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COASTAL UPWELLING AT TERENGGANU AND PAHANG COASTAL WATERS: INTERACTION OF HYDROGRAPHY, CURRENT CIRCULATION AND PHYTOPLANKTON BIOMASS

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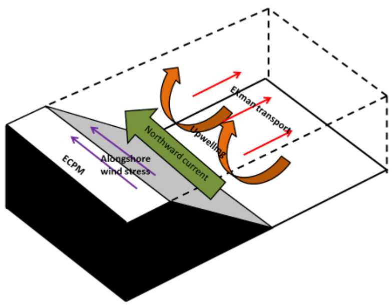
Graphical abstract



Abstract

The hydrographic characteristics and current circulation in Terengganu and Pahang coastal waters were examined for their spatial and temporal variability based on the seasonal influence during the transition period (April 2014) and southwest monsoon (June and August, 2014). The results of this study demonstrated the presence of slightly cooler water during June and August, 2014 compared to April, 2014, which indicate the existence of coastal upwelling. Furthermore, the uplifting of isotherms towards the coast during the study trip was also a good evidence of upwelling. The current flow generated by the wind was the possible reason of the features. Furthermore, this study also makes the first attempt to observe the coupling effects between coastal upwelling and the phytoplankton biomass in Terengganu and Pahang coastal waters, which is still sparse. Interestingly, apart from the nutrient availability, the coastal upwelling was believed to influence the phytoplankton biomass at the study area.

Keywords: Upwelling, sea surface temperature, wind stress, Ekman transport, chlorophyll *a*

Abstrak

Ciri-ciri hidrografi dan pergerakan arus di perairan pantai Terengganu dan Pahang dikaji untuk kepelbagaian tempat dan masa berdasarkan perubahan musim semasa musim peralihan (April 2014) dan monsun barat daya (Jun dan Ogos, 2014). Dapatan kajian menunjukkan kewujudan air yang lebih sejuk pada bulan Jun dan Ogos, 2014 jika dibandingkan dengan bulan April, 2014, yang membuktikan kewujudan julang air. Selain itu, angkatan isoterma ke arah pantai semasa lawatan kajian juga adalah bukti yang baik terhadap kewujudan julang air. Pergerakan arus yang disebabkan oleh angin adalah penyebab kepada keadaan ini. Selain itu, kajian ini adalah yang pertama melihat perkaitan julang air pesisir pantai dan biojisim fitoplankton di perairan pantai Terengganu dan Pahang, yang masih kurang. Menariknya, selain daripada kewujudan nutrien, kewujudan julang air pesisir pantai adalah dipercayai sebagai faktor yang mempengaruhi biojisim fitoplankton di kawasan kajian.

Kata kunci: Julang air, suhu permukaan laut, stres angin, angkutan Ekman, klorofil *a*

1.0 INTRODUCTION

On the east coast of Peninsular Malaysia (ECPM), the presence of coastal upwelling had been documented through the satellite observations of sea surface temperature (SST) (Figure 1). Generally, the coastal upwelling at the ECPM is initiated in June and the cold tongue water started to spread along the ECPM in July. Meanwhile, upwelling reached its maximum intensity in August [1]. Previous study by D'Croz and O'Dea [2] showed that the upwelling is manifested by the presence of cooler and saline water, which flushed nutrients to the upper layer that enhance phytoplankton growth near the surface. Moreover, upwelling is also responsible to facilitate the elevated chlorophyll concentrations during the monsoon season [3].

By using the Regional Ocean Modeling System (ROMS), the occurrence of upwelling in ECPM was documented by Daryabor *et al*. [4], where a strong southwest monsoon wind over this region leads to the existence of elongated cooler SST which indicates an upwelled water at about 104 °E longitude. Similar results were obtained by Kok *et al*. [5] whose showed the upwelling along the ECPM during the southwest monsoon are among the indicative factors in the formation of SST front, which is resulted from advection of cooler water off the region. Apart from SST, another evidence of the upwelling event is the uplifting of isotherms towards the coast [4]. Furthermore, during the upwelling period, strong western boundary current in this region will cause a movement of cooler water along the ECPM from southern to northern part [4].

Along the ECPM, the environmental factors governing upwelling formation as well as other physical processes has been discussed in few researches [4, 5]. However, none of the study tries to relate the coupling effects between coastal upwelling and the spatial distribution pattern of the phytoplankton biomass. Therefore, this study attempts to elucidate the physical governing factors of the upwelling and how they affect the phytoplankton biomass and nutrient availability in this area.

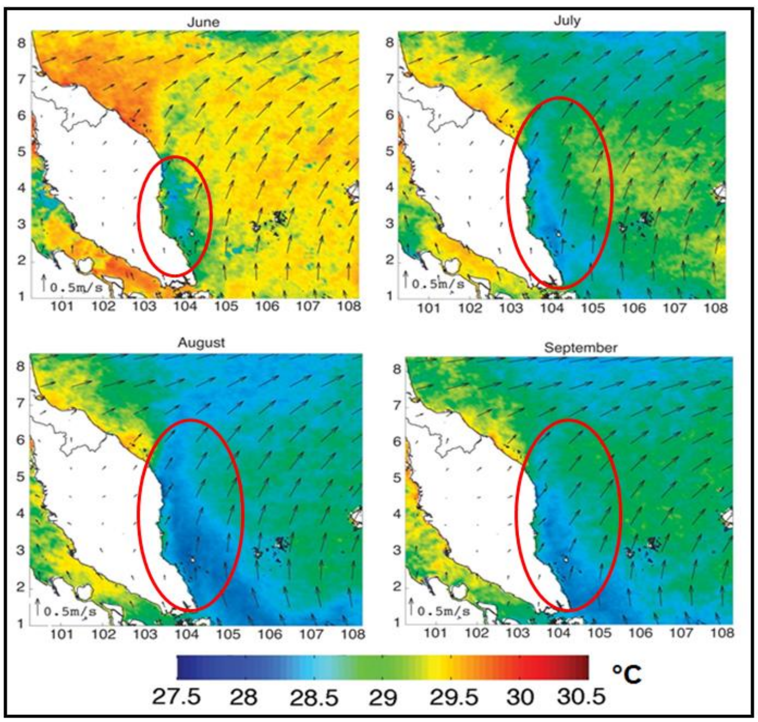


Figure 1 Average monthly MODIS-Terra SST climatology during the southwest monsoon from 2000 – 2012, along with average monthly wind speed [1]

2.0 METHODOLOGY

Specifically, the area of interest was limited to Terengganu and Pahang waters extending between 1.7 °N – 4.8 °N latitude and 103.5 °E – 105.0 °E longitude along the ECPM coast. This area is basically a shallow continental shelf basin with an average depth of 60 m. A total of three sampling voyages was conducted under the Malaysia Coastal Observation Networks (MyCON) project (April and June, 2014) and the Higher Institution Centre of Excellence (HICoE) in the Marine Science project (August 2014) by Universiti Malaysia Terengganu (UMT). The month of April was chosen to represent the non-upwelling period while June and August denoted the upwelling period in accordance to previous studies by Akhir *et al*. [1] and Daryabor *et al*. [4].

The sampling surveys during April and June, 2014 were carried out on board as outlined in Figure 2. Station 1 for each transects in this study was plotted 7.4 km from the onshore. The distance between each sampling station was approximately 7 km and extended from Station 1 to 70 km offshore. The first five stations were known as nearshore stations while the last five stations were classified as offshore stations. In this study, the classification of nearshore and offshore stations was done based on the distance from onshore, where the nearshore stations located between 7 – 35 km from onshore while offshore stations situated 42 – 70 km from onshore. Furthermore, the placement of each station was set-up to include the upwelling area along the ECPM, which is at 104 °E longitude. Since there were some technical problems, MyCON cruise during August, 2014 was covered by HiCOE cruise. Therefore, stations 61 – 104 (Figure 2) of HiCOE cruise during August, 2014 were used to demonstrate the appearance of coastal upwelling at the study area.

The main equipment used during the study period was SBE Plus19v2 Conductivity, Temperature, Depth (CTD) for the collection of hydrographic parameters (i.e., temperature and salinity) and SonTek Acoustic Doppler Current Profiler (ADCP) for current flow. Basically, for the determination of phytoplankton biomass in this study, chlorophyll *a* and nutrients, which are nitrite (NO_2^-), phosphate (PO_4^{3-}) and nitrate (NO_3^-) were analysed using spectrophotometric method in accordance to the American Public Health Association (APHA) [6]**.** In particular, water samples for chlorophyll *a* concentrations were collected using the 5L Niskin water sampler at Station 1, 3, 5, 7 and 9 for surface (2 m water depth), middle (4 – 33 m water depth) and bottom layers (7 – 66 m water depth). Water samples for chlorophyll *a* analysis were immediately filtered through the Sartorius Stedim GF/F (47 mm diameter, nominal pore size 0.7 µm) and stored in ice chest filled with ice cubes until further analysis. Using the same water sampler, water samples for nutrient analysis, was collected at selected stations (Station 2 and 10) from surface and bottom layers. For this analysis, 500 mL seawater was filtered through Whatman cellulose nitrate membrane filters (47 mm diameter, nominal pore size 0.45 µm). The water was immediately transferred into polyethylene bottles with 1 mL 6N HCl and stored in ice chest filled with ice cubes for preservation.

In meteorological aspects, the wind speed and wind direction together with rainfall data for the study areas were obtained from the Malaysian Meteorological Department. The wind data are presented in the form of vector plot which is an hour recorded wind speed and wind direction. An additional daily wind data were obtained from the European Centre for Medium-range Weather Forecast (ECMWF) Interim Reanalysis (ERA Interim) with 0.25° X 0.25° resolution. Changes in upwelling favourable wind conditions were evaluated from the data provided. Furthermore, to give a clear visualization of SCS upwelling processes, monthly satellite-derived sea surface temperature (SST) and 8-days chlorophyll *a* data, which was obtained from Aqua-MODerate-resolution Imaging Spectrometers (Aqua-MODIS) with 4 km resolution were used to improve the restriction of in situ measurements.

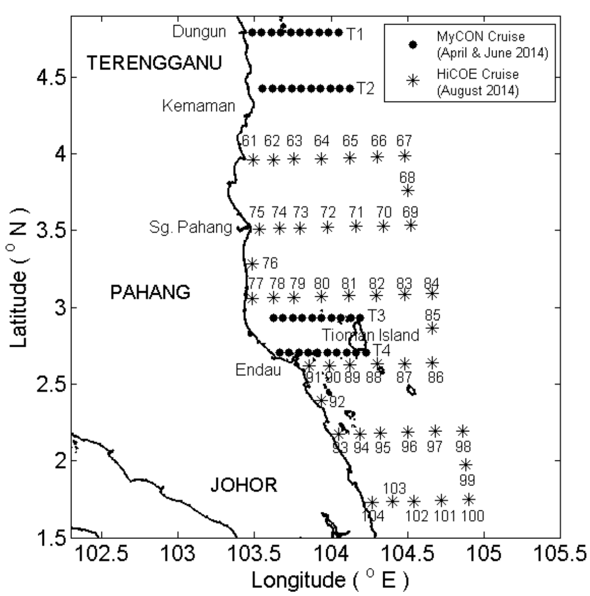


Figure 2 The location of study sites along the east coast of Peninsular Malaysia. The dot indicate the stations of MyCON cruises during April and June, 2014 meanwhile the star indicate the stations of HiCOE cruise during August 2014

3.0 RESULTS

3.1 Temperature and Salinity Distribution

Table 1 shows the surface temperature value between nearshore and offshore stations during the study period. In all transects, a common character was observed where the surface temperature during August 2014 was slightly cooler than April and June, 2014. However, there was temperature variability between the nearshore and offshore stations. In both Terengganu transects (T1 and T2), the nearshore stations recorded slightly cooler surface temperature readings compared to the offshore stations during April, June and August, 2014. Meanwhile, the surface temperature records at T3 show that, warmer temperature was noted at the nearshore stations than the offshore stations during all three sampling period. In T4, there was slightly warmer surface temperature in the nearshore stations compared to offshore stations during April 2014. However, during June and August, 2014, the average surface temperature at the nearshore stations was slightly cooler than the offshore stations.

Table 1 Surface temperature difference between nearshore and offshore stations

Transects	Temperature (°C)					
	April		June		August	
	Nearshore	Offshore	Nearshore	Offshore	Nearshore	Offshore
T1	29.5 – 29.9	29.6 – 30.1	–	29.6 – 31.0	28.0 – 28.6	28.6 – 29.1
T2	29.5 – 29.8	29.6 – 29.9	29.2 – 29.7	29.6 – 30.0	–	–
T3	29.5 – 30.9	29.2 – 29.7	29.0 – 29.8	28.9 – 29.4	28.8 – 29.4	28.7 – 29.3
T4	29.7 – 30.1	29.3 – 29.8	28.8 – 29.6	29.1 – 29.7	28.5 – 29.7	28.9 – 29.2

The surface salinity difference between the nearshore and offshore stations is shown in Table 2. In April 2014, the nearshore stations had less saline water compared to offshore stations for all transects. In opposite, the nearshore stations recorded slightly saline water than the offshore stations during June and August, 2014. For monthly comparison, June 2014 recorded slightly saline water than April 2014, where the average surface salinity values spread between 34.4 – 34.8 psu compared to 33.1 – 34.5 psu. The presence of slightly saline water was a good feature of coastal upwelling however, during August 2014, low-salinity water (32.5 – 33.9 psu) was observed in the study area. This strong low-salinity water was believed to be under the influence of large river discharge.

Table 2 Surface salinity difference between nearshore and offshore stations

Transects	Salinity (psu)					
	April		June		August	
	Nearshore	Offshore	Nearshore	Offshore	Nearshore	Offshore
T1	33.5 – 33.6	33.8 – 35.0	–	34.2 – 34.6	32.7 – 33.2	32.8 – 33.0
T2	33.4 – 33.9	34.0 – 34.8	34.6 – 34.7	34.5 – 35.9	–	–
T3	33.7 – 33.9	33.8 – 33.9	34.7– 34.8	34.4 – 34.7	32.4 – 33.1	32.4 – 32.8
T4	32.2 – 33.7	32.8 – 34.1	34.4 – 34.8	34.3 – 34.7	32.4 – 33.0	32.3 – 32.8

For a clear visualization of the upwelling, the vertical profiles of temperature and salinity in the study area are presented in contour plot. The vertical distribution of temperature at T1 during April 2014 (Figure 3a) shows stratification at a depth of 10 – 20 m, meanwhile during August 2014, strong stratification was observed at a depth of between 30 – 40 m (Figure 3b). It is important to note that, thermocline uplifting can be seen at 103.7 – 103.9 °E longitude. A similar feature was observed in the vertical distribution of salinity, where the stratification was detected during April 2014 (Figure 3c) and there was halocline uplifting during August 2014 (Figure 3d). Figure 4 demonstrates the vertical distribution of temperature and salinity at T2. Both temperature and salinity profiles (Figure 4a and 4c) shows stratification during April 2014, which was observed at a depth of 10 – 20 m. On the other hand, stratification was observed below 30-m water depth during June 2014 (Figure 4b and 4d). Besides, the thermocline uplifting could also be seen at the same longitude of T1. For T3 and T4, during April and June, 2014, two separated events were remarked through the cross shore observation (Figure 5 and 6). Mixing was documented in the nearshore stations, while distinct vertical temperature difference showed stratification below 20-m water depth that occurred at the offshore stations. The thermocline uplifting found in this part was believed to be a feature related to upwelling. Even though the thermocline did not reach the surface and was not obvious due to stratification, somehow there was a signal of thermocline uplifting, a classical evidence of upwelling.

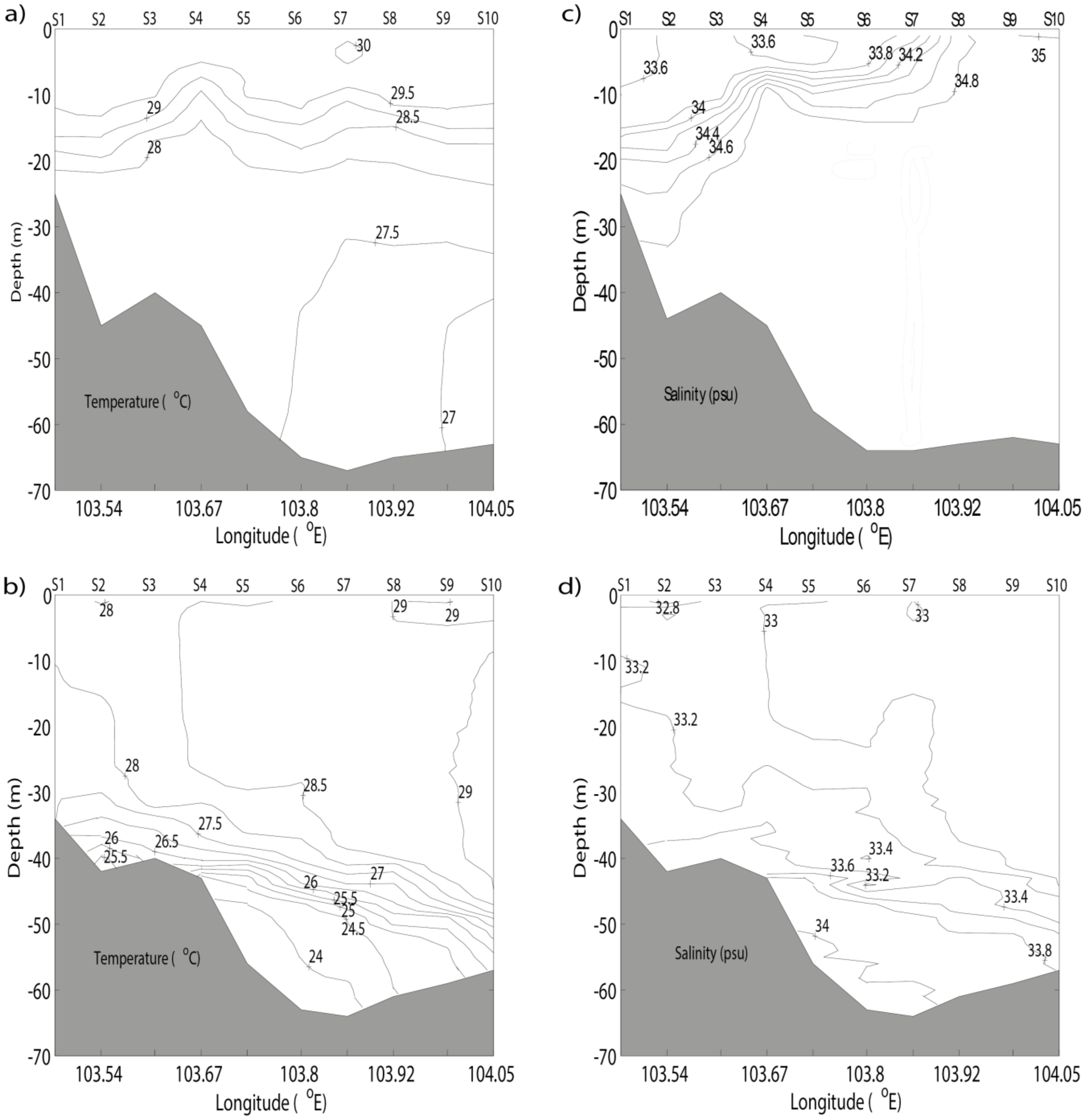


Figure 3 Contour plot of vertical temperature and salinity profile in T1 during April 2014 (a + d) and August 2014 (b + d). Please note that, the temperature and salinity profile during June 2014 was not plotted due to data limitation

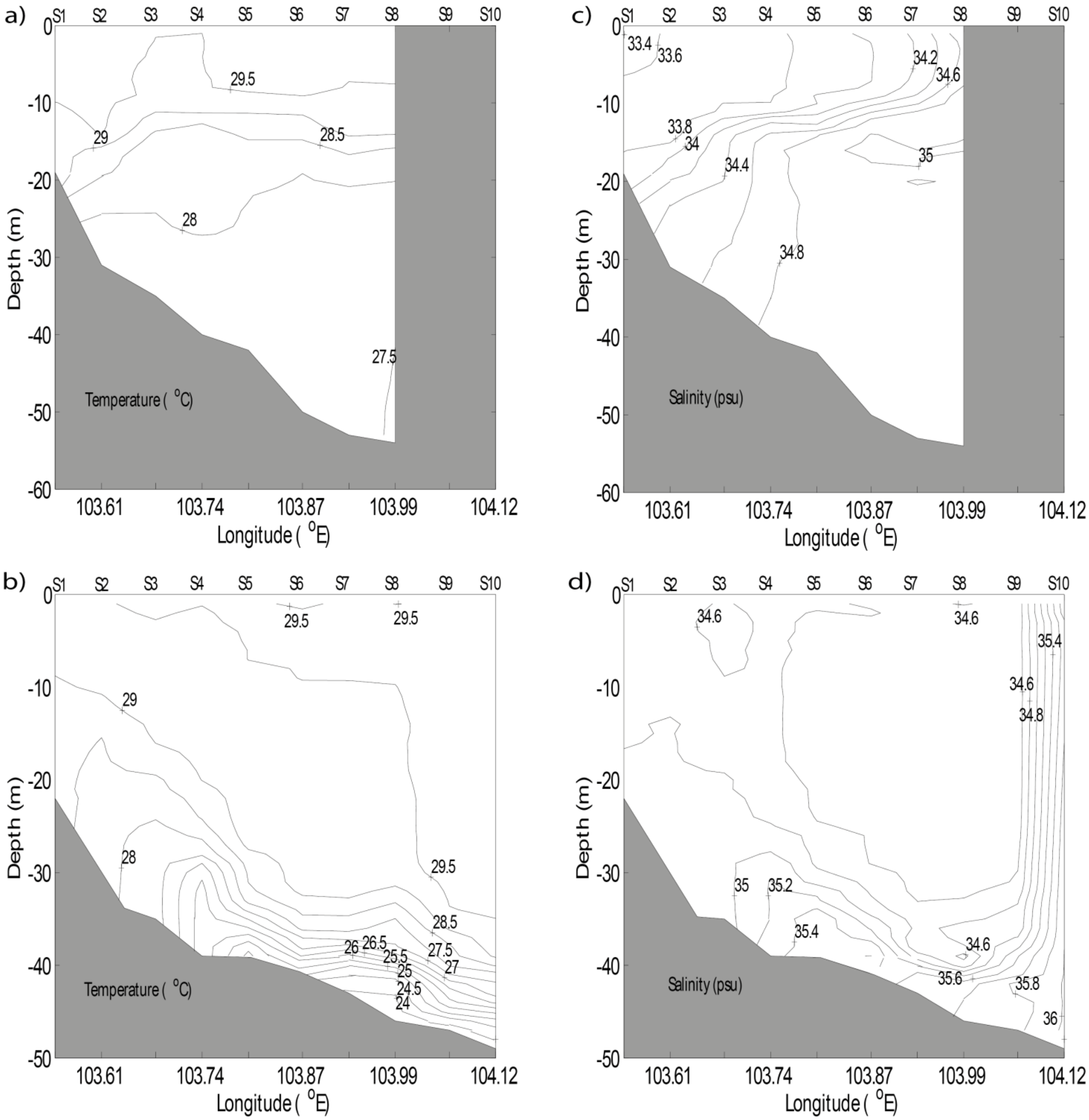


Figure 4 Contour plot of vertical temperature and salinity profile in T2 during April 2014 (a + c) and June 2014 (b + d). Please note that there was no data available during August

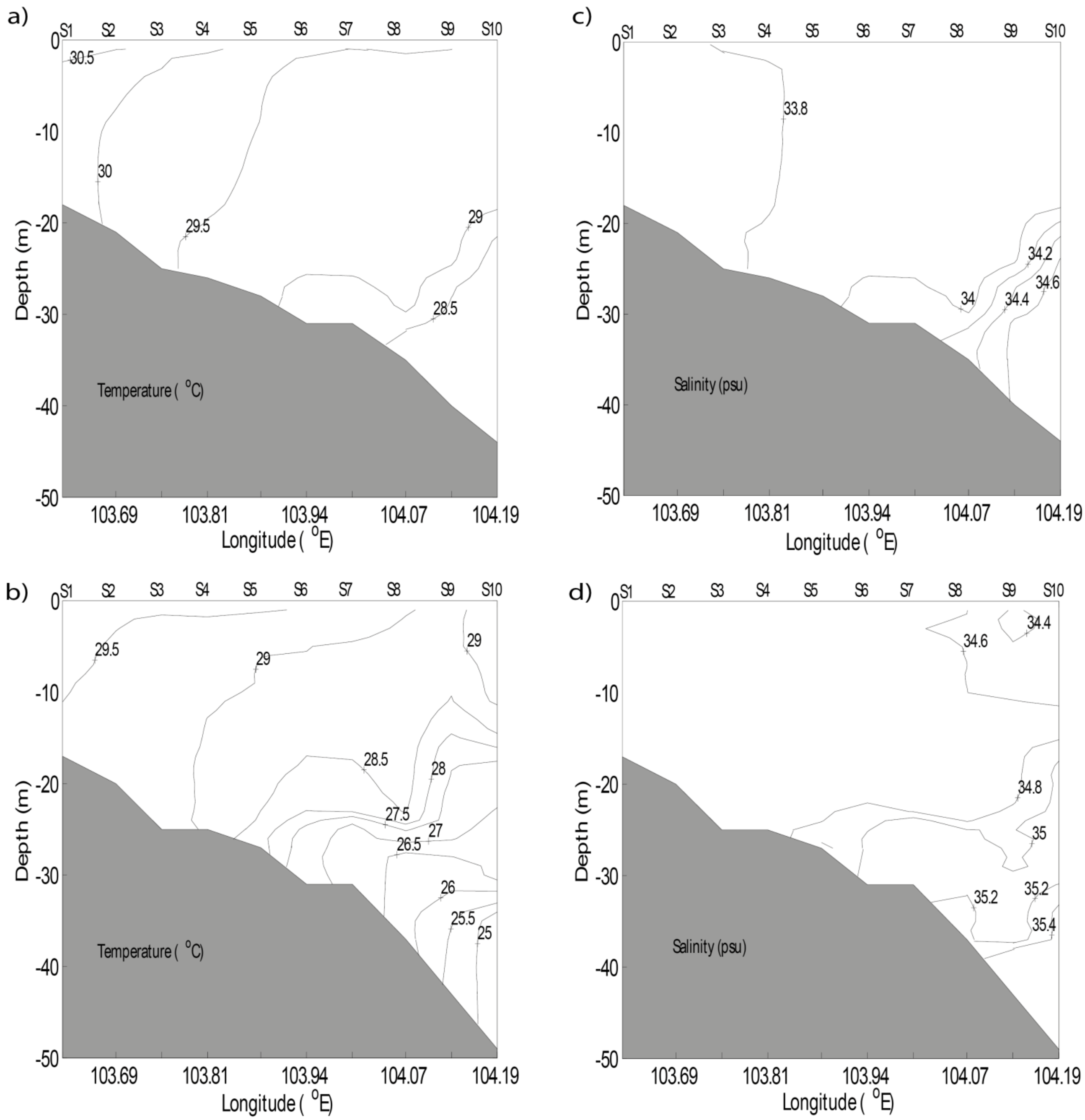


Figure 5 Contour plot of vertical temperature and salinity profile in T3 during April 2014 (a + c) and June 2014 (b + d). Please note that, the temperature and salinity profile during August 2014 was not plotted due to data limitation

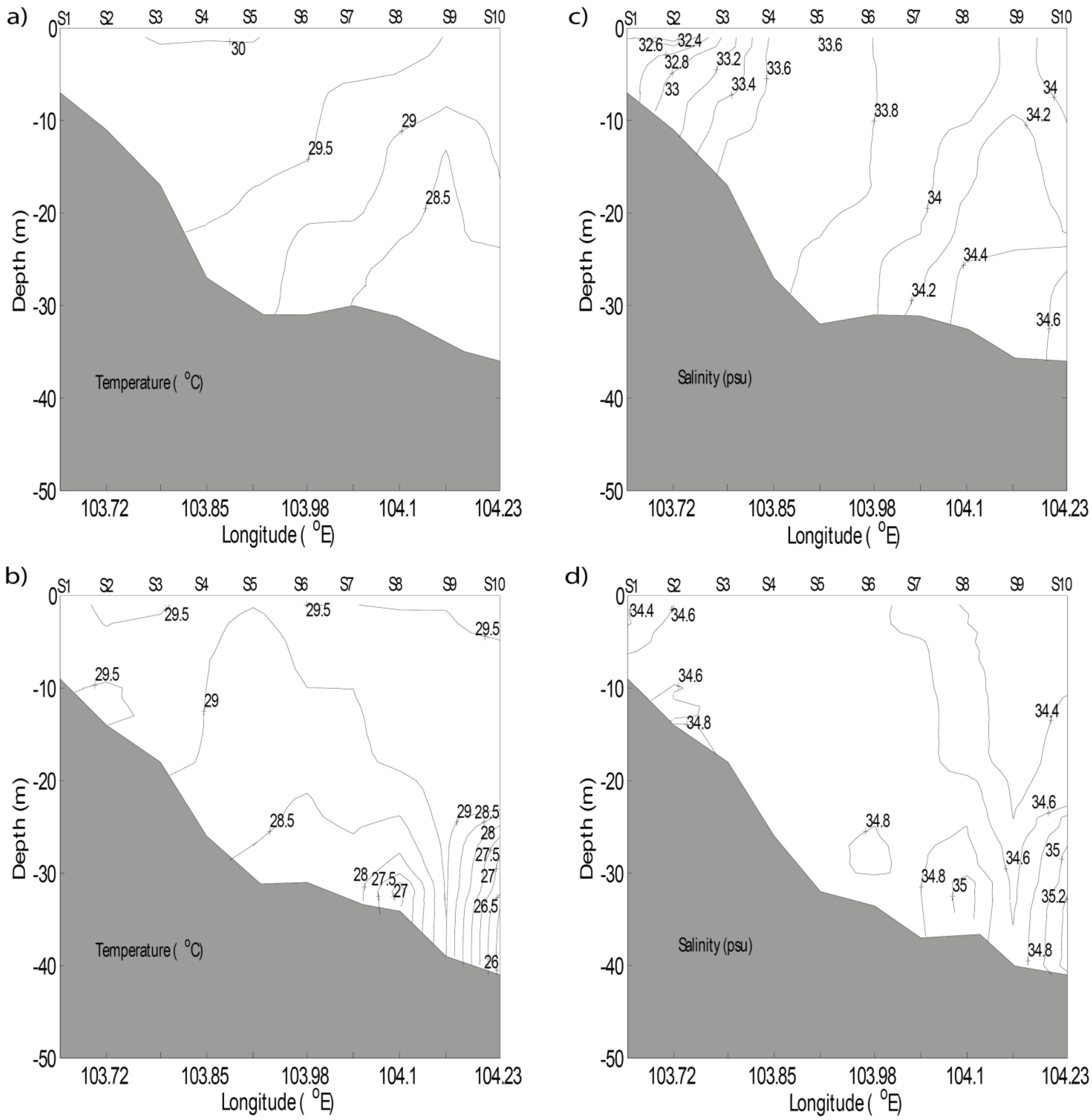


Figure 6 Contour plot of vertical temperature and salinity profile in T4 during April 2014 (a + c) and June 2014 (b + d). Please note that, the temperature and salinity profile during August 2014 was not plotted due to data limitation

3.2 Current Characteristics

Figure 7 shows the composite plot for the current flow off the Terengganu and Pahang coast during April, June and August, 2014 at selected depths (3m, 15m and 30m). The general surface current flow pattern during the study took after earlier studies of [7] and model simulation of [4]. Detailed examination of the current flow pattern in April 2014 (Figure 7a and 7d) showed that the surface and sub-surface layer of Terengganu and Pahang waters maintained a southward background flow that indicated the persistent of northeast monsoon dynamics. On the other hand, under the influence of the southwest monsoon, northward background flow was demonstrated in June (Figure 7b and 7e) and August (Figure 7c and 7f) for all transects. The magnitude of the current during this period was also relatively stronger than April. Interestingly, the current flow pattern of Pahang water maintained an identical direction in both surface and sub-surface layer. In opposite, the current direction in the selected depth observed at the nearshore stations of Terengganu area was slightly different. This situation was probably due to other dynamical influence at the nearshore area. From the result obtained, the major features of the current flow at Terengganu and Pahang water was under the monsoonal influence that include a southward flowing current during the transition period and northward background flow in southwest monsoon.

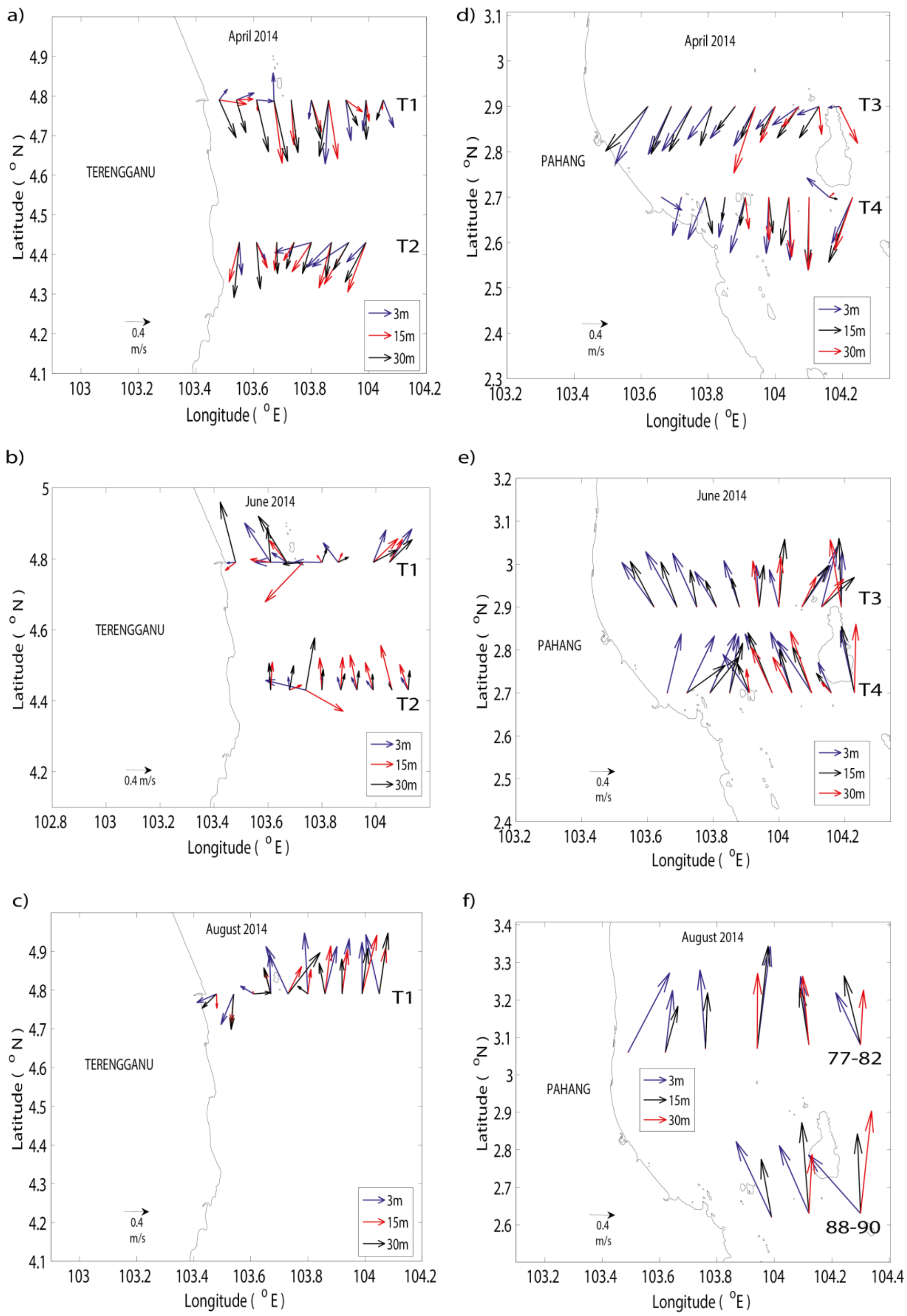


Figure 7 Composite plot for current component at 3m, 15m and 30m water depth at Terengganu (left panel) and Pahang (right panel) during April (a + d), June (b + e) and August (c + f) of 2014

3.3 Variations of Chlorophyll *a*

In order to understand the distribution pattern of the phytoplankton biomass under the seasonal influence, the extraction of surface chlorophyll *a* data obtained from level 3 of 8-days composite of MODIS satellite images at 4 km resolution was done according to the sampling stations. As mentioned earlier, chlorophyll *a* was selected in the analysis since they are reflecting the amount of phytoplankton biomass. Although analysis of the chlorophyll *a* was done on the water samples collected during the sampling trips, they were insufficient to represent the phytoplankton biomass in the study area. Therefore, the data extraction of MODIS chlorophyll *a* was carried out to give an overview of the phytoplankton biomass featuring monsoonal influence. Hence, Figure 8 shows the surface chlorophyll *a* concentrations extracted from MODIS satellite images during April, June and August, 2014. In general, the surface chlorophyll *a* concentrations for all transects during August 2014 with an average of 0.47 mg/m^3 were much higher than June (0.37 mg/m^3) and April (0.21 mg/m^3) of 2014. Furthermore, it was clear that the surface chlorophyll *a* concentrations at Pahang transects; T3 and T4 (Figure 8c and 8d) were much higher than the Terengganu transects; T1 and T2 (Figure 8a and 8b). It is worth noting that a maximum surface chlorophyll *a* of 1.27 mg/m^3 was observed at S1 of T4 during August 2014, whereas the minimum surface chlorophyll *a* of 0.076 mg/m^3 was noted at S9 of T1. The data described above suggests that the surface chlorophyll *a* concentrations during southwest monsoon (June and August, 2014) were slightly higher than the transition period (April 2014).

Figure 8a reveals that, the surface chlorophyll *a* concentrations at the nearshore stations of T1 were slightly higher than the offshore stations during April 2014. However, during June and August, 2014, there was a slight increase of surface chlorophyll *a* concentrations between 103.8 – 104.0 °E longitudes which possibly could be due to the coastal upwelling. A similar case was observed at T2; Figure 8b where S6 – S8 (103.8 – 104.0 °E) also recorded a slight increase of surface chlorophyll *a* concentrations during June and August, 2014. At T3 (Figure 8c), the slight increase of surface chlorophyll *a* concentrations was also observed 103.8 – 104.0 °E longitudes during June and August, 2014. But, there was also a slight increase of surface chlorophyll *a* concentrations at 104.0 – 104.1 °E longitudes which was due to the location of the stations within the coastal water of Tioman Island. On the other hand, at T4; Figure 8d, the surface chlorophyll *a* concentrations at S1 and S2 during June 2014 were slightly higher than August 2014 which was probably due to larger freshwater intrusion during June 2014 which might facilitate the invasion of nutrient rich water. Furthermore, both stations were less than 10-m water depth which might speed up mixing. However, in the other remaining stations, chlorophyll *a* concentrations during August 2014 was still higher than June 2014. Despite the differences, a slight increase of surface chlorophyll *a* concentrations in between 103.8 – 104.1 °E longitudes were observed in both months. This section managed to demonstrate the phytoplankton biomass featuring the coastal upwelling during June and August, 2014. It was expected that an increase of the surface chlorophyll *a* concentrations during both months were resulted from the development of coastal upwelling during the southwest monsoon.

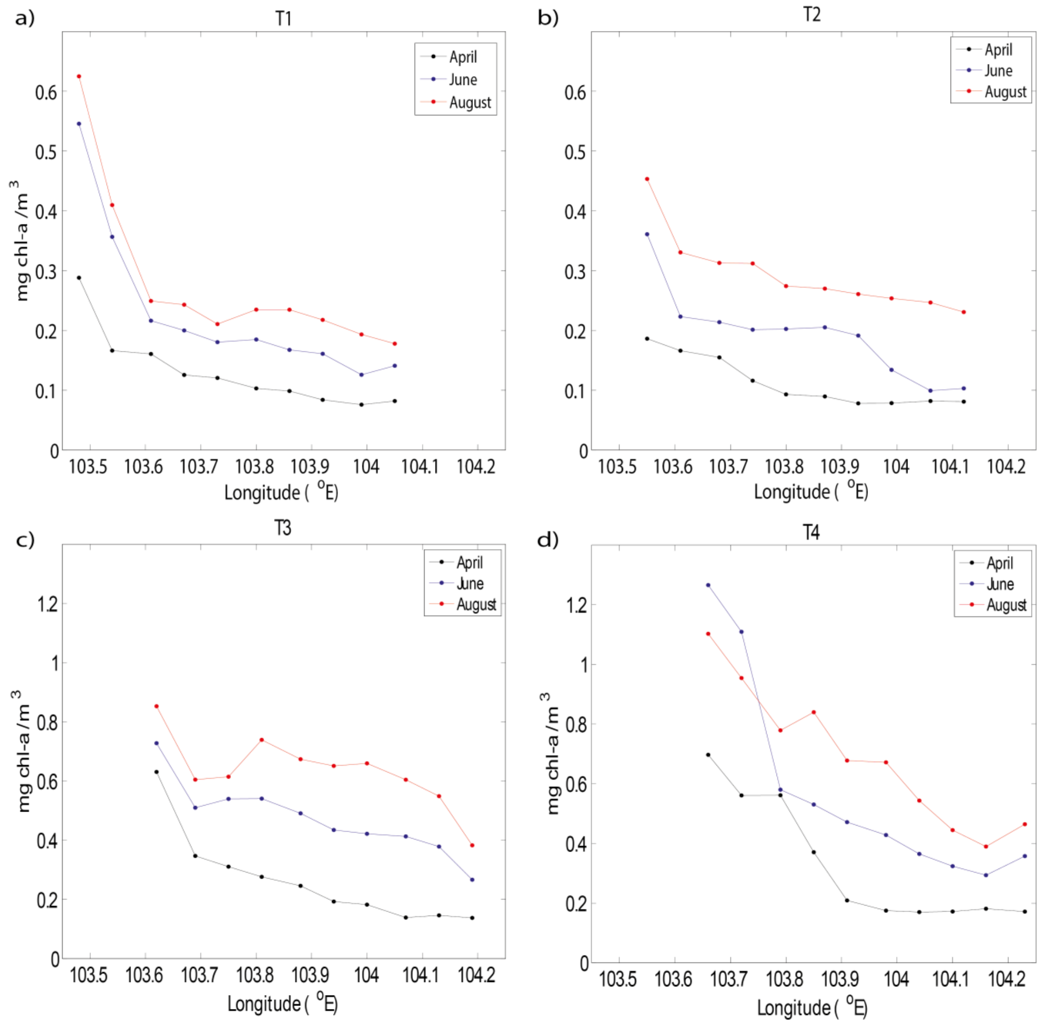


Figure 8 The surface chlorophyll a concentrations extracted from MODIS satellite images during April, June and August, 2014 at (a) T1, (b) T2, (c) T3 and (d) T4

3.4 Seasonal Variation of Nutrients

In order to further understand the phytoplankton biomass pattern under a different monsoonal season, the knowledge of the nutrients distribution is required since the change in the nutrient status could alter the phytoplankton community [8]. Therefore, the surface distribution pattern of nitrite (NO_2^-), nitrate (NO_3^-) and phosphate (PO_4^{3-}) during April and June, 2014 for the nearshore and offshore stations were presented in Figure 9. In general, the surface NO_2^- concentrations at the nearshore stations (Figure 9a) was slightly higher during April 2014 than June 2014 with an average concentrations of 0.0107 mg NO_2^--N/L and 0.0023 mg NO_2^--N/L respectively. The same case was noted at the offshore stations where April 2014 (0.0059 mg NO_2^--N/L) recorded slightly higher average surface NO_2^- concentrations than June 2014 (0.0006 mg NO_2^--N/L). Furthermore, a common feature of nutrient distribution was observed, where the surface NO_2^- concentrations at the nearshore stations was slightly higher than the offshore stations, which was due high nutrient input from river transport [9].

For the surface nitrate in Figure 9c and 9d, the nearshore stations recorded slightly higher NO_3^- concentrations during April 2014 with an average concentration of 8.55 µg NO_3^--N/L compared to 8.23 µg NO_3^--N/L in June 2014. However, no clear seasonal trend was observed from the surface NO_3^- concentrations at the offshore stations. Regarding the PO_4^{3-} concentrations, the average surface concentrations during April 2014 (0.0169 mg PO_4^{3-}-P/L) at the nearshore stations (Figure 9e) was lower than June 2014 (0.0295 mg PO_4^{3-}-P/L). On the other hand, the surface PO_4^{3-} concentrations at the offshore stations (Figure 9f) showed that, April 2014 recorded slightly higher PO_4^{3-} concentrations (0.0522 mg PO_4^{3-}-P/L) than June 2014 (0.0298 mg PO_4^{3-}-P/L). In summary, the nutrient concentrations at the study area fluctuated and no clear trend was evident, which was assumed as insufficient to give an overview of the nutrient distribution featuring seasonal influence.

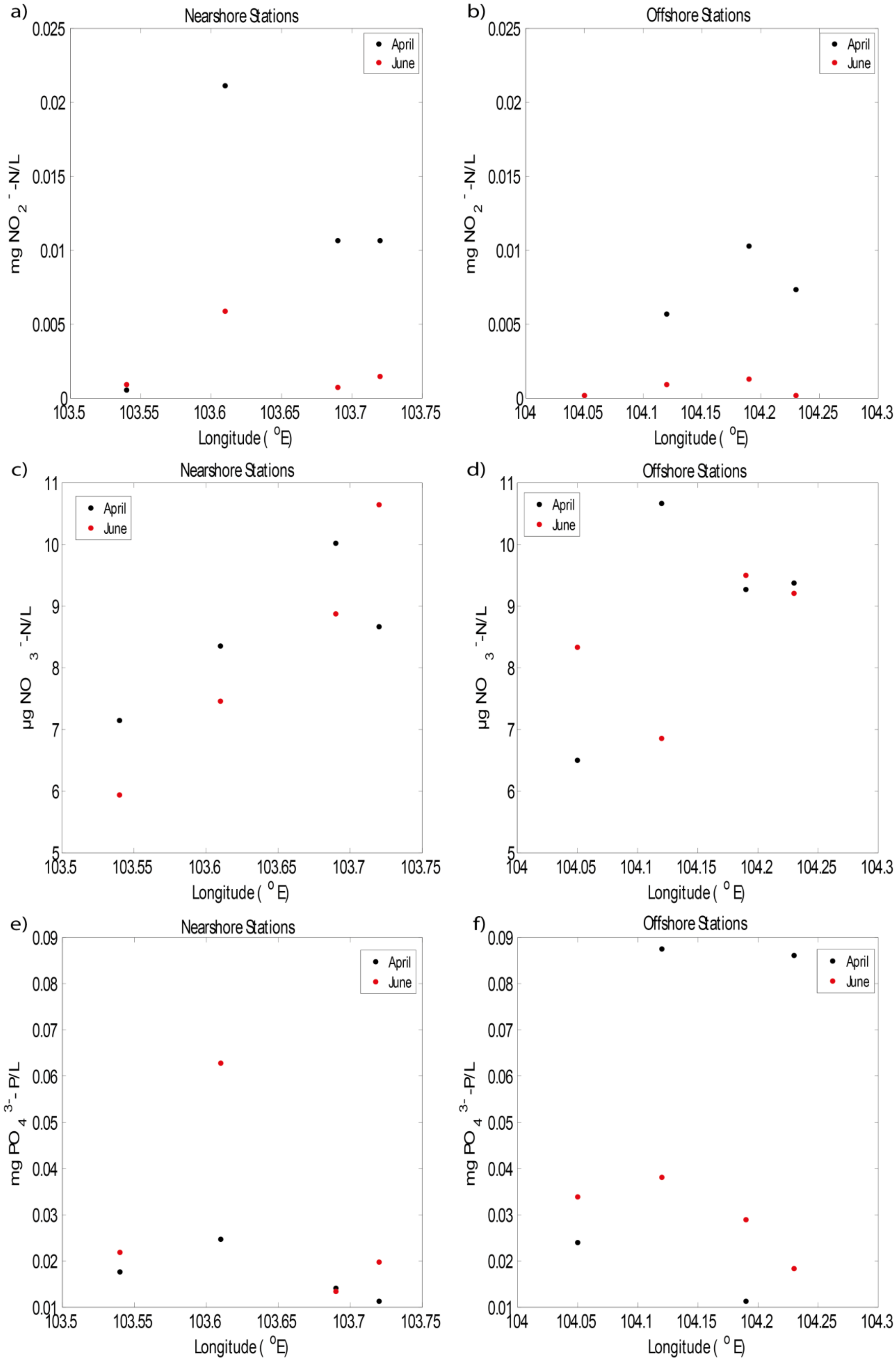


Figure 9 The surface distribution pattern of nitrite (NO2-) (a + b), nitrate (NO3-) (c + d) and phosphate (PO43-) (e + f) during April and June, 2014 for the nearshore (left panel) and offshore stations (right panel)

4.0 DISCUSSION

4.1 Evidences of Coastal Upwelling at Terengganu and Pahang Coasts

The spatial and temporal features of physical parameters confirmed the different behaviour of temperature during the transition period (April) and southwest monsoon (June and August). Generally, the surface temperature during August 2014 was slightly cooler than June and April, 2014 for all transects. On the other hand, the cross-shore observations revealed that at Terengganu transects (T1 and T2), the surface water at the nearshore stations was slightly cooler than the offshore stations, whereas at Pahang transects, the nearshore stations of T3 and T4 recorded slightly warmer surface temperature than the offshore stations. This observed difference is possibly due to two reasons. The first and most important is the presence of upwelling process. The surface water temperature during April 2014 was expected to be higher than June and August, 2014 since it was under the presence of large sea surface heating and weak wind [7]. However, slightly cooler surface temperature during August 2014 compared to June 2014 was believed to be as a result of coastal upwelling. In general, the occurrence of upwelling can be detected from the presence of cooler water that rises from the deep layers to replace the surface water. This process as reported before [4,10], brings low temperature water towards the surface. In addition, previous study by Jing *et al*. [11] also suggested that the appearance of the abnormal low temperature in the surface and subsurface water are good indicators of the upwelling. Secondly, the difference in the surface temperature between the nearshore and offshore stations of T1 and T2 was probably due to the intrusion of the low-temperature water, which was originated from the eastern coast of Vietnam. Similar finding was obtained by Akhir and Yong [12], where the low-temperature water from the eastern coast of Vietnam flowed to Malaysia due to strong southward. Interestingly, the current flow pattern during April 2014 (Figure 7a and 7d) agreed on this statement. Thirdly, the presence of slightly warmer surface temperature at the nearshore stations of T3 and T4 compared to the offshore stations suggested that the nearshore stations of both Pahang transects were mainly controlled by sea surface heat flux [7]. Moreover, due to shallow water depth at the nearshore stations of these transects, which was less than 30 m, quicken the mixing (Figure 4a and 4b) that lead to a homogenous water column [13].

A similar observation was obtained from the vertical profile of salinity where June 2014 recorded slightly saline surface water than April 2014. In addition, during June and August, 2014, the nearshore stations for all transects recorded slightly saline water than the offshore stations. The possible reason of this observation was the existence of upwelling, which bring cooler and slightly saline water towards the surface. Previous study by Song *et al*. [14] agreed on the statement since the presence of relatively low temperature and high salinity water was a common observation during upwelling. However, during August 2014, less saline water was observed compared April and June, 2014. This low-salinity water was expected as a result of the large river discharge. Similar results was obtained by Akhir *et al*. [1] and Yanagi *et al*. [15]. Although this study did not emphasize on the river discharge, however the rainfall data obtained from the Malaysian Meteorological Department (not shown) agreed that there was an increase in the amount of rainfall during August 2014 compared to April and June, 2014.

Apart from temperature and salinity variation, this study had managed to prove the presence of shallow thermocline at the nearshore stations and deeper thermocline at the offshore stations for all transects during June and August, 2014. It has been suggested that this situation was in response to southwest monsoon wind [4,15]. To further confirm the role of southwest monsoon winds towards the upwelling process, monthly wind stress and Ekman transport during the study period was plotted. Upon comparison of the wind stress (Figure 10a – 10c) between transition period and southwest monsoon, it can be inferred that the wind pattern during April 2014 was slightly slower than June and August, 2014. Similar finding was observed in previous study by [16], where weak southwesterly monsoon wind had resulted in a weaker wind stress during April – August. Furthermore, Marghany [13] also found that the wind pattern during transition period does not have consistent flow. In this study, the wind stress intensity off the Terengganu coast (Figure 10a) was stronger than Pahang coast during April 2014 that could possibly lead to the mixing at the nearshore stations of T3 and T4 (Figure 4a and 4b). Interestingly, in June and August, slightly strong northward wind stress was noted parallel to ECPM (Figure 10b – 10c). This condition supported our observation on upwelling at ECPM where strong positive wind stress is usually associated with the upwelling process [17]. Moreover, this alongshore wind stress recorded at ECPM during southwest monsoon was also believed to generate the offshore Ekman transport showed in Figure 10d and 10e. Despite its role in bringing cooler water towards the surface, this offshore Ekman transport also responsible in the deepening of thermocline layer and uplifting of isotherms towards the coast [15]. Remarkably, the absence of this offshore Ekman transport would lead to the disappearance of the upward flow of cool water from bottom to surface water [4] during upwelling. Therefore, it was strongly believed that the southwest monsoon winds played a great role in upwelling formation at Terengganu and Pahang area.

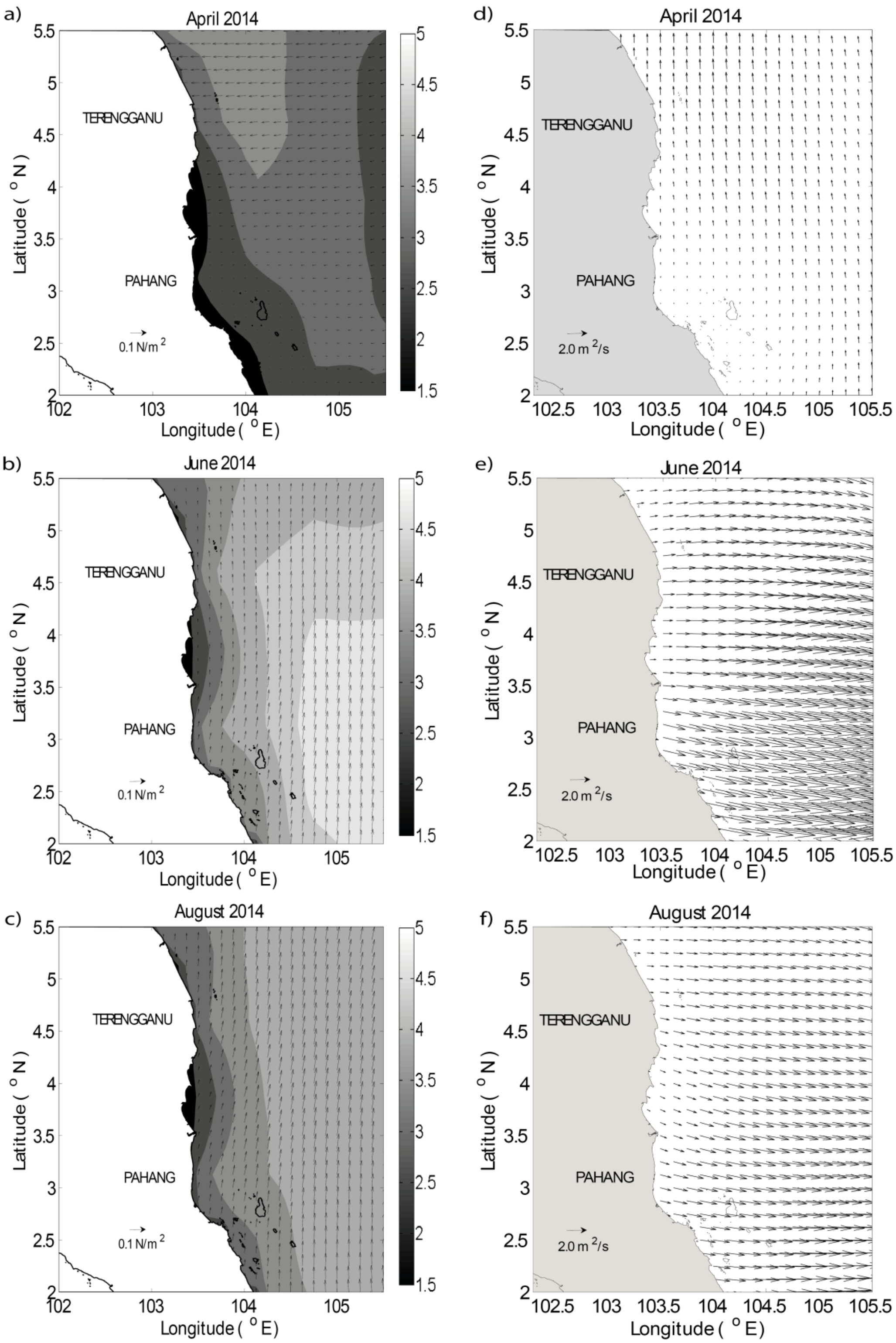


Figure 10 Monthly wind stress for (a) April, (b) June, (c) August, 2014 and monthly Ekman transport for (c) April, (d) June, (e) August, 2014

Apart from *in situ* data collection, monthly satellite data derived from Aqua-MODIS, which represent the study area during the transition period (April 2014) and southwest monsoon (May – September, 2014) was also used for detailed discussion on this topic. Horizontal distribution of monthly composite of sea surface temperature (SST) from the MODIS data is shown in Figure 11. Compared with *in situ* observation of temperature, similar patterns of SST could be found along the ECPM. They were generally low during August compared to April and June. Coastal upwelling process was believed to be the main causative factor of this cooler SST water. It was predicted that through the presence of upwelling, the alongshore wind can easily pump the cold water beneath the subsurface layer towards the surface along the ECPM. After being initiated in June, with the help of the strong western boundary current (Figure 11) the cool water was transported from southern to northern part along the ECPM in July specifically at 104 °E longitude. Obviously, the SST distribution revealed that coastal upwelling along the ECPM was fully developed in August and started to diminish in September.

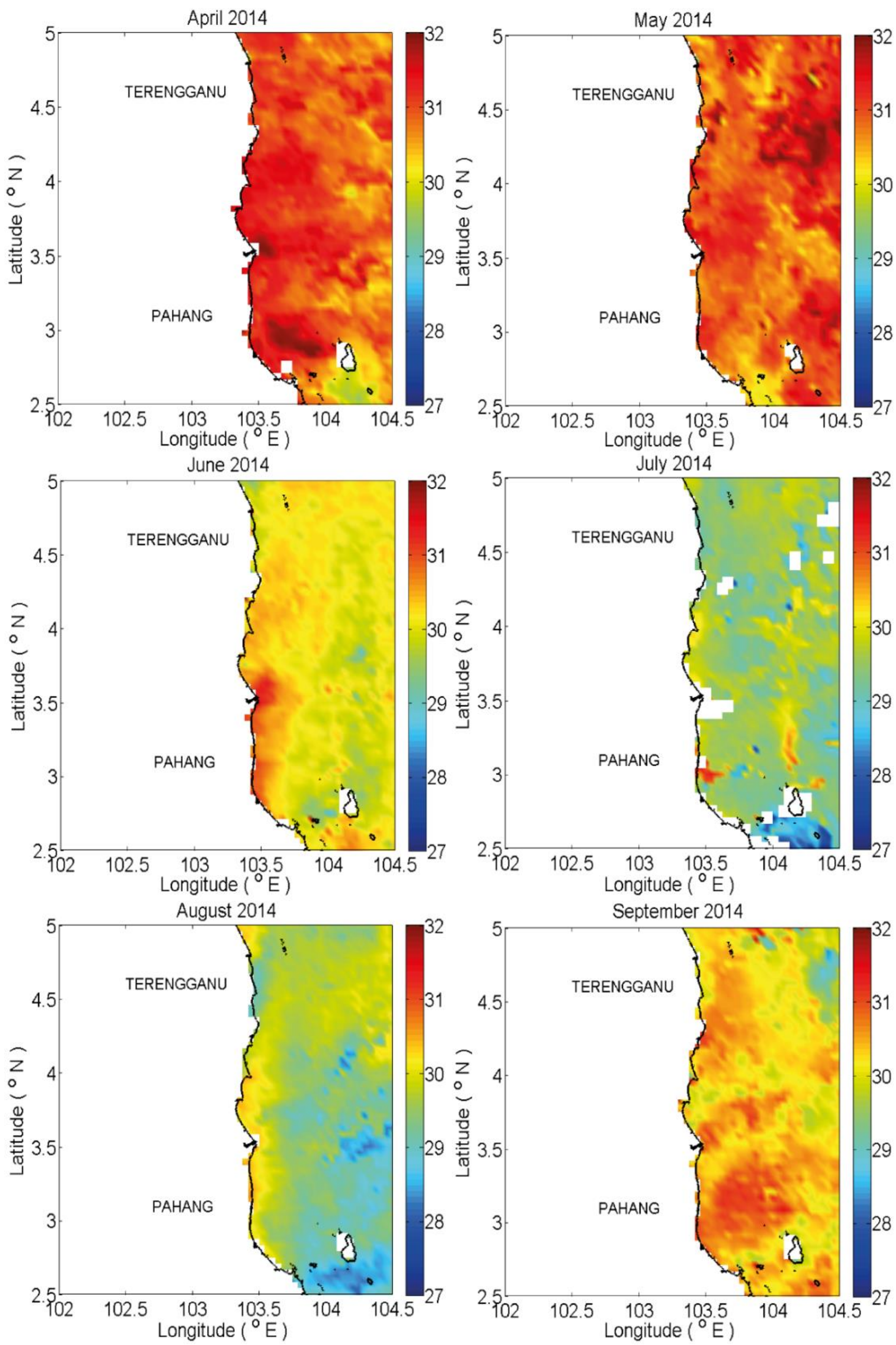


Figure 11 Monthly SST (°C) from MODIS during the transition period (April 2014) and the southwest monsoon (May – September, 2014)

4.2 Temporal Variations of Phytoplankton Biomass at ECPM

Before a further discussion of the phytoplankton biomass is made, it was believed that the satellite data validation is required to interpret the satellite measurements. Therefore, the chlorophyll *a* concentrations obtained from the study cruise was used to validate the satellite data obtained from Aqua-MODIS. The relation between the in situ chlorophyll *a* measurements and the data extracted from MODIS satellite images was presented in Figure 12. The correlation analysis between the *in situ* and MODIS chlorophyll *a* showed that the in situ concentrations was positively related to the data extracted from the satellite with the R^2 = 0.83. Therefore, we could conclude that the data extracted from the satellite images were pretty similar to the *in situ* measurements and could be used to represent the study area.

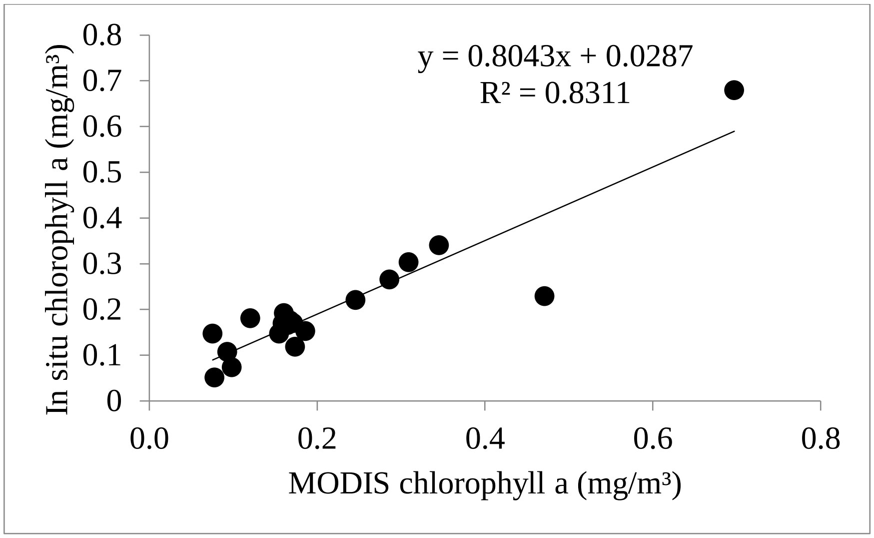


Figure 12 Correlation of MyCON in situ chlorophyll a (mg/m3) and 8-days composite of MODIS satellite chlorophyll a images (mg/m^3)

The physical and biological parameters discussed before suggested that the distribution of phytoplankton biomass at Terengganu and Pahang coast was influence by monsoonal season. It also revealed that the phytoplankton biomass along Pahang transects (T3 and T4) was generally higher than the Terengganu transects (T1 and T2). The coastal upwelling and the freshwater intrusion are the possible reasons for the difference.

In this region, due to upwelling that brings nutrient-rich water, the amount of phytoplankton biomass also increases during the southwest monsoon than the transition period. Although the nutrient data in this study were insufficient to prove the statement, however previous study Nazmi *et al*. [18] did find that the surface chlorophyll *a* concentrations were highly determined by nutrient availability. Moreover, it has been suggested that the abundant nutrient supply could help to stimulate the phytoplankton growth [19]. Such a mechanism was also found in other SCS area [14,20,21].

Interestingly, during the southwest monsoon, the chlorophyll *a* concentration in August 2014 for all transects (Figure 8) was slightly higher than June 2014, which clearly demonstrated the phytoplankton biomass featuring coastal upwelling condition. This is because, June is usually the initiation phase of upwelling, meanwhile August is associated with the fully-develop upwelling [1]. Therefore, slightly higher surface chlorophyll *a* concentrations during August 2014 was believed to be associated with the well-developed upwelling and this condition is believed to be adequate to support the evidence of coastal upwelling at the study area.

Apart from coastal upwelling, the second factor to look at is the freshwater intrusion. As mentioned earlier, Pahang transects are located near to the main river of the area. This may facilitate the intrusion of freshwater along the Pahang area and bring in more nutrient loadings which support the variation of phytoplankton biomass as demonstrated in Figure 8. Similar results obtained by previous researches [19,21,22], where the freshwater discharge did affect the phytoplankton community. Therefore, it can be assumed that despite the coastal upwelling that acts as a key role in shaping the phytoplankton biomass at ECPM, the freshwater intrusion, which flushed in nutrient, might also affect the growth of phytoplankton.

4.0 CONCLUSION

In conclusion, the results demonstrated the presence of upwelling during the southwest monsoon. During the southwest monsoon (June and August, 2014), it seems that both Terengganu and Pahang waters recorded slightly cooler surface temperature than the transition period (April 2014). Furthermore the surface temperature records at the nearshore stations were also cooler than the offshore stations. The presence of upwelling process and the freshwater intrusion were the possible reason of this observation. Apart from the existence of cooler water, the uplifting of isotherms and isohalines was also indicating the upwelling process. Other than *in situ* data observation, the MODIS SST images also verified the presence of upwelling at Terengganu and Pahang coasts. Stronger northward currents resulted from strong southwest monsoon winds was believed to be the causative factor in the appearance of upwelling in this region. The offshore Ekman transport generated from positive wind stress was also a good indicator in determining the existence of upwelling at both Terengganu and Pahang area. Finally, coastal upwelling and nutrient availability was believed to influence the phytoplankton biomass during the study trips. Interestingly, the area of high phytoplankton biomass at the ECPM was also well-agreed with the area of elongated cooler SST along the ECPM that indicate the influence of upwelling mechanism.

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