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TEMPERATURE AND SALINITY CHARACTERISTICS IN THE SOUTHERN SOUTH CHINA SEA AND STRAIT OF MALACCA

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Abstract: Temperature and salinity characteristics in the southern South China Sea and Strait of Malacca are investigated using CTD data and the global ocean model HYCOM. CTD data were obtained from cruises taken in March 2015, March 2019, and July-August 2019. The results showed that the average reading of temperature and salinity in the Strait of Malacca during March 2015 was 28.60±0.708 °C and 32.61±1.01 psu, respectively. The average readings during March 2019 were 29.31±1.593 °C and 32.38±0.884 psu, respectively. The average temperature and salinity in the Strait of Malacca during the August 2019 cruise were 29.63±0.701 °C and 32.52±0.553 psu, respectively. Meanwhile, in the southern South China Sea, the average readings in July 2019 were 28.98±0.310 °C and 33.07±0.126 psu and in August 2019 were 27.94±1.01 °C and 33.36±0.363 psu. Seasonal variations presented by the 15-years (1997-2012) HYCOM climatological model show that the sea surface temperature is warmer by approximately 1 - 2 °C during the southwest monsoon months (June-July-August) than during the northeast monsoon (December-January-February) in the southern South China Sea. The seasonal temperature variations in the Strait of Malacca are not significant except for the southern part. The sea surface salinity exhibits no clear seasonal cycle except for the coastal areas.

Keywords: Undergraduate research, Temperature, Salinity, Southern South China Sea, Strait of Malacca.

Introduction

Peninsular Malaysia is part of Southeast Asia's countries. It is surrounded by the Strait of Malacca (SoM) at the west and the southern South China Sea (sSCS) at the east. SoM is located between the west coast of Peninsular Malaysia and the east coast of Sumatra. SoM is one of the important canals for interaction and transfers between its adjacent seas (Ibrahim & Yanagi, 2006). It is connected to the Andaman Sea and the Indian Ocean in the north. As the straits extend to the south, it is ended in between Tanjung Piai, Malaysia and Pulau Karimun Kecil, Indonesia and then join the Singapore Strait (Rusli, 2012). SoM is the longest strait in the world (Hii *et al.,* 2006), where the distance between the Andaman Sea and SCS is approximately 550 miles or 885 km. The width of the straits is 1.5 nautical miles or 2.8 km at its narrowest point, which is in Singapore Straits (Evers & Gerke, 2011). The SoM has complex bathymetry and irregular depth gradients. The water body of SoM is characterised by a shallow and narrow basin (Thia-Eng *et al.,* 2000) where the average depth of the strait is approximately 100 m. The deep and steep bathymetry is located in the northern part of the straits, while the shallow section (10 – 60 m depth) can be found at the center and the southern part of the SoM (Chandra, 2016).

South China Sea (SCS) is a semi-enclosed basin between the western Pacific and the Indian Ocean. SCS is encompassed several countries, including Malaysia, Vietnam, Thailand, Philippines, China, Taiwan and Hong Kong. The bathymetry of SCS consists of a shallow continental shelf named Sunda Shelf (averaging a depth of less than 100m) at the southern part and connected with a continental slope and deep basin at the center of SCS.

SoM and sSCS were influenced by the inter-annual and decadal sea-level variability associated with El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) in the Pacific Ocean and Indian Ocean Dipole (IOD) in the Indian Ocean (Soumya *et al.,* 2015). SoM and sSCS also experienced seasonal variability affected by monsoon seasons (Tan *et al.,* 2006). Two monsoon seasons occur in the region: the northeast monsoon (NEM) and the southwest monsoon (SWM). SWM occurred from late May to September, the NEM occurred from November to March; and there are transitional months between these two monsoons in April and October (Roseli & Akhir, 2014). Southeast Asia experienced dry and rainy seasons during SWM and NEM, respectively (Thia-Eng *et al.,* 2000). Southeast Asia receives much more annual rainfall during NEM (Hastenrath, 2015). The seawater temperature during this season is lower than in the SWM. Meanwhile, during NEM in November-December and at the end of the SWM in late October, SoM has experienced heavy rainfall throughout the season. During the SWM season, precipitation trends can be seen, especially on the west coast of peninsular Malaysia near SoM (Suhaila *et al.,* 2010).

Due to monsoonal changes, the temperature and salinity in the sSCS and SoM varied seasonally. Seasonal variation of sea temperature and salinity in the sSCS and SoM has been the subject of few studies, either using the global ocean model, regional model simulation or observational data. SST is usually warmer during southwest monsoon compared to the northeast monsoon in the sSCS (Tangang *et al.,* 2011; Akhir, 2012). Based on observational data, the coastal area of sSCS is characterised by saltier sea surface salinity (SSS) during the inter-monsoon in April and less salty during the inter-monsoon in October (Yong & Akhir, 2011; Akhir *et al.,* 2011; Roseli & Akhir, 2014; Roseli *et al.,* 2015). Other than seasonal variation, few studies have shown the important roles of SoM and sSCS as inter-connection passages for heat and salt transports between SCS, the Andaman Sea and the Java Sea (Daryabor *et al.,* 2015; Daryabor *et al.,* 2016; Kok *et al.,* 2021). Meanwhile, in the SoM, the variation between southwest and northeast monsoon is significant in the northern part of SoM. The SST was cooler during the northeast monsoon and started to warm during the inter-monsoon (April) until October (Isa *et al.,* 2020).

In this paper, the variability of temperature and salinity in the sSCS and SoM is studied using recent in-situ datasets and the global ocean model. This paper is organised as follows: Section 2 mentioned the in-situ data measurement and the global ocean model. Section 3 discussed the temperature and salinity characteristics in both sSCS and SoM during cruises in 2015 and 2019. Since in-situ measurement presented a synoptic overview of temperature and salinity characteristics in the study area, the climatology of the global ocean model is included in the analysis to show the seasonal variation of the study area. Section 4 summarises the findings from both in-situ and global ocean models.

Materials and Methods

Hydrographic Data

Hydrographic data were collected during three oceanographic cruises conducted aboard RV Discovery, the research vessel from Universiti Malaysia Terengganu during March 2015, March 2019, and July-August 2019 (hereafter referred to as M15, M19 and JA19, respectively). The equipment used to collect the data is the conductivity-temperature-depth (CTD) by Sea-Bird Electronics (SBE). At each station, CTD observations were made for temperature, salinity (calculated from conductivity), and depth (calculated from pressure) down to a maximum depth of 60 m. The CTD measures temperature, conductivity, and pressure at 4 scans/sec (4 Hz) and provides high accuracy and resolution of datasets. The specifications of the profiler are as follows: temperature accuracy is 0.001 1°C, temperature resolution is 0.0002 1°C;

conductivity accuracy 0.0003 sm^{-1} and resolution 0.00004 sm^{-1}; pressure accuracy 0.125 dB and resolution 0.0125 dB. Post-cruises processing of the CTD data set was performed using Sea-Bird Data Processing software. In the Ocean Data View software, the outliers for each parameter were removed. The basic statistics of mean and standard deviation were then calculated from the corrected datasets. Four transects were selected for further discussion. Transects A and B were used to represent the northern and middle of SoM, respectively. Meanwhile, transects C and D were used to represent sSCS stations.

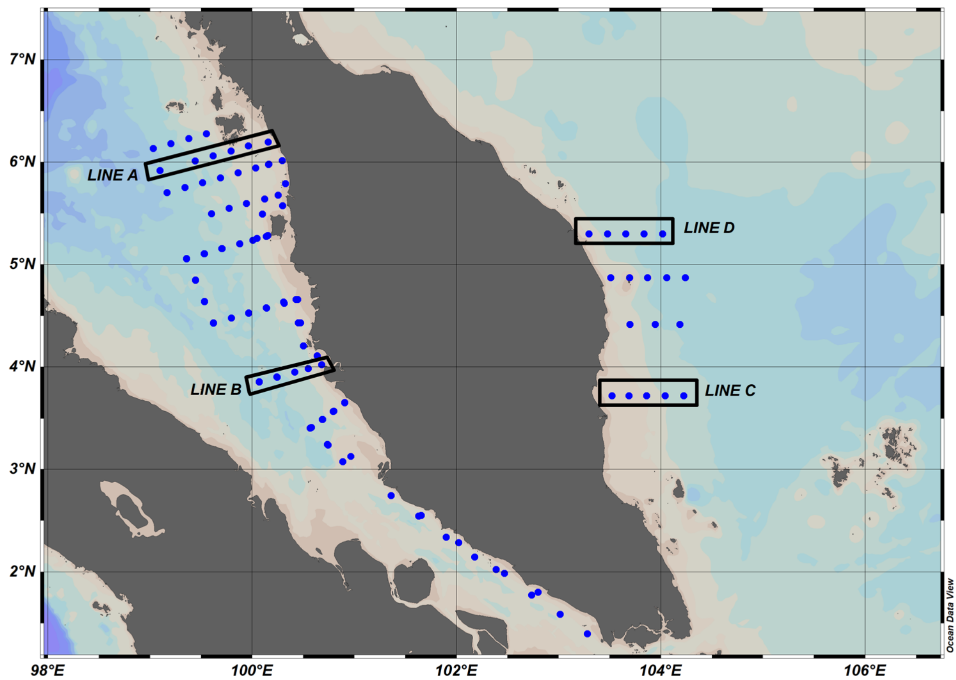

Figure 1: Sampling stations encompassed the area of the Strait of Malacca and the east coast of Peninsular Malaysia, Southern South China Sea. Four transects were selected for cross-section plots

Global Ocean Model

The temperature, salinity, and currents data in this study were obtained from the global ocean model, HYbrids Coordinate Ocean Model (HYCOM). HYCOM used in this study encompassed an area of 0 to 15° N latitude and 100°E to 115°E longitude. HYCOM is a program to develop and evaluate the three-dimensional assimilated ocean model sponsored by the National Ocean Partnership Program (NOPP) as part of the U. S. Global Ocean Data Assimilation Experiment (GODAE). HYCOM merges various approaches for representing the vertical coordinate in the mode, including z-level, terrain-following (sigma) and isopycnic. HYCOM provides access to a near real-time global ocean prediction system through the website https://www.hycom.org/data/glbu0pt08/expt-19pt1. The mean climatology data on temperature, salinity, and current circulation at the surface from 1997-2012 was selected to be analysed in this study. The resolution of these datasets was 1/12.5° or ~0.08° with 32 vertical layers. We used surface layers datasets to calculate the monthly climatology.

Results and Discussion

Hydrographic Characteristics

Three scientific cruises were done in March 2015, March 2019, and July-August 2019 in the SoM and sSCS. Table 1 presents basic statistics of the datasets based on cruises. Figures 2 and 3 presented the vertical temperature and salinity profiles from those five cruises done in SoM and sSCS, respectively. In the SoM, the average temperature collected from three cruises ranged from 28.6 – 29.6 °C, while the salinity was 32.4 – 32.6 psu. The potential density anomaly is ranged from 19.99 – 20.3 kg/m^3. In the sSCS, the average temperature, salinity and potential density anomaly from two different cruises are 27. 9 -28.98 °C, 33.07 – 33.36 psu and 20.6 – 21.2 kg/m^3 respectively.

Table 1: Basic statistics of data

Parameters	Cruise	Sampling Area	Sampling Time	Mean	Stand. Dev.	Min.	Max.
Temperature (°C)	Lima ‘15	SoM	March 2015	28.60	0.71	26.93	33.34
	Lima’ 19	SoM	March 2019	29.31	1.59	24.06	31.60
	UMT-FIO 2019 Leg 1	sSCS	July 2019	28.98	0.31	27.46	29.37
	UMT-FIO 2019 Leg 2	sSCS	August 2019	27.94	1.01	25.28	29.95
	UMT-FIO 2019 Leg 3	SoM	August 2019	29.63	0.70	26.73	30.90
Salinity (PSU)	Lima ‘15	SoM	March 2015	32.61	1.01	26.00	34.09
	Lima’ 19	SoM	March 2019	32.38	0.88	30.78	34.18
	UMT-FIO 2019 Leg 1	sSCS	July 2019	33.07	0.13	32.90	33.68
	UMT-FIO 2019 Leg 2	sSCS	August 2019	33.36	0.36	31.18	34.03
	UMT-FIO 2019 Leg 3	SoM	August 2019	32.52	0.55	25.58	33.99
Potential Density Anomaly, σ_θ (kg/m^3)	Lima ‘15	SoM	March 2015	20.32	1.04	15.40	21.82
	Lima’ 19	SoM	March 2019	19.99	1.17	18.29	23.01
	UMT-FIO 2019 Leg 1	sSCS	July 2019	20.63	0.19	20.41	21.59
	UMT-FIO 2019 Leg 2	sSCS	August 2019	21.18	0.58	18.95	22.53
	UMT-FIO 2019 Leg 3	SoM	August 2019	19.99	0.63	15.14	22.00

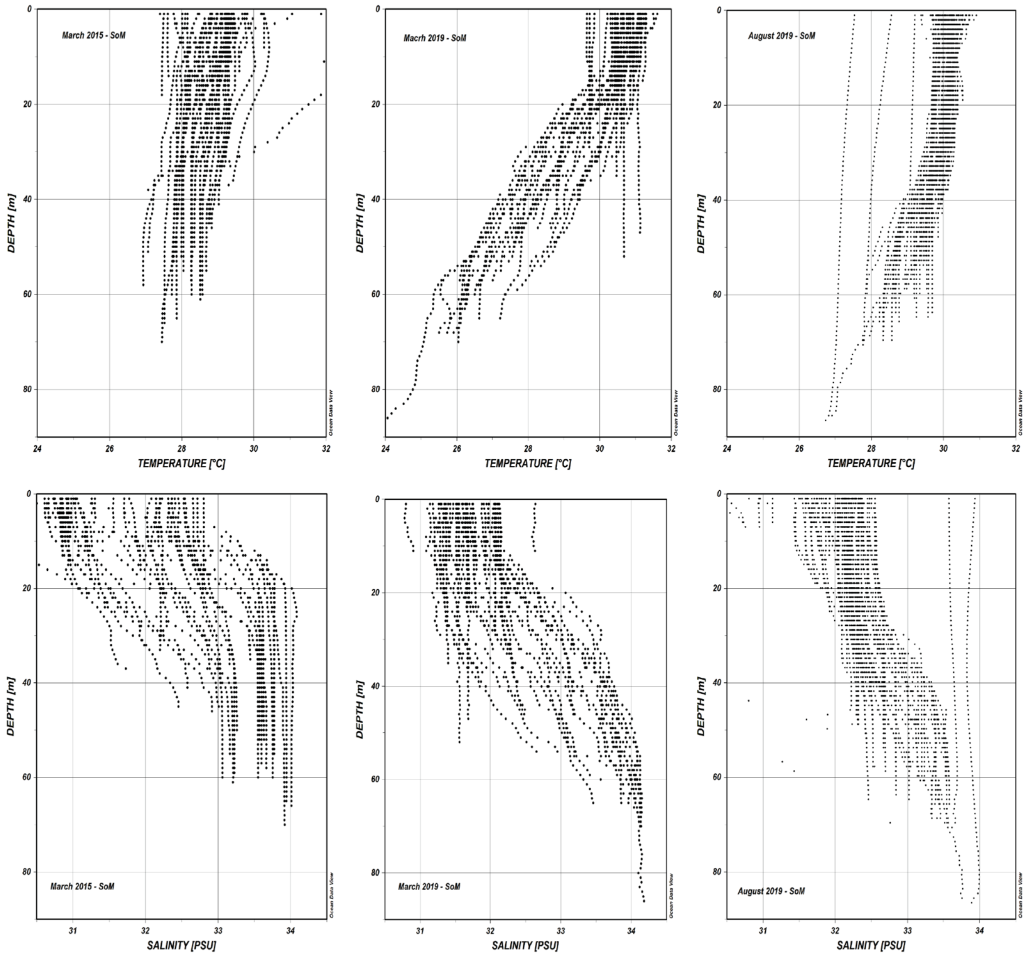

Figure 2: Temperature and salinity profiles at SoM during three cruises; March 2015, 2019 and August 2019. Temperature units are in °C and salinity units are in psu

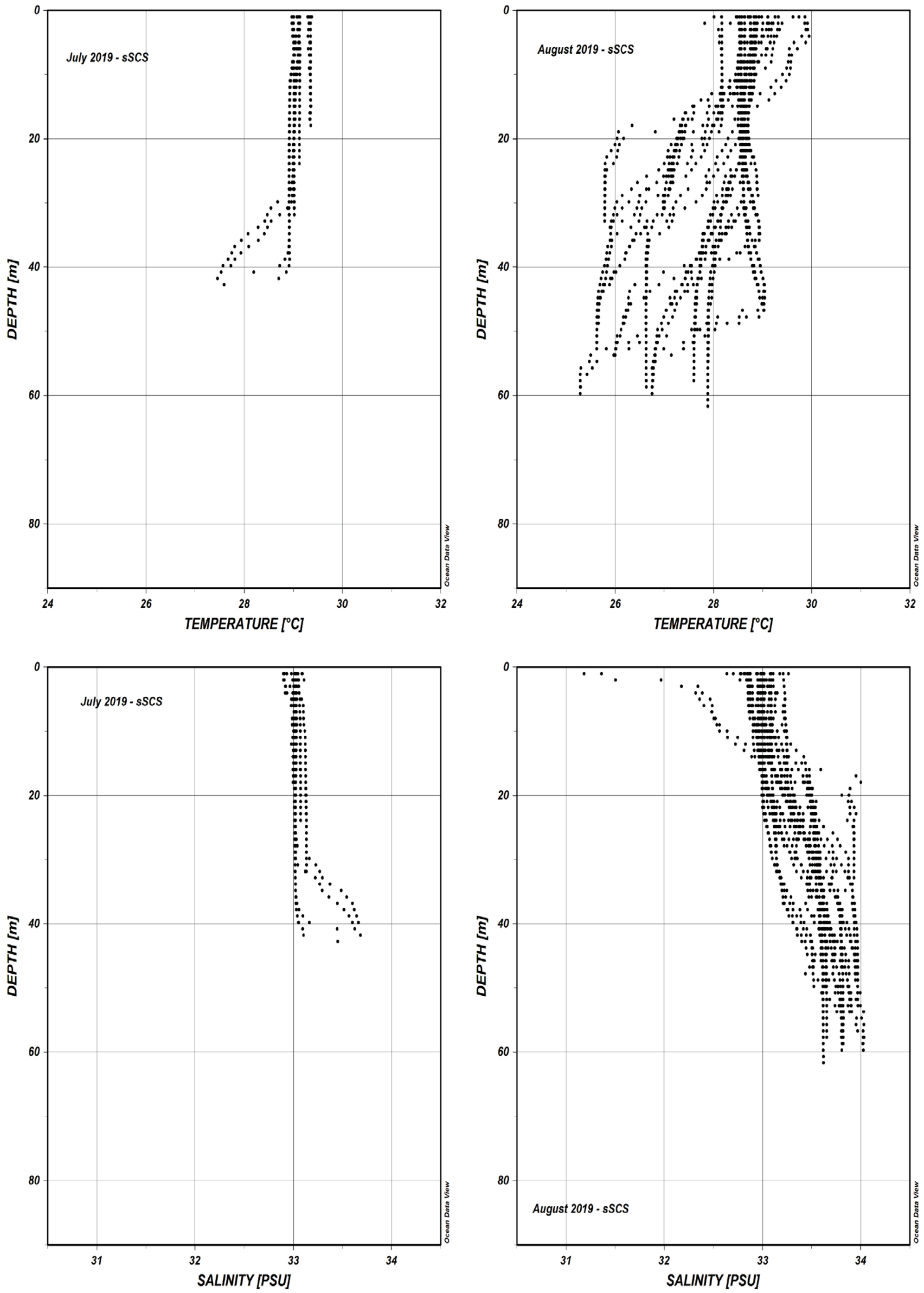

Figure 3: Temperature and salinity profiles at sSCS during two cruises; July 2019 and August 2019. Temperature units are in °C and salinity units are in psu

Vertical sections of temperature and salinity in the SoM at two different transects, Line A (northern SoM) and Line B (middle SoM) are presented in Figures 4 and 6, respectively. In the northern SoM, the selected transect occupies part of the transition zone of water mass between the Andaman Sea and the SoM. The layer of $\sigma_\theta > 21$ kg/m^3 containing relatively saltier water corresponds to the deeper layer of more than 10-m and 40-m depth observed in March 2015 and August 2019, respectively. The densest water mass of $\sigma_\theta > 22$ kg/m^3 containing saltier and cooler water was observed in March 2019 at more than 40 m. The high dense water mass mostly occupies the deeper-offshore area while the less dense water occupies the upper layer and nearshore area. During all three surveys, salinity played a major role in the σ_θ distribution of potential density anomalies in the northern SoM. Freshening and warmer near-surface water and saltier and cooler deeper water contributed to the development of stratification in the northern SoM. The high saline waters are presumably the results of water intrusion from the Andaman Sea into the SoM (Isa *et al.,* 2020). The possible source for the relatively fresher water was from the local rivers that discharged into the SoM. It appears that weak transition winds (March) and southwest monsoon winds (August) maintained the stratification within the water column (Isa *et al.,* 2020). The spreading of fresher water from the nearshore area towards the offshore area is probably due to the advection process and not the vertical mixing.

Meanwhile, in the middle of SoM, stable stratification was observed in March 2015 and 2019, an almost homogenous water column was observed in August 2019. The densest water mass was found during March 2019, $\sigma_\theta = 21 – 21.5$ kg/m^3. A water mass of $\sigma_\theta > 22$ kg/m^3 was not observed in the transect, indicating the intrusion of the Andaman Sea was not reached the middle SoM. Like in the northern SoM, pycnocline is shallower during March 2015 than in March 2019. The stratification is the most stable in March 2019 due to the warmer temperature at the surface and cooler water near the bottom.

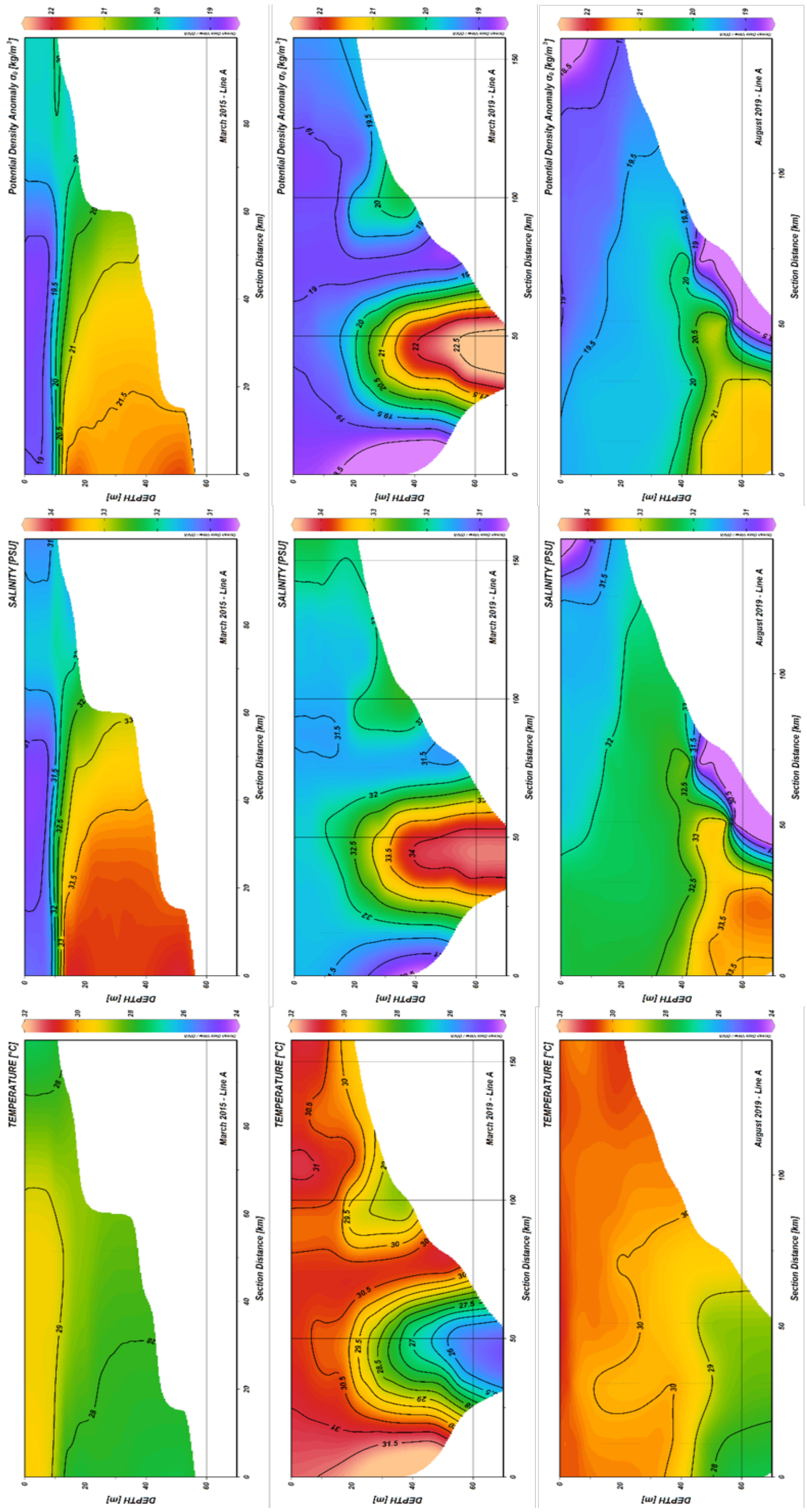

Figure 4: Cross-section of temperature, salinity, and potential density anomaly at northern transect of SoM (Line A)

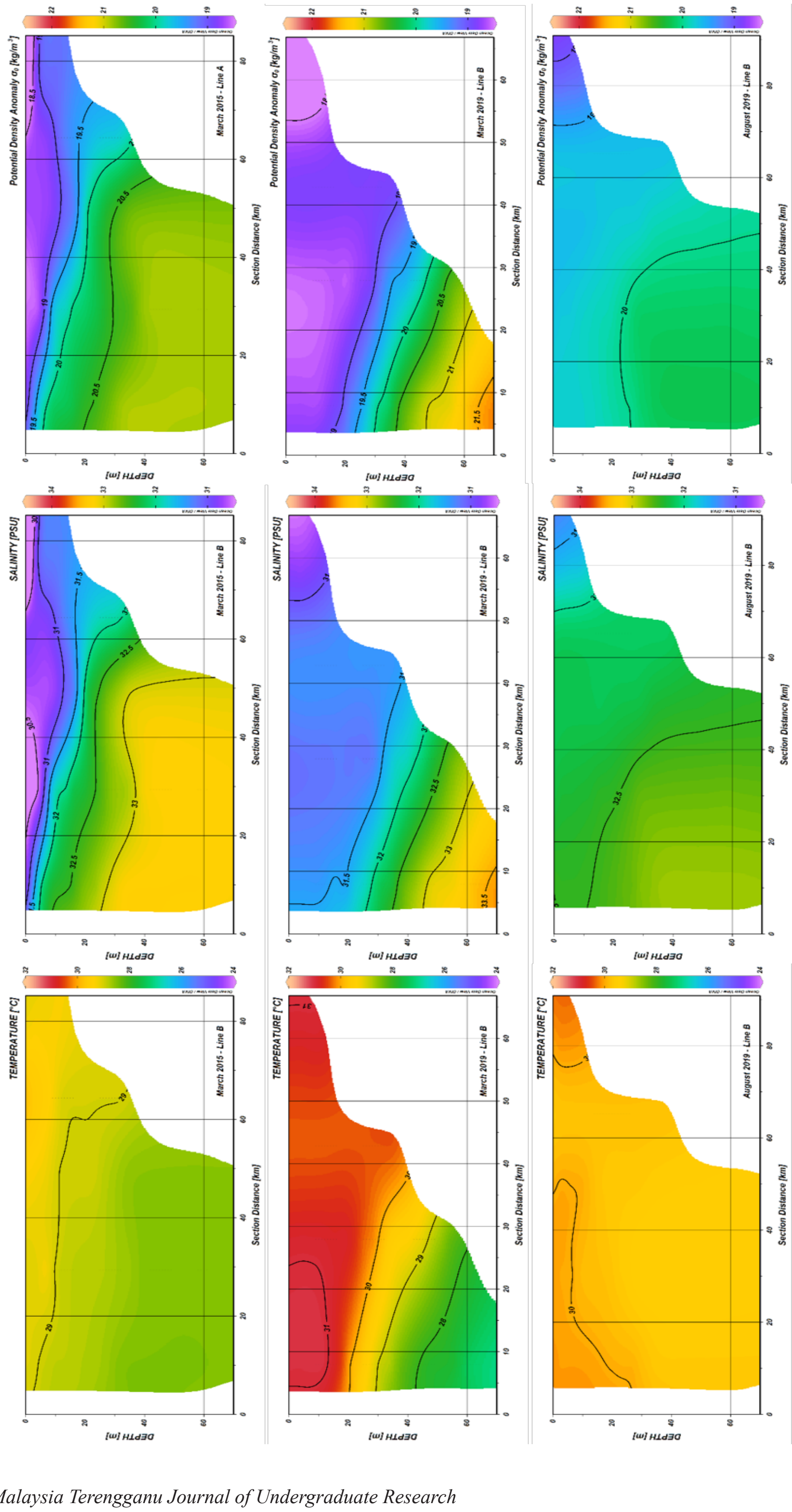

Figure 5: Cross-section of temperature, salinity and potential density anomaly at middle transect of SoM (Line B)

Figure 6 demonstrated the cross-sectional plots of temperature, salinity, and potential density anomalies in the middle (Line C) and northern (Line D) ECPM (in this study, it would sometimes refer to as sSCS). In SoM, the potential density anomalies in the sSCS were influenced by the temperatures. Less saline water occupies nearshore surface water in the northern transect of sSCS (Line D). This fresher and warmer water was separated by the cooler and saltier upwelling water mass (T <26; S>33.5 psu; $\boldsymbol{\sigma_\theta}$ = 22 kg/m3) at 20-m depth. The offshore stations did not record the same water mass near the bottom. This water mass was uplifted from the deeper area that was outcropped in the image. A previous study found that this water mass existed at more than 50 m at the offshore stations (Roseli *et al.,* 2015). The middle transect was almost homogenous until 40-m depth. Due to shallow stations, the upwelling water mass was not observed in the transect. However, cooler water was observed in the coastal area of Line D. This indicates the uplifting of upwelling water mass from the bottom offshore into the subsurface of the coastal area in Line D in August. Kok *et al.* (2015) had identified that upwelling is strengthened in August, especially near Terengganu water.

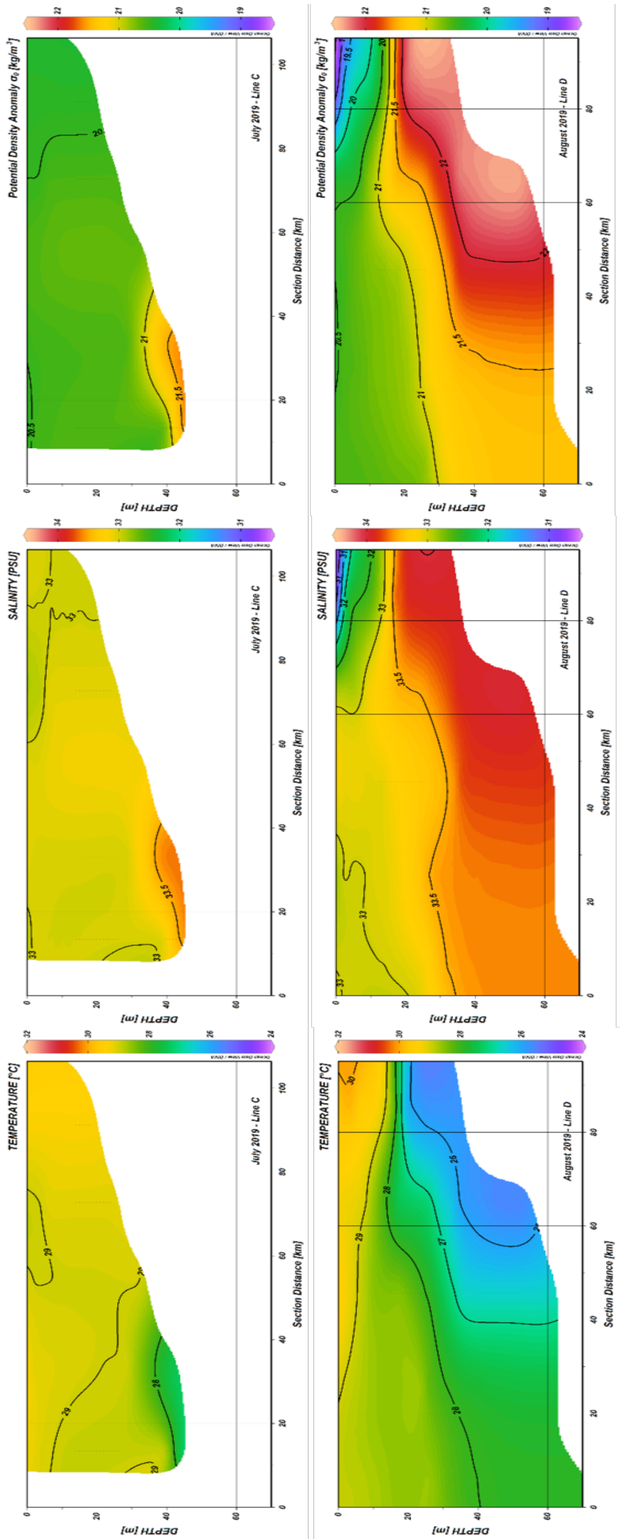

Figure 6: Cross-section of temperature, salinity, and potential density anomaly at the middle (Line C) and northern (Line D) of ECPM

Seasonal Variations from HYCOM

Figure 7, 8 and 9 demonstrated the seasonal climatology of SST, SSS and surface circulations, respectively, in the SoM and sSCS from HYCOM global ocean model. Seasonal variations of SST in the sSCS are significant compared to in the SoM. In the sSCS, the coolest SST can be found during DJF months (<30 °C). During MAM and JJA, the SST in sSCS is significantly increased (>30 °C) except along the Vietnamese coastline where cooler water was observed. This cooler water results from upwelling events that mostly occur during the southwest monsoon. During SON, the SST in the sSCS is slightly decreased, especially in the offshore area. SST at SoM during all months recorded high SST (31-32 °C). However, during NEM season (DJF), the horizontal SST variation that separated the cooler (southern) and the warmer (northern) water can be observed. As for other seasons, SoM recorded almost the same SST along the SoM canal.

Figure 8 shows the seasonal variation of SSS in the sSCS. The lowest salinity values of less than 32 psu can be found mostly in the Gulf of Thailand (GoT) and SoM during all seasons. During DJF months, the entire ECPM and SoM coasts were occupied by fresher water. These low-saline waters are maintained during MAM in the SoM but slowly disappear on the ECPM's coast. During JJA and SON, this low-saline water was observed only in the northern SoM. Meanwhile, the southern SoM was occupied by saltier water. In the offshore area of sSCS, the SSS are the saltiest in all seasons with values of more than 34 psu.

SST and SSS in DJF months, especially in SoM and along the ECPM coast were the lowest compared to the other months. According to Wyrtki (1961) and Yanagi *et al.* (2001), sSCS receives cold-high dense water mass with high salinity during the northeast monsoon. Less solar radiation and heavy precipitation during the northeast monsoon caused the SST and SSS during DJF months to be cooler and fresher. During the first transitional period (MAM) and the southwest monsoon (JJA), the SST and SSS had increased in the sSCS and SoM. During the transition period (SON) from southwest to northeast monsoon, the SST and SSS are lower compared to the transition period (MAM) from northeast monsoon to southwest monsoon. Weakening winds, increasing sensible and latent heat flux and low amounts of total cloud in March and April caused the increase in SST and SSS values in these areas (Isa *et al.,* 2020; Roseli *et al.,* 2014).

During southwest monsoon which usually starts in late May, the warm and weak southwesterly wind blows and causes the current circulation in the sSCS to flow northward and northwestward. During the northeast monsoon (DJF), the cold northeasterly winds blew over the SCS because of the Siberian high-pressure system located over the East Asian continent. Radiative cooling and persistent cold air advection in weather conditions keep the same cold air over SCS. Usually, during these months, the coastal water was less saline and lower in temperature. In the offshore area, the salinity is the highest and the temperature is the lowest.

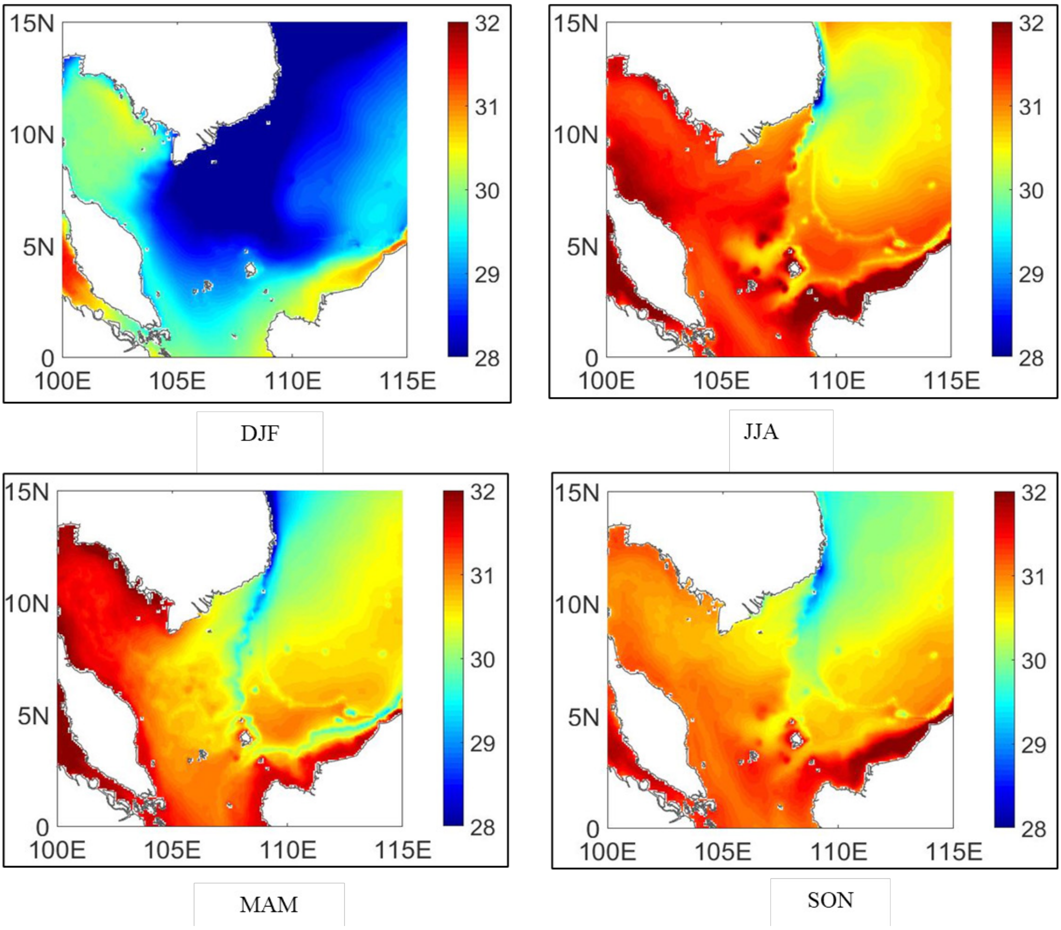

Figure 7: Seasonal variation of climatology SST during DJF, MAM, JJA and SON in the sSCS for 1997-2012

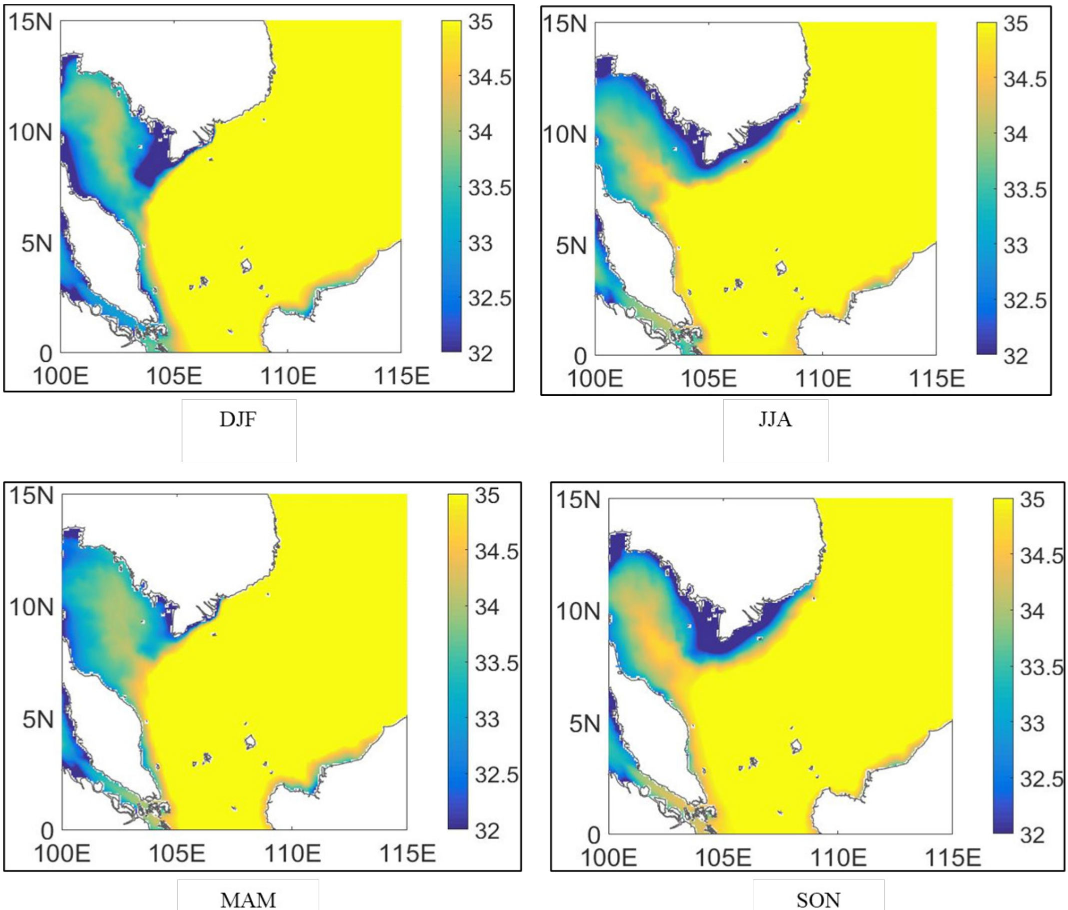

Figure 8: Seasonal variation of climatology SSS during DJF, MAM, JJA and SON in the sSCS for 1997-2012

The seasonal variation of surface current circulation in the sSCS is presented in Figure 9. During DJF months, strong currents moved southward along the Vietnamese coast and then flowed into the ECPM's coast. Meanwhile, during JJA months, the currents reversed their direction and moved northward along ECPM and northeastward along the Vietnamese coastline. Strong jets can be observed along the Vietnamese coast during both periods. During the transitional periods in MAM and SON, the surface currents are slower and varied in directions.

Current around SoM does not show any special characteristics compared to sSCS. The surface currents for all months flow northward into the Andaman Sea. The surface currents are much slower than sSCS due to Sumatera, which protects strong currents flow over SoM.

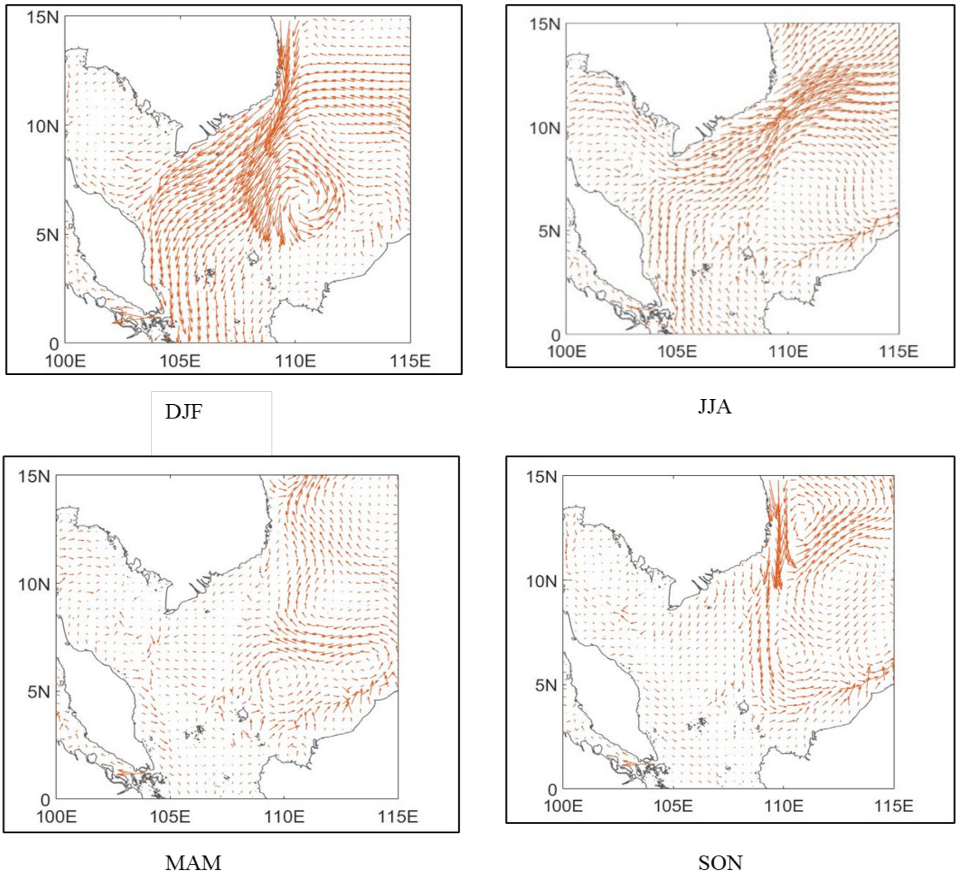

Figure 9: Seasonal variation of climatology current circulation during DJF, MAM, JJA and SON in the SSCS for 1997-2012

Conclusion

This study showed seasonal temperature and salinity variation from in-situ measurements and the global ocean model. Seasonal variation of SST, SSS and surface current circulation in the sSCS and SoM is mainly influenced by two major monsoon systems, SWM (JJA) and NEM (DJF), and the transitional monsoon months (MAM and SON). These monsoons system can cause variation in seawater characteristics and current circulation. The in situ data collected synoptically in March (SoM) and July-August (sSCS) revealed seasonal variation in both areas. March was considered the transition month from the cold northeast monsoon to the warmer southwest monsoon. Due to weakening monsoon winds in March, the temperatures are slightly warmer compared to the southwest monsoon season in July-August. Reversed wind direction due to the monsoonal wind system also caused the current circulation to vary according to season. In-situ data are critical for a complete understanding of the oceans because it provides information on the ocean's real condition. Due to limited in-situ data, especially in the SoM and sSCS regions, this paper can contribute to the information on real seawater's conditions in both areas. As many researchers admit that using in situ data was highly reliable, ocean model data allow them to see the variability in spatial scale. This is true when the in-situ data is lacking on the spatial and temporal scale.

Acknowledgements

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