Acta Oceanol. Sin., 2015, Vol. 34, No. 11, P. 1–5
DOI: 10.1007/s13131-015-0754-y
http://www.hyxb.org.cn
E-mail: hyxbe@263.net

Scientific questions about South China Sea ocean dynamics

HUANG Rui Xin[1, 2*], DU Yan[1]

[1] State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China

[2] Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

Received 19 March 2015; accepted 15 May 2015

Abstract

South China Sea, its circulation and connection with other parts of the world oceans, poses important scientific questions. From the prospective view, we postulate ten key research directions to be pursued in the coming future, including ventilation of a monsoon dominated sea, water mass formation/transformation, heat/salt and water mass balance, energetics and mixing, mesoscale eddies, the role of typhoon, deep circulation and paleoclimate records, interaction with adjacent oceans, upwelling and ecology system, and response to climate changes.

Key words: South China Sea, ocean dynamics, circulation, gyre interaction, ventilation, mixing

Citation: Huang Rui Xin, Du Yan. 2015. Scientific questions about South China Sea ocean dynamics. Acta Oceanologica Sinica, 34(11): 1–5, doi: 10.1007/s13131-015-0754-y

1 Introduction

South China Sea (SCS) is one of the largest marginal seas in the world oceans. The SCS is both a marginal sea and a deep sea; its circulation includes both the wind-driven and thermohaline components. SCS is rich in many complicated dynamic processes, including wind-driven gyres forced by wind stress which is also dominated by the annual cycle of the monsoon. SCS is a combination of a marginal sea and a deep sea; thus, its dynamic structure is regulated by turbulent processes taking place in the relatively shallow marginal sea and the deep ocean driven by mechanical energy provided by tides and internal wave breaking. Climate variability signals can be exchanged via both the atmospheric bridge and the oceanic bridge, which can be interpreted as the exchange of energy and other dynamic elements with the open Pacific, through the exchange with the adjacent oceans via the South China Sea Throughflow (SCSTF). Therefore, SCS is a quite unique dynamic system, as sketched in Fig. 1. Due to its small size, it is relatively easy to examine its circulation with fine resolution; thus, the SCS may serve as a mini world ocean, and its study may provide a good example for the circulation in the world oceans.

Furthermore, the SCS is in a regime dominated by strong annual

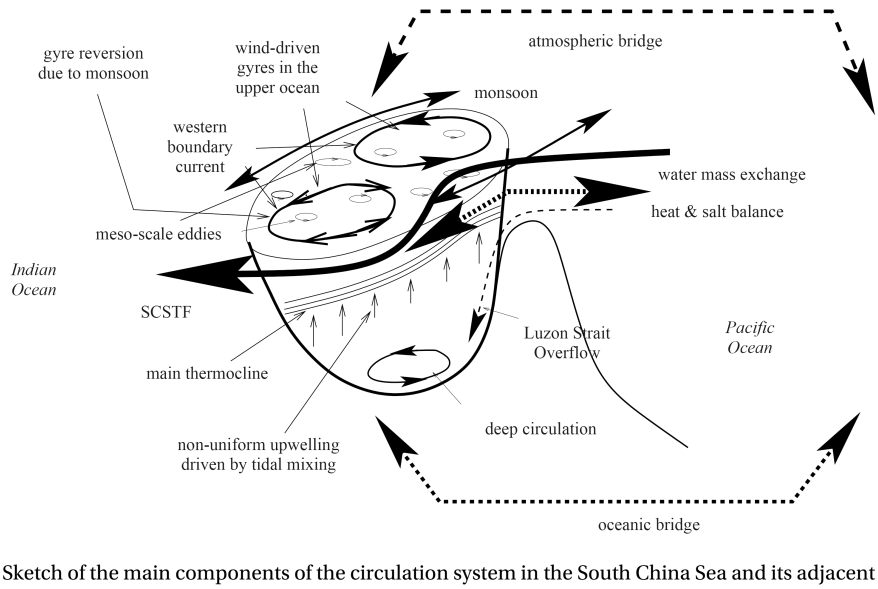

Fig. 1. Sketch of the main components of the circulation system in the South China Sea and its adjacent oceans.

Foundation item: The Strategic Priority Research Program of the Chinese Academy of Sciences under contract Nos XDA11010103 and XDA11010203; the National Natural Science Foundation of China under contract No. 41176024; the Chinese Academy of Sciences/State Administration of Foreign Experts Affairs (CAS/SAFEA) International Partnership Program for Creative Research Teams.

*Corresponding author, E-mail: rhuang@whoi.edu

cycle of monsoon. The SCS also serves as an important connection between Pacific and Indian Oceans. Hence, circulation in the SCS is of great importance for our understanding of the circulation in the world oceans and climate change.

Despite great efforts made over recent decades, many critically important aspects of the SCS circulation remain unclear. For the readers interested in finding out previous results about the SCS circulation, there is a long list of papers about the SCS circulation, and these papers can be found in several comprehensive reviews. Our modest goal in this article is a short list of interesting and important questions to be explored in the coming years. We hope this incomplete list may serve as some starting points for young investigators who might be hungry for meaningful topics.

2 Ventilation of a monsoon dominated sea

In the open oceans, seasonal cycle of wind stress is relatively weak; hence, a theory built on annual mean wind stress is quite useful. In fact, theory of ventilation and structure of the main thermocline associated with wind-driven circulation in the open ocean forced by annual mean wind stress has been developed since 1980s; it is now considered to be more or less completed, with the contributions due to mesoscale and sub-mesoscale eddies to be explored.

On the other hand, for the monsoon dominated seas (such as the Somali coast and the Vietnamese coast) the major part of the wind stress may reverse its direction with season. In these areas the Ekman pumping induced by change in wind stress can vary greatly with season. Therefore, wind-driven circulation, in particular the coast upwelling/downwelling and coastal jet, can change with season greatly.

The wind-driven circulation sets up the ventilation of the thermocline and water mass formation/erosion in the upper ocean. Some of the typical diagnosis tools of water mass formation have been developed, such as the annual mean subduction and obduction rates, which are well-defined for the open ocean without strong monsoon components in wind stress.

Structure of the wind-driven gyre and ventilation of a basin, such as the SCS, dominated by monsoon winds has received little attention. Many questions remain open: Can we construct a simple model for the wind-driven gyre with strong seasonal cycle in a monsoon-dominated basin? What is the fundamental character of the thermocline in a monsoon-dominated closed basin?

3 Water mass formation/erosion and transformation

In a semi-closed basin like the SCS, water mass transformation includes contribution due to the local dynamics and the exchange with the open ocean, such as the Western Pacific and Eastern Indian Oceans. In fact, water mass formation/erosion in the SCS should consist of following three equally important components.

First, water mass formation in the upper ocean is linked to subduction/obduction. Annual mean subduction/obduction rate in the open ocean is defined in terms of a 12 month period of effective subduction/obduction. In the case of a monsoon dominated basin, using such a 12 month period of time window may not be the best way. Can we define something equivalent, but suitable for the semi-annual cycle of wind stress? Can we use a 6 month window to define something called semi-subduction and semi-obduction by following trajectories released from the base on the mixed layer in the month of its annual maximum depth?

Second, the SCS is located at low latitudes where winter temperature is much higher than the corresponding potential temperature of the bottom water; thus, deep water masses found at the bottom level of the SCS cannot be formed locally; instead, they must be formed outside the basin and imported through the deepest sill, the Luzon Strait. The exchange of the deep water overflow through the Luzon Strait involves complicated dynamics; the rate of exchange and its variability with the season and other factors remains unclear.

Besides, all water masses below the ventilation thermocline (about 120 m) must originate from the adjacent oceans; through mixing (driven by eddies, tides, and internal waves in the SCS) they give rise to the water masses observed in the SCS. Luzon Strait is the only passage for the subsurface high salinity water (about 150 m) and intermediate layer of low salinity water (about 500 m) from the Pacific to enter the SCS. The open questions: how does the Pacific water intrude the SCS? Can we separate the intrusion into two components: the quasi-constant inflow/throughflow and intermittent leakage? What is role of mesoscale eddies?

Thirds, due to diapycnal mixing driven by tidal dissipation, the cold and dense deep water masses upwell and become the modified water masses at shallower levels where they are exchanged and mixed with the open ocean through straits like the Luzon Strait and other channels. The exchange of water masses at shallower levels can be directly linked to the pressure difference at the corresponding levels, which in turn is closely linked to the entire circulation system. What really controls the water mass exchange at shallow levels? Forcing factors inducing climate variability may include the surface wind stress and thermohaline forcing within the SCS and in the adjacent open ocean; however, which one really plays the dominating role?

4 Balance of heat, salt and freshwater

Balance of heat, freshwater, and salt is an important part of the circulation; these fluxes are closely related to mass transport in the ocean. On the average, the SCS receives heat flux from atmosphere at a rate of 10–50 W/m^2, i.e., a total heat gain of (0.1–0.2)×10^{15} W. With the deep atmospheric convection over the region, the annual mean precipitation minus evaporation plus river discharge is about (0.2–0.3)×10^6 m^3/s. The input of heat and freshwater must be balanced through exchange with the adjacent seas, in particular through the Indonesian Seas and conveyed to the Indian Ocean.

Air-sea flux observations (e.g., shortwave radiation, latent heat flux, precipitation) are inadequate and inaccurate to provide reliable estimates of the salt, freshwater, and heat fluxes, and, water exchange; its contribution on the thermal stratification in and out of the SCS are hardly investigated. Thus, we are facing the challenge: can we explain the climate variability in this region?

Most numerical models do not conserve internal energy, or the commonly called heat content. If numerical models are used in diagnosis, then mass conservation in the diagnosis may be a critical issue. First, most numerical models are based on volume conservation, plus the assumption of constant specific heat under constant pressure. A model which truly conserves heat should be based on mass conservation, plus a variable heat capacity under constant pressure. Such a model is not currently available. Furthermore, in most models with data assimilation heat conserving is further damaged in the process of applying the data assimilation schemes which completely ignores the conservation of energy.

In terms of diagnosis of salt and freshwater fluxes, the situation is even worse. As most models are based on the so-called Boussinesq Approximations, the mass conservation law is replaced by the volume conservation approximation. As such, the *in-situ* salinity, which is defined in terms of mass fraction, is replaced by the volume concentration of salt. For example, in the deep ocean the *in-situ* density of sea water can be as high as 1 060 kg/m^3; thus, ignoring the mass conservation may introduce errors on the order of a few percentages.

In the ocean there are two fluxes related to salt transport: the salt flux and the freshwater flux. However, in a volume conserving model, there is only one flux — the virtual salt flux, and it may not have a clear physical meaning. In fact, only under very restricted assumptions, the virtual salt flux diagnosed from a Boussinesq model can be interpreted as an equivalent freshwater flux, after multiplying a factor and flipping the direction. Can we interpret the physical meaning of the time-dependent virtual salt flux diagnosed from such models?

5 Role of typhoon

The SCS is rich in typhoon, and typhoons can be generated within the SCS or imported from the open Pacific. Although typhoons are the product of the air-coupled system, the role of typhoon in oceanic circulation and ecology can be explored from the oceanic point of view.

Typhoons contribute mechanical energy into the ocean through: surface waves, geostrophic and ageostrophic flows in the surface, plus the near inertial waves which may penetrate deep into the subsurface ocean.

The SCS is one of the places in the world oceans where typhoon activity is very strong, and thus mechanical energy from typhoons can be a substantial part of the basin energy budget.

Due to energy input from typhoons, diapycnal mixing rate in the SCS can be substantially higher than other parts of the world oceans. The strength and frequency of typhoons in the SCS vary greatly on interannual and decadal time scales. The open questions are: how does the impact of typhoons to the circulation in the SCS vary on decadal time scales? How will typhoon's role vary with global warming?

In addition, typhoons are closely linked to the ecologic activity in the ocean, through upwelling and diapycnal mixing. Due to the strong wind stress associated with the cyclonic eddy in the atmosphere, there is strong upwelling associated with moving core of the typhoons. The strong stirring associated with the turbulent energy from the typhoons also gives rise to strong diapycnal mixing; as result, ecologic activity is enhanced. Can we provide accurate account of how much the nutrients are brought from the subsurface ocean into the upper ocean and what happens, if the strength and frequency of typhoon changes?

6 Deep current, bottom boundary layer, sediments and paleoclimate records

Deep circulation in the SCS remains a most challenging target. With advance in observation programs, the situation may change soon. Conceptually, deep water overflow the Luzon Strait may follow a cyclonic path around the edge of the SCS. Due the complicated bottom topography, the exact pathway of the deep circulation remains unclear. In the simplest tube model, the trajectory of the deep water is controlled by the competition between the gravity force, the Coriolis force, and the bottom drag; the major unknown is the mixing with the environmental water, which depends on dynamical of the bottom boundary layers.

Bottom boundary layers can exist in many different forms, depending on which dynamical process is dominating. If the downstream topographic slope is large, i.e., the flow is moving down a steep path, the turbulent activity of the flow is sustained by the conversion from the kinetic energy of the mean flow; as a result, the boundary layer can be quite thick. On the other hand, over relatively gentle slope, the turbulent activity is weak, and the boundary layer is relatively thin.

There is however, another type of bottom boundary layer which is primarily regulated by the strong diapycnal mixing induced by baroclinic tidal dissipation, as indicated by observations in the Brazil Basin. Due to strong baroclinic tidal breaking, bottom boundary layer can have thickness on the order to 800–1 000 m. Flows within such bottom boundary layers are primarily regulated by the mixing controlled stratification and topography in the vicinity of the bottom.

Sediment dynamics is vitally important for our understanding of paleoclimate records; but, without the accurate knowledge of dynamics of the bottom boundary layer, it is impossible to understand the sedimentation process. However, due to the difficulty in collecting data from great depth and the focus of climate on relatively short time scale, study and simulation of bottom boundary layer remains a great challenge. Most oceanic general circulation models pay no special attention to resolve the bottom boundary layer; thus, rather coarse vertical resolution (about 100 m) is used in general. As such, the structure of the bottom boundary in the SCS remains unknown. Can we build up a model which can resolve the bottom boundary layer in the SCS?

The core of sedimentation dynamics is basically the bottom boundary layer coupled to the two-phase fluid dynamics with turbulence. Sediments in the SCS is a treasure box for reconstructing the climate changes associated with the plate tectonic movement, the formation of the Himalaya Plateau and the establishment of monsoon in the Asia and in the Pacific and Indian Oceans, plus its variability. These are clearly many open questions waiting for answers.

7 Interaction with North Pacific and South China Sea Throughflow

The SCS is located in the western edge of the North Pacific. Thus, signals (momentum or pressure gradient forces; different forms of energy, including kinetic energy, internal energy of the mean state and the mesoscale eddies) generated in the Pacific interior can travel westward and thus affect many aspects of the SCS circulation, such as the interior circulation and the western boundary currents.

The feedback of the SCS circulation to the open Pacific remains, however, unexplored. Exchange of water between SCS and North Pacific can be treated in terms as a water mass source/sink along the western boundary, which can affect the western boundary currents in the open Pacific. It is well known that the exchange through the Luzon Strait appears in the form of a sandwich, i.e., inflow near the 2 000 m level or below, outflow at the mid-depth and exchange in both directions near the surface. The exchange of water masses at different depths serve as source/sink and affect the western boundary currents in the open Pacific at the corresponding depth. How do these sources/sinks affect the bifurcation latitude of the western boundary current in the North Pacific?

Furthermore, water mass transformation within the SCS is a non-negligible part of the water mass transformation in the entire North Pacific. Cold and dense water masses formed at high latitudes must mix with warm light water above and return to surface, and external sources of mechanical energy are consumed; such mechanical energy in the deep ocean is closely linked to tidal dissipation associated with steep and rough bottom topography.

Tidal dissipation in the open North Pacific seems weak in general, with a few exceptions, such as near the Hawaii Islands. As a result, diapycnal mixing rate in the open Pacific is relatively low. The thermohaline circulation in the North Pacific may be a special case in which water mass transformation takes place primarily in the marginal seas, such as the SCS, the Japan Sea, and the Okhotsk Sea. How much does water mass transformation in the SCS contribute to the thermohaline circulation and water mass transformation in the entire Pacific?

Recently, the conveyer belt transporting the Northwest Pacific water at the Luzon Strait, passing the SCS, to the adjacent seas was named as South China Sea Throughflow (SCSTF). There are many open questions about the SCSTF: What is the major driver of the SCSTF? Does it feedback to large circulation system in the Indo-Western Pacific? Since a major part of the inflow water comes from the deep Pacific; thus, the natural question is: how does the hydraulic-driven deep overflow couple with intermediate and upper ocean circulations? How does it return to the upper ocean and what is the final destiny of SCSTF water? Which pathway is the pivotal passage, Mindoro Strait or Karimata Strait? Do the mesoscale/wave activities play an important role in the processes?

Island Rule has been used to evaluate the SCSTF, i.e., wind stress is taken as the important player. However, mixing in the SCS might play certain role. Can we make a link between SCSTF with mixing and stratification in the SCS and adjacent oceans?

8 Response to ENSO and global warming

Climate variability, such as ENSO and global warming, can affect the SCS through the atmospheric bridge and oceanic bridge. The connection/feedback between the atmospheric bridge and oceanic bridge might be the key to understand the variety of the elusive character of the regional oceanography and regional climate.

Through the atmospheric bridge, ENSO can impact on the SCS directly or indirectly. Changes in atmospheric circulation and cloud cover cause the simultaneous response of the SCS to ENSO. Observations indicate that the SCS also bears dramatic changes in the summer following ENSO. The tropical Indian Ocean basin-wide warming/cooling (IOB) is regarded as a major cause. A local climate driver, anomalous atmospheric circulation in the Northwest Pacific, or Pacific-Japan/East Asian-Pacific (PJ/EAP) pattern, might be important as well. An interesting question is how to separate the contributions of local forcing from remote forcing.

The oceanic bridge includes exchange of dynamic information through many channels linking the SCS with the Pacific and Indian Oceans. There are many open questions: how does the baroclinic flow through the Luzon Strait respond to ENSO or other climate modes? Which ocean dynamics regulate these exchanges? What is the role played by the wind-driven circulation and thermocline circulation in the adjacent oceans?

Wind-driven circulation in the SCS is primarily controlled by wind stress, so that its response to climate variability is mostly through the atmosphere bridge. On the other hand, thermohaline circulation requires sources of external mechanical energy from wind and tides; thus, thermohaline circulation in the SCS is regulated by mixing and surface fluxes, including wind stress and thermohaline forcing.

Wind energy input into the interior of the SCS may primarily due to the contribution of the atmospheric bridge. Variability of the tidal dissipation associated with climate variability may be quite different from that of wind. It is well known that a large fraction of tidal energy dissipated in the SCS comes from the open Pacific. Such energy input may sensitively depend on the stratification in the SCS, which vary with the climate. Therefore, baroclinic tidal energy exchange through the Luzon Strait may be the combining result of the oceanic bridge and the atmospheric bridge.

As the consequence of global warming, many aspects change gradually, including the atmospheric circulation (and thus the wind), the mean sea level, the surface heat and freshwater fluxes. Observations indicated that the SCS is a region undergoing the most robust warming trend in the global ocean. Sea level observations show that both natural decadal-variability and long term change are significant. However, what happens in the deep SCS basin? Even in the upper layer, it remains unclear how to separate the contribution of the natural forcing from anthropological forcing in the East Asian Marginal Seas, including the SCS.

In general, climate anomalous signals in the world oceans can be classified into three basic categories: warming/cooling, freshening/salinification, and heaving. Heaving is isopycnal motions subject to no heat and salinity exchange with the environment, and they represent the adiabatic motions induced by wind stress. Can we identify these components of climate variability in the SCS?

9 Mesoscale eddies/waves activity

Most previous studies are focused on basin scale circulation, but the role of mesoscale eddy remains unclear. Collecting data on such refined scales require new generation of instruments. There is certainly new development along this line, such as the expansion of the ARGO program, automatic instruments, such as glider, and seismic oceanography.

It is a top priority to know the three-dimensional structure of mesoscale eddies; however, we do not have much data for revealing the three-dimensional structure of mesoscale eddies. Although recent study indicated that on the lowest order, mesoscale eddies in the world ocean may have some kind of universal structure in the stratification stretched z-coordinate. It is however, inconceivable that mesoscale eddies in the world oceans should have a universal structure to higher order. In contrast, mesoscale eddies in different parts of the world oceans should have special characters which is due to the dynamic environment when they are generated and where they survive, such as the stratification and horizontal/vertical shear of the currents.

The well-known example of the eddy's role in regulating the large-scale circulation is the so-called eddy saturation associated with the Antarctic Circumpolar Currents (ACC). Previous studies indicated that if eddies were not resolved in the model, the zonal volume flux of the ACC increase with the amplification of zonal wind stress. On the other hand, for eddy resolving or eddy permitting models, although the transport of the ACC increases with the zonal wind stress, after the zonal transport of the ACC reaches a plateau, it will be level off, despite of further increase of zonal wind stress. Physically, the extra amount of wind energy input is consumed by the mesoscale eddies. This example demonstrates that eddies may play a critical role in regulating the wind-driven circulation in the ocean.

Eddies in the ocean can be generated through many different dynamical processes, such as the atmospheric forcing, the barotropic and baroclinic instability of the oceanic state. The SCS is very rich in eddies. In fact, for a semi-closed basin like the SCS, eddies can be generated outside the basin and then transported into the basin. The Luzon Strait may provide such a channel. In particular, the Kuroshio bifurcation or intrusion may provide a suitable dynamical mechanism for sending new eddies into the SCS. There is, however, a controversial issue.

Identifying westward perturbations through the Luzon Strait from altimetry data may be difficult. In fact, satellite data analysis showed only a few eddies/waves passing through the strait. However, there is other possibility — the Luzon Strait may work as a tunnel through which the perturbation energy associated with eddies/waves can pass through and re-emergent in the interior of the SCS. If this is the case, then how much energy does this mechanism contribute to the eddy/wave energetics in the SCS? Similarly, we want to know: how much kinetic energy is transferred through passages linking the SCS with adjacent seas?

The Rossby waves formed in the Pacific encounter the west boundary and might leak the energy into the SCS through the straits around the Philippine Islands in the form of coastal Kelvin waves. There are also coastal Kelvin waves moving around the deep part of the SCS basin. How much energy is dissipated along their path?

10 Upwelling and ecology system

Nutrient concentration in the upper ocean is low, but it is high in the deep ocean; hence, upwelling is a critically important mechanism to bring the rich nutrients from the subsurface to the upper ocean and thus maintain the ecology activity in the oceans.

Coastal upwelling in the SCS is one of the most outstanding features during summer. The southwest monsoon is the dominant player driving the persistent summer upwelling in the northern shelf and western coast of the SCS. Tidal mixing triggers the coastal upwelling in the west coast of Hainan. In fall and winter seasons, northeast monsoon drives divergence in most part of the SCS, gives rise to upward motions and thermocline shoaling. As a result, primary productivity is high and ecology system has rich variety in the SCS basin.

The Ekman suction in the interior of cyclonic wind-driven gyre gives rise to gyre-wise upwelling, which rate is relatively low, and insufficient for sustaining strong ecological activity. However, other dynamic processes can generate strong upwelling: coastal upwelling induced by along shore wind, upwelling induced by tidal mixing, upwelling induced by typhoon, and upwelling induced by flow over topography and coastal geometry.

In addition, upwelling associated with the sub-mesoscale fronts along the edge of mesoscale eddies can be quite strong and thus contribute to the enhancement of ecological activity in the SCS. Note that the dynamic processes associated with the sub-mesoscale fronts may vary greatly, depending on the background currents and stratification; thus, a clear dynamical picture of such effect remains to be explored.

11 Energetics and mixing

Energetics of a semi-closed basin is a fundamental aspect of the circulation system; it includes the balance of all forms of energy, such as internal energy (or enthalpy) and mechanical energy. The balance of mechanical energy should include kinetic energy and gravitational potential energy. Thermohaline circulation in the ocean is a dissipation system; as such, the maintenance of the thermohaline circulation requires the external sources of mechanical energy, and variability of such sources play critical role in regulating the circulation in the ocean.

Mechanical energy from wind includes the energy input through the surface geostrophic flows, the energy input to the ageostrophic flows associated with the Ekman layer, and the energy input through the surface waves. For a semi-closed basin like SCS, the open questions are: how much the wind energy input varies with climate? What is the exchange of wind-generated mechanical energy input through the Luzon Strait and other straits? How does this exchange vary with time?

Tidal dissipation is a direct source of kinetic energy sustaining turbulence and mixing in the coastal area and the deep ocean. For a semi-closed basin like the SCS, the exchange of tidal energy through the connecting oceans is an important part of the basin budget. It is estimated that 3/4 of the tidal dissipation energy comes from the open Pacific. Tidal flow and the associated energy import from the open Pacific may depend on the current state of three-dimensional stratification in SCS, which in turn is regulated by wind and surface thermohaline forcing, plus tidal dissipation (a typical chicken and egg problem). Furthermore, it may depend on the history of the circulation, such as wind energy input, in particular, the energy input from typhoon in SCS.

Finally, the circulation in SCS (in particular the SCSTF) is intimately related to diapycnal mixing sustained by the external sources of mechanical energy. The balance of mechanical energy, including the exchange of energy through the open straits may depend on the competition of wind, surface thermohaline forcing, and tidal energy both inside the semi-closed basin and the adjacent open oceans. In particular, both the surface thermohaline forcing and mechanical energy input play their own roles, but which one is the dominating player remains unclear. The related questions are: How big is the tidal energy input? What is the dominating factor regulating this energy? How does it vary on different time scales?