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# REVIEW OF CURRENT CIRCULATION STUDIES IN THE SOUTHERN SOUTH CHINA SEA

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**Abstract:** Studies of current circulations research progress in the region of the southern South China Sea (SCS) are reviewed. Scientific research exploration in the area is relatively low compared to other areas in the SCS, thus the understanding of the current system and its dynamics are lacking. In general, SCS basins circulation is influenced by monsoon seasons which provide cyclonic circulation in winter (northeast monsoon) and anti-cyclonic circulation in summer (southwest monsoon). Near Peninsular Malaysia, the alongshore current which is part of the bigger circulation flow southward/northward during winter/summer, respectively. Recently, numerical modeling studies are able to provide more insight of the dynamics by illustrating the influence of bathymetry on circulation and the formation of subsurface eddys in the middle of the region. Furthermore, the current circulation pattern changes throughout monsoon seasons and transition monsoon period were elaborated. This review gathers properties and current dynamics from field observation and numerical models research and summarized it in terms of the SCS seasonal circulation and interaction between the main basins and the southern region of Peninsular Malaysia.

KEYWORDS: South China Sea, current circulation, Peninsular Malaysia, Sunda shelf, field measurement, monsoon, numerical model.

## Introduction

The SSCS is a semi-enclosed tropical continental shelf sea primarily located between the east coast of Peninsular Malaysia and the island of Malacca. The region includes the Vietnam coast to the north, Borneo to the southeast, Indonesia to the south and the Gulf of Thailand (Figure 1). It consists primarily of the Sunda shelf, a shallow continental shelf with an almost consistent depth of ~ 60 m. At the southeast, near Borneo, the continental shelf connects to the main SCS deep basin where the depth increases rapidly up to 2000 m at the continental slope.

The SCS is subjected to seasonal monsoon cycles (Dale, 1956; Wyrtki, 1961; Shaw and Chao, 1994; Saadon and Camerlengo, 1996; Mao, 1999; Hu *et al.*, 2000). The northeast monsoon dominates the SSCS region from November to March, which results in strong north easterly monsoon wind stress. This strong monsoon wind causes a strong south westerly current at the east coast of Peninsular Malaysia. Meanwhile, the southwest monsoon dominates the SSCS region from April to August. Relatively weaker south westerly summer monsoon wind stress results in a wind stress that drives a northward coastal current off east coast of Peninsular Malaysia.

In terms of scientific exploration, the physical oceanography of the southern South China Sea (SSCS) was documented extensively by Wyrtki (1961) in his scientific report of marine investigations of the South China Sea and the Gulf of Thailand during 1959-1961 (NAGA report). The report is still considered a *magnum opus* for SCS oceanographic study, especially in the region of the southern Sunda shelf, where data and understanding of regional oceanographic processes is very limited. Later, few major cruises took place, named the Matahari Expedition (1985-1986), South East Asian Fisheries Development Centre (SEAFDEC) Cruise (1995-1996), and South China Sea Expedition (2002-2007). These cruises remain among the most comprehensive fieldwork ever conducted in the area.

Geographically, SCS basin is separated into northern and southern zones. The northern part of the basin covers most of the middle and northern part of the sea and has received attention from researchers since the 1980's (Xu *et al.*, 1982; Hu *et al.*, 2001). Field data becoming more abundant and the research subsequently increased oceanographic understanding of the region. The southern zone, which encompasses the SSCS received less attention, reflect of limited data and scientific publications. Only a few publications include the SSCS system as part of the presented data (Chu *et al.*, 1999; Fang *et al.*, 2002; Wendong *et al.*, 2002). Most publications have focused on the northern region of the SCS instead.

Satellite and remote sensing technology, and the advancement of numerical modeling in oceanography has added more data to the oceanographic research in the region. Studies of global ocean models using Ocean Circulation and Climate Advanced Modelling project (OCCAM) results have been conducted by Akhir (2012) and has given new insight into how numerical models can contribute to the study of the SSCS. Tangang *et al.,* (2011) provided a very comprehensive modeling study which explains in detail the dynamics of the circulation. Numerical modeling has become a method that attracts many oceanographers, but this effort is still new in the region and has huge potential in the near future.

This review paper compiles some of the significant efforts that have expanded knowledge of the circulation in SSCS. The main content will discuss physical oceanography which concentrate on the current circulation in the region through two perspectives, observational field data and numerical modeling analysis.

## History of Field Data Collection in the Southern South China Sea

In the late 1950's, large amounts of oceanographic data were gathered by Wyrtki (1961) during his investigation of oceanographic properties in the SCS. The effort was novel, and gathered baseline information on the physical oceanography of the area. It wasn't until 1985 that another important and significant cruise was organized in the area of the SSCS near Terengganu (5.5 °N, 104 °E). The cruise was a joint effort between the Malaysian and Japanese governments known as the Matahari Expedition. This became a benchmark for several other expedition cruises held afterwards.

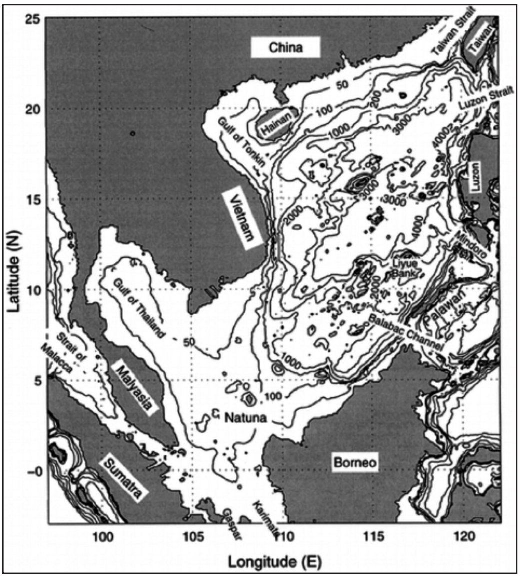

Figure 1: Bathymetry of the South China Sea
Note: Dotted line is the area referred in this study as SSCS. Adapted from Chu *et al.,* (1999).

SEAFDEC carried out two intensive field observation campaigns for oceanographic data collection in the western part of the Gulf of Thailand and the SCS near Peninsular Malaysia in September 1995 and April-May1996. The first trip was conducted from 5-28 September 1995 (before the northeast (NE) monsoon season) and from 24 April to 17 May 1996 (after the NE monsoon season). The cruises started at the northern coast of the Gulf of Thailand and ended at the southern coast of Johor, Peninsular Malaysia, covering more than 80 sampling stations (Saadon *et al.*, 1997) (Figure 2). This cruise considered to be the first cruise that provide a significant amount of oceanographic data along the east coast of Peninsular Malaysia.

Later, under the stewardship of the Institute of Oceanography (INOS), Kolej Universiti Sains dan Teknologi Malaysia (KUSTEM), six cruise expeditions were conducted to enhance scientific knowledge on the productivity and oceanographic processes in the SSCS (Figure 2). The three-year coastal oceanographic cruise program managed to answer those needs. The cruise series was one of the greatest achievements for oceanographic studies in the region. The resolution of the data coverage is finer than the SEAFDEC cruise (81 stations) and the NAGA Expedition (47 stations). Nonetheless, the output from the data are not well documented. Very little publication or results were published so far which explain physical oceanography of Pahang and Johor area (Akhir and Yong, 2011; Roseli and Akhir, 2014).

These cruises have contributed priceless oceanographic data on the SSCS. Nevertheless, advancement in ocean technology has allowed other methods to provide better input in terms of data and understanding towards the ocean processes and dynamics. For example, satellite and remote sensing technology, and numerical modeling in oceanography managed to compliment field research and enhance our understanding of the ocean. Although they may not completely replace field work, they did so far compelement and advance the progress of the valuable oceanographic research in this region. For the past 20 years, many researches using these new technology has contributed significantly in producing new output and understanding which is almost impossible to be derived base on the available field data alone.

## Physical Oceanography of the Southern South China Sea

### *Circulation Pattern and Water Characteristics from Field Observations*

Observational studies on SSCS circulation indicate that the entire basins of the SCS are under the influence of the monsoon system. Reversal of wind systems cause the direction of circulation to change according to the monsoon seasons. Early hydrographic charts prepared by the U.S. Navy (1945) support this argument and were later documented by Dale (1956) and Wyrtki (1961). Both agreed that the seasonal circulation in the SSCS basins are forced by monsoon winds (Figure 3a and 3b). Xu *et al.,* (1982) gathered historical observation data from 1921 to 1970 while conducting intensive studies on the physical oceanography of the SCS. The study indicates seasonal characteristics of current patterns affecting the SCS basins. The dynamics of the system were similar to earlier findings, but new eddy systems within the basins were also noted.

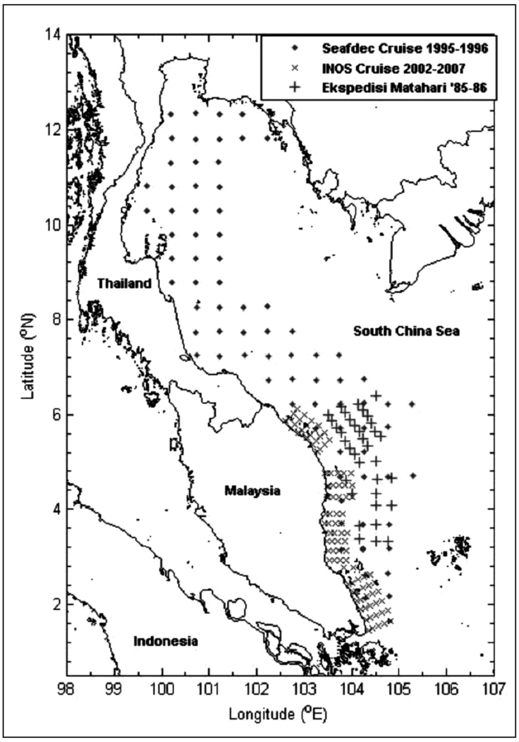

Figure 2: Sampling Stations along Peninsular Malaysia from Three Main Cruises between 1995-2007

Near the SSCS basins, a cyclonic eddy was observed during the winter monsoon between 5-10 °N. During the summer monsoon, an anti-cyclonic eddy covered the entire southern basins (Xu *et al.*, 1982). Later, studies using geostrophic current fields showed similar circulation patterns where the existence of eddy during both winter and summer were obvious (Yu and Liu, 1993; Rong, 1994). A research conducted using Levitus (1982) climatological data identified annual and seasonal surface elevation and geostrophic surface current, which further confirmed the circulation pattern involving eddy systems in the region (Zhou *et al.*, 1995).

To date, areas in the SSCS basins have not been studied sufficiently. Very low resolution of temporal data limits understanding of current circulation in the area. The earliest cruises mainly published data on current circulation. The eddy circulation pattern in the middle of the SSCS basins is closely related to that of the southern part, especially along Peninsular Malaysia. Previous field studies indicate that the current flows southward along the coast of Peninsular Malaysia during the winter monsoon and reverses during the summer monsoon.

Water characteristics also have seasonal influences. Studies of historical data and climatological temperature-salinity in the SCS are closely related to wind stress curl and eddy circulation (Qu *et al.*, 2000). Despite the strong influence of wind stress curl during monsoon, in the southern region of Peninsular Malaysia, studies during the transitional periods of monsoon show different characteristics. Data from the SEAFDEC Cruise shows stratification was likely to happen during the months of April and May, while during the month of September the water is less stratified (Yanagi *et al.*, 2001). Sea surface wind, heat flux, river discharge, and density-driven and wind-driven currents influence the stratification and mixing during the monsoon periods. Local influence, such as influx, is considered important considering the location on the continental shelf. During April, large sea surface heating and weak sea surface wind develop stratification, while during September, river discharge, increased wind stress and overcast skies reduce the stratification. Similar observations were discovered when analyzing SCS Expedition data near the Johor area (Akhir and Yong, 2011).

The distribution of sea surface temperature also changes with the monsoon. The winter monsoon (November-April) usually increases the cold water influx from the north into the region and consequently deepens the thermocline layer. An increase of surface water temperature of around 1 °C and results in a shallower thermocline during the southwest monsoon (Camerlengo and Saadon, 1996). Although advection of cold water from SCS basin circulation contributes to the temperature distribution change between the monsoons, the effects of atmospheric influence also plays a role. This change is part of the exchange experience during the height of monsoon season, where density-driven and wind-driven currents transport water into the region and subsequently alter water characteristics.

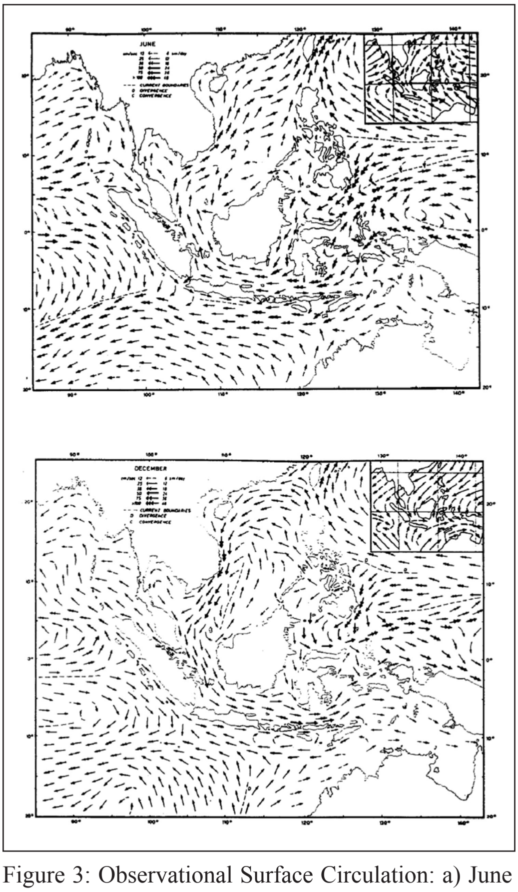

Figure 3: Observational Surface Circulation: a) June and b) December (after Wyrtki, 1961)

### *Circulation Pattern and Water Characteristics from Numerical Models*

Numerical models have become very important tools in oceanographic studies, especially in the area of the SCS. Chu *et al.,* (1998) earlier work has been followed by several modeling studies of SCS basins. SCS circulation carried out by Chu *et al.,* (1999), is one of the most comprehensive analyses to provide an overall view of spatial, seasonal and dynamic study of the circulation system. Such work has been essential in overcoming limitations on spatial and temporal data coverage and resolution. The basic intention of numerical modeling is to compliment observation data and reduce its limitations. Observation data is still important to confirm findings from numerical models. The SCS region has benefited remarkably from this combination of research methods.

For a comparison study, circulation for the month of September and December was selected to represent southwest monsoon and northeast monsoon accordingly. During these months, the current circulation of the SCS basins gains significant speed due to the influences of the southwest monsoon (September) and northeast monsoon (December). During September, the inflow agrees with Chu *et al.,* (1999) that the surface circulation generally exhibits anti cyclonicity in the southern basin (Figure 4b). The model also clearly shows the inflow from the Karimata Straits in the south and the outflow through the Taiwan Straits in the North and eastern Luzon Straits. Strong current along the Vietnam coast (western boundary current) also presents (Figure 5). Chu *et al.,* (1999) suggested that the western boundary current splits into two at 12 °N. An OCCAM model showed similar results although slightly south at 10 °N (Akhir, 2012).

During the northeast monsoon, the current intensifies, starting from the Taiwan coast (20 °N), and flows south along the Vietnam coast. The flow spreads and becomes wider as it leaves the Vietnam coast and approaches Peninsular Malaysia. Again, this is similar to simulated results produced earlier by Chu *et al.,* (1999). The presence of the anticyclonic Natuna Eddy was also predicted from the model with a location at 5 °N (Figure 4b and 6).

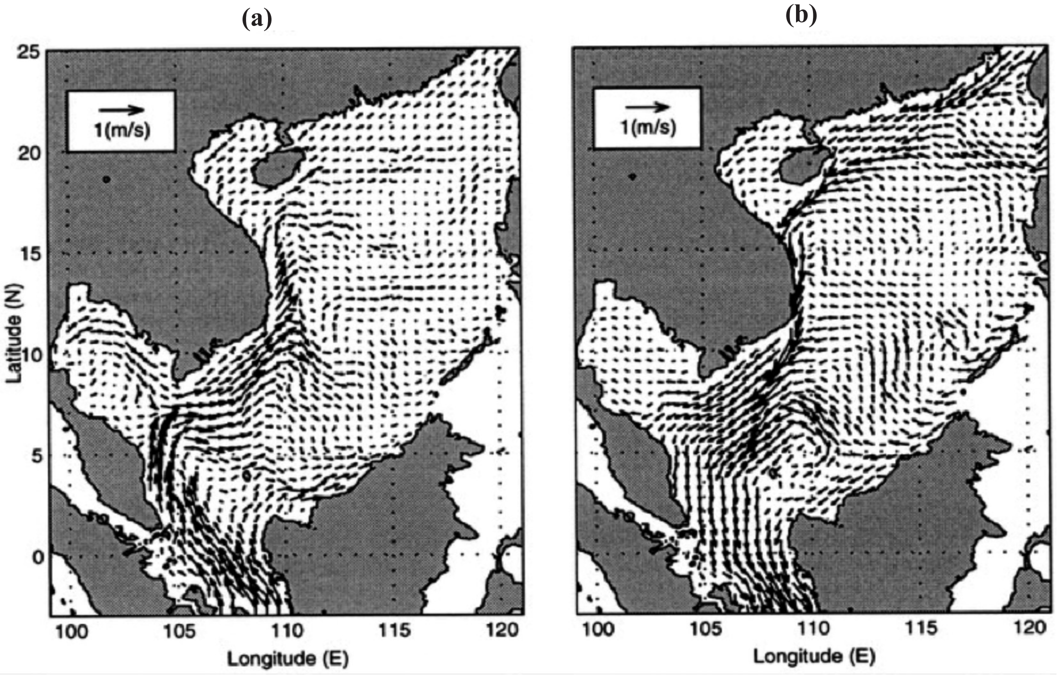

Figure 4: Mean Surface Circulation for Control Run During: a) Summer and b) Winter (after Chu *et al.*, 1999)

Previous studies demonstrated important eddies present during both monsoon seasons. Xu *et al.,* (1982) pointed out the presence of cyclonic eddy in the SSCS during winter. The study's model data predicted the Natuna Eddy's size and position. In summer, a small cyclonic eddy off the Vietnam coast was clearly demonstrated by the model. Both eddies featured in the subsequent monsoon seasons and agree with hydrographical data determined by Xu *et al.,* (1982). This was later confirmed by Zhou *et al.,* (1995) who used the Levitus (1982) climatological data set to diagnose annual and seasonal surface elevations of the SCS.

Throughout the model, the circulation within the SSCS area was clearly distinguishable compared to SCS central basins. Meanders flows, observed along the strong current,were one distinct difference from the model results, compared to the previous models, i.e. Chu *et al.,* (1999), which showed a much smoother flow. Nonetheless, this meanders does not alter the main circulation. The best explanation for the meanders presence in the model results is the vorticity equation used in the OCCAM model. By utilizing the complete depth-integrated vorticity equation, it was found that bottom pressure torques balance the advection of planetary vorticity in both the surface and bottom (Saunders *et al.*, 1999).

One of the most comprehensive models ever conducted for the whole SCS region was the study of the seasonal ocean circulation structure in the SCS by Chu *et al.,* (1999) using the Princeton Ocean Model (POM). The objective of the study was to simulate the overall circulation of the SCS and to define the thermohaline structure with regards to seasonal variability. Although the study covered the entire SCS, the output of the study indirectly resolve the circulation patterns within the scope of the SSCS.

In general, the circulation was similar to earlier findings, with anticyclonic summer circulation and cyclonic winter circulation. The details of the study provide an important dynamic explanation about the structure of circulation systems. Sea surface heights for the winter showed a 0.2-m depression over the deep basin in the centre of the SSCS, with maximum values in the southwestern part over the Sunda shelf and the Gulf of Thailand. This suggests that the southwest monsoon wind, during summertime, piles up the water in the northeast near Luzon and drives the current system in the SSCS northward. The northeast monsoon wind, during winter, piles up the water in the southwest over the Sunda shelf and the Gulf of Thailand, which increases the geopotential gradient in the north and drives current northward along Peninsular Malaysia. The POM model also successfully simulates a mesoscale eddy in the middle of the SSCS at the Sunda shelf, namely the Natuna Island eddy. This eddy is cyclonic during winter monsoon and anticyclonic during the summer monsoon, similar to the eddy system explained by Xu *et al.,* (1982).

Recent study has taken a closer look into the area of the SSCS, especially along the coast of Peninsular Malaysia. Tangang *et al.,* (2011) conducted a wave–tide–circulation coupled model based on POM to study the seasonal circulation in the Malay Peninsular Eastern Continental Shelf region (MPECS). The model successfully reconstructs the observed seasonal variation of the circulation in the region, as well as the main currents. At first, the simulated tidal harmonic constants, SST and sea surface height anomaly, agreed accordingly with the observations. The study was confined to winter and summer systems. The model dynamics showed that the upper-layer circulation in the region was mainly controlled by the monsoon winds.

An anti-cyclonic eddy was detected off the Peninsular Malaysia's east coast in summer, centered at 5 °N and 105.5 °E. The eddy found was similar to that observed by Xu *et al.,* (1982) and numerical models data from Chu *et al.,* (1999). They also suggest that the eddy was confirmed by the observed TOPEX/Poseidon sea surface height data. Detail analysis, using two numerical experiments for dynamics comparison, found that both wind stress curl and bathymetry steering were responsible for the formation of the anti-cyclonic eddy.

Both studies found that during June to August, the cyclonic circulation resembled the circulation during September to November. Interestingly, it was noted that there is a sub-surface cyclonic eddy off the northern Peninsular Malaysia's coast present in the simulation. The eddy is something new to the circulation of the area and it can clearly be seen at a sub-surface of 30 m depth (Figure 5). The circulation during March/April/May is somewhat different, with the flow in the SSCS being predominantly a westward cross-basin flow. Stronger and broader Borneo Coastal Currents are simulated, which later feed into the southward flowing western boundary current along the Peninsular Malaysia coast. The northern branch of the cross-basin flow also feeds into the northward flowing boundary current along the Vietnam coast.

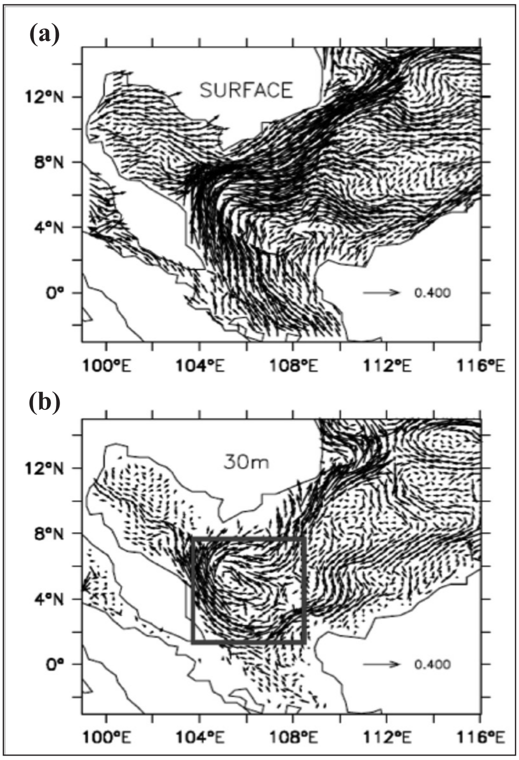

Figure 5: Average Current Flow during June/July/August: a) surface and b) 30 m
Note: Highlighted area is where subsurface eddy is suspected to form. (After Tangang *et al.,* 2011)

Akhir (2012) used OCCAM global ocean model output to conduct a detailed study on SCS current circulation and SST distribution along coastal Peninsular Malaysia. The study analysed the seasonal influence from both monsoon and transitional periods. The model was one of the most reliable global ocean models available for high resolution data output in the area of the SCS. The forcing used within the model is realistic for regional scale studies. Overall, monsoon circulation recorded was similar to previous findings. SSCS circulation is northward during the southwest monsoon when the Peninsular Malaysia coastal current flows from Karimata Straits and continues north into the Gulf of Thailand before heading towards Vietnam (Figure 6). In addition, recent findings suggest that the dynamics of southwest monsoon system is contributing to the presence of upwelling along the east coast (unpublished).

The circulation in May is one of the interesting features of this study. The reversing currents flow into each other and converge near 2 °N. Earlier models, developed by Chu *et al.,* (1999), also showed the sudden change in direction as the northward flow approached 5 °N. The convergence happens slightly further north than predicted by OCCAM, but both are almost the same. The transition period between the two monsoon seasons is believed to be the catalyst for such a feature.

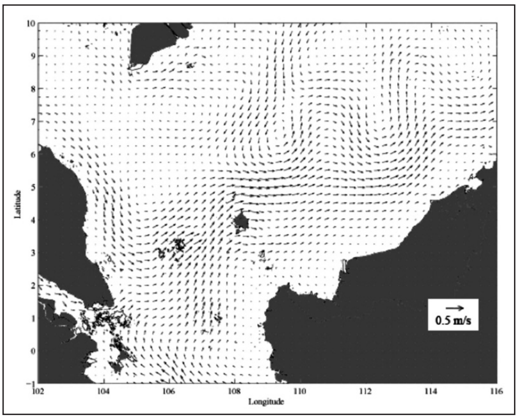

Figure 6: Average Surface Circulation During May from OCCAM (after Akhir, 2012)

SST within the region also vary through the season. Combined data from OCCAM and satellite data from MODIS show advection of cold water from the north influenced the SST in the region. The presence of a cold tongue is pronounced in the middle of the SSCS, consistent with earlier findings (Lim and Tuen, 1991; Marghany *et al.*, 1996; Saadon and Camerlengo, 1996). Cold advection water develops during the northeast monsoon and transports colder water into the region. During southwest monsoon, the central SSCS temperature is 3 °C higher. During this time, northward flowing current brings warm tropical waters from the Karimata Straits (Akhir, 2012).

## Conclusion

Research exploration from observation data and the establishment of numerical modeling techniques for the study of physical oceanography in the region has contributed vast amounts of information that was lacking before. Until recently, the surface circulation described by Xu *et al.,* (1982) in their comprehensive field data study and Wyrtki (1961) provided the small base of knowledge about this region. Since then, numerical modeling study has helped to further enhance our understanding of the SCS. All studies agree on the general terms of the circulation pattern and dynamics systems, and every recent finding added new knowledge to the system.

From numerical modelling, Chu *et al.,* (1999) was able to describe in detail the dynamics that drive the current system and build a comprehensive understanding, building upon the foundation of Xu *et al.,* (1982). Their circulation model described the main cyclonic and anti-cyclonic forces of the system according to seasons. Most importantly, they detailed the wind stress influence and difference in sea surface height that drives the circulation. Tangang *et al.,* (2011) suggested that bathymetry also plays an important role in determining the circulation of the region. That study concluded the probability of a subsurface eddy offshore the Terengganu coast during the summer. Using that study, Akhir (2012) provided a proper overview of the plain along the coastal area of Peninsular Malaysia through a global ocean model. Seasonal circulation and temperature variation during interseasons and transitional periods were described accordingly. The overall combination of research listed in this review has provided the physical oceanography groundwork for the SSCS, but it is far from complete. Studies of the area must continue through a combination of field measurements, numerical models and satellite oceanography input, to build upon the immense contribution of the scientific community in producing and publishing this data.

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