: C10008

69 Isoguchi O, Kawamura H. MJO-related summer cooling and phytoplankton blooms in the South China Sea in recent years. Geophys Res Lett, 2006, 33: L16615

70 Liu Q Y, Jia Y L, Liu P, et al. Seasonal and intraseasonal thermocline variability in the central South China Sea. Geophys Res Lett, 2001, 28: 4467–4470

71 Fang W D, Fang G H, Shi P, et al. Seasonal structures of upper layer circulation in the southern South China Sea from *in situ* observations. J Geophys Res, 2002,107: 3202

72 Xiu P, Chai F, Shi L, et al. A census of eddy activities in the South China Sea during 1993–2007. J Geophys Res, 2010, 115: C03012

73 Wang G H, Xie S P, Qu T D, et al. Deep South China Sea circulation. Geophys Res Lett, 2011, 38: L05601

74 Hu J Y, Gan J P, Sun Z Y, et al. Observed three-dimensional structure of a cold eddy in the southwestern South China Sea. J Geophys Res, 2011, 116: C05016

75 Chen G X, Hou Y J, Chu X Q. Mesoscale eddies in the South China Sea: Mean properties, spatiotemporal variability and impact on thermohaline structure. J Geophys Res, 2011, 116: C06018

76 Chen G X, Hou Y J, Chu X Q, et al. The variability of eddy kinetic energy in the South China Sea deduced from satellite altimeter data. Chin J Oceanol Limnol, 2009, 27: 943–954

77 Chen G X, Gan J P, Xie Q, et al. Eddy heat and salt transports in the South China Sea and their seasonal modulation. J Geophys Res, 2012, 117: C05021

78 Chu P C, Chang C P. South China Sea warm pool in boreal spring. Adv Atmos Sci, 1997, 14: 195–206

79 Wang W Q, Zhu X H, Hou Y J. The role of ocean dynamics in spring warm pool of the South China Sea (in Chinese). Chin J Atmos Sci, 2005, 29: 565–572

80 Wang D X, Xie Q, Du Y, et al. The 1997–1998 warm event in the South China Sea. Chin Sci Bull, 2002, 47: 1221–1227

81 Gao R Z, Zhou F X. Monsoonal characteristics revealed by intraseasonal variability of sea surface temperature in the South China Sea. Geophys Res Lett, 2001, doi:10.1029/2001GL014225

82 Alexander M A, Blade I, Newman M, et al. The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans. J Clim, 2002, 15: 2205–2231

83 Qu T D, Kim Y Y, Yaremchuk M. Can Luzon Strait transport play a role in conveying the impact of ENSO to the South China Sea? J Clim, 2004, 17: 3644–3657

84 Qu T D, Du Y, Gan J P, et al. Mean seasonal cycle of isothermal depth in the South China Sea. J Geophys Res, 2007, 112: C02020

85 Wang C Z, Wang W Q, Wang D X, et al. Interannual variability of the South China Sea associated with El Niño. J Geophys Res, 2006, 111: C03023

86 Xu H M, Xie S P, Wang Y Q, et al. Orographic effects on South China Sea summer climate. Meteorol Atmos Phys, 2008, 100: 275–289

87 Liu Q Y, Jiang X, Xie S P, et al. A gap in the Indo-Pacific warm pool over the South China Sea in boreal winter. J Geophys Res, 2004, 109: C07012

88 Xie Q, Wu X Y, Yuan W Y, et al. Life cycle of intraseasonal oscillation of summer SST in the western South China Sea. Acta Oceanol Sin, 2007, 26: 1–8

89 Wu X Y, Xie Q, He Z, et al. Free and forced Rossby waves in the western South China Sea inferred from Jason-1 satellite altimetry data. Sensors, 2008, 8: 3633–3642

90 Zhuang W, Xie S P, Wang D X, et al. Intraseasonal variability in sea surface height over the South China Sea. J Geophys Res, 2010, 115: C04010

91 Zeng L L, Wang D X. Intraseasonal variability of latent-heat flux in the South China Sea. Theor Appl Climatol, 2009, 97: 53–64

92 Qu T D, Du Y, Meyers G, et al. Connecting the tropical Pacific with Indian Ocean through South China Sea. Geophys Res Lett, 2005, 32: L24609

93 Wang D X, Liu Q Y, Huang R X, et al. Interannual variability of the South China Sea throughflow inferred from wind data and an ocean data assimilation product. Geophys Res Lett, 2006, 33: L14605

94 Meyers G. Variation of Indonesian throughflow and the El Niño-Southern Osciallation. J Geophys Res, 1996, 101: 12255–12263

95 Wei Z X, Qiao F L, Fang G H, et al. Diagnostic study of the world ocean circulation-current field and stream function (in Chinese). Adv Mar Sci, 2004, 22: 1–14

96 Fang G H, Suisanto D, Soesilo I, et al. A note on the South China Sea interocean circulateon. Adv Atmos Sci, 2005, 22: 946–954

97 Yu Z J, McCreary J, Yaremchuk M, et al. Subsurface salinity balance in the South China Sea. J Phys Oceanogr, 2008, 38: 527–539

98 Lebedev K V, Yaremchuk M. A diagnostic study of the Indonesian throughflow. J Geophys Res, 2000, 105: 11243–11258

99 Yaremchuk M, McCreary J, Yu Z, et al. The South China Sea throughflow retrieved from climatological data. J Phys Oceanogr, 2009, 39: 753–767

100 Qu T D, Du Y, Sasaki H. South China Sea throughflow: A heat and freshwater conveyor. Geophys Res Lett, 2006, 33: L23617

101 Liu Q Y, Huang R X, Wang D X. Implication of the South China Sea throughflow in the interannual variability of the regional upper-ocean heat content. Adv Atmos Sci, 2012, 29: 54–61

102 Tozuka T, Qu T D, Yamagata T. Dramatic impact of the South China Sea on the Indonesian throughflow. Geophys Res Lett, 2007, 34: L12612

103 Wang W W, Wang D X, Zhou W, et al. Impact of the South China Sea throughflow on the Pacific low-latitude western boundary current: a numerical study for seasonal and interannual time scales. Adv Atmos Sci, 2011, 28: 1367–1376

104 Qu T D, Song Y T, Yamagata T. An introduction to the South China Sea throughflow: Its dynamics, variability, and application for climate. Dyn Atmos Oceans, 2009, 47: 3–14

105 Liu Q Y, Wang D X, Zhou W, et al. Covariation of the Indonesian throughflow and South China Sea throughflow associated with the 1976/77 Regime Shift. Adv Atmos Sci, 2010, 27: 87–94

106 Liu Q Y, Huang R X, Wang D X, et al. Interplay between the Indonesian throughflow and the South China Sea throughflow. Chin Sci Bull, 2006, 51: 50–58

107 Du Y, Qu T D. Three inflow pathways of the Indonesian throughflow as seen from the simple ocean data assimilation. Dyn Atmos Oceans, 2010, 50: 233–256