Indian Journal of Geo Marine Sciences
Vol. 47 (12), December 2018, pp. 2532-2540

Upwelling event characteristics of chlorophyll-a concentration in the surface layer of Sabah waters

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Received 05 May 2017; revised 24 July 2017

Using satellite-based remote sensing data, the study analysed Chl-a levels throughout Sabah's coastal waters and correlated the Chl-a levels with the corresponding SST levels for that time and region. It was found that upwelling in Sabah coastal waters was most strongly noted in Labuan during the Northeast Monsoon (NEM), which brings strong northeasterly winds to Sabah's west and north coast. The strong winds can be cited as the main source of increased upwelling as SST levels did not sufficiently change to suggest a strong relationship between SST and Chl-a levels.

[**Keywords*:*** Upwelling; Sabah; chlorophyll-a; remote sensing; sea surface temperature]

Introduction

Upwelling is an oceanographic phenomenon that involves wind-driven motion of dense, cooler, and usually nutrient-rich water towards the ocean surface, replacing the warmer, usually nutrient-depleted surface water. The three mechanisms that drive the occurrence of upwelling event are the wind, Coriolis effects, and Ekman transport. Winds blowing across the ocean surface push water away and then cold water rises up from beneath the surface toreplace the warm water that was pushed away. During the wind-water interaction, Coriolis forces are the frictional forces that dictate which way the water will move. Ekman transport moves the surface layer of water away from the direction of the wind. Details of the mechanism of upwelling process are discussed elsewhere. Due to the biomass of phytoplankton and presence of cool water in these regions, upwelling zones can be identified by cool sea surface temperatures (SST) and high concentrations of chlorophyll-a [1–3].

There are at least five types of upwelling: coastal upwelling, large-scale wind-driven upwelling in the ocean interior, upwelling associated with eddies, topographically-associated upwelling, and broad-diffusive upwelling in the ocean interior. Wind-driven coastal upwelling is one of the best-known types of upwelling which usually occurs along the coastal region. It is also most related to human activities as it supports some of the most productive fishing zones in the world. This is because one of the most significant effects from upwelling event is the turbulence on the density and distribution of chlorophyll-a concentration in the up welled region areas[4,5]. Besides, coastal upwelling ecosystems are well known to feature cold, nutrient-rich and high biological production which contribute to rich fisheries. Chlorophyll-a (Chl-a) is a proxy measurement of phytoplankton biomass and photosynthetic potential. Ocean chl-a concentration governs the most important property that characterizes marine trophic level and is highly related to marine production [6].

Uiboupin & Laanemets (2009)identified upwelling characteristics from satellite-obtained SST data in the Gulf of Finland and the Baltic Sea. Upwelling events were noted in terms of their size, location and temperature difference relative to the surrounding water. The study established that water in an area undergoing upwelling would be cooler than the surrounding water by 3-15^{O}C.Goela *et al.* (2016) analyzed the relationship between SST and upwelling conditions by statistical analysis of publically available data in the North Atlantic off southern Portugal. By comparing SST and longitudinal and latitudinal Ek man transports (net motion of fluid caused by the Earth's rotation and turbulent drag), the study found that positive upwelling, as shown by anomalies in Ekman transports, would be followed by a noticeable decrease in SST levels. It was also noticed that there was a delay of a few days between the upwelling and the drop in SST, which was attributed to the time taken for the upwelled current to travel to the coastal research area from the upwelling area further offshore. An overview of physical and biogeochemical processes and eco system dynamics in the Taiwan Strait also revealed that hydrographical features with an emphasis on upwelling is the key driver as whole [9]. The growth of phytoplankton is also governed by several other factors such as intensity of light reaching the surface water [10], the rate of warming of cold upwelled water [11], depth of stratified up welled layer [12]and cumulative wind stress[7,13].

Some upwelling systems bring continuous and others bring periodic pulses of nutrients to the surface water. Due to large area extent, ship surveys are unlikely to capture periodic upwelling events. Satellite remote sensing, on the other hand, has the advantages of synoptic and repetitive coverage to identify and monitor the upwelling characteristics. Many past studies have focused on the primary productivity of chlorophyll-a concentration and its variability in the equatorial South China Sea via satellite remote sensing[14,15], but none has really scrutinized into Sabah waters. Present study consists the temporal variation and spatial distribution of chlorophyll-a concentration on the basis of remote sensing observation before, during and after upwelling event in Sabah waters.

Materials and Methods

Data for this study was obtained from the OceanColorWEBsite (http://oceancolor.gsfc.nasa.gov/cgi/l3) operated by the National Aeronautics and Space Administration (NASA). This website compiles and distributes all data obtained by NASA-operated remote sensing equipment. When used together with SeaDAS Visualization, an analyzing application, data obtained from Ocean Color WEB can be visualized and interpreted. This study used chlorophyll-a (Chl-a) and SST data as obtained from the Aqua MODIS sensor. Two sets of data each were obtained; annual composites covering 13 years (2002-2015) and monthly averages covering 36 months (July 2013-June 2016). Table 1 states the full specifications of the datasets used for this study. Research areas used in this study were defined to sufficiently cover Sabah waters, with Table 2 showing the dimensions of the research areas and Figure 1 visualizing the research areas on Google Earth.

Results & Discussion

Figure 2 shows the bar chart and box plot of the Chl-a concentration for the five study areas in Sabah coastal waters measured from 2002 to 2015. Within the study period, Labuan waters recorded the highest mean Chl- a concentration at approximately 2.65 mg/m^3, and Tawau waters recorded the second highest mean at1.22 mg/m^3. Other study areas recorded low Chl-a concentration of less than <1.00 mg/m^3 with the lowest in Kudat (0.75 mg/m^3), followed by Sandakan (0.77 mg/m^3), and Kota Kinabalu (0.96 mg/m^3). Over the years, the variability of Chl-a concentration was the highest in Labuan waters with std. dev. ±0.35 and the lowest in Sandakan and Tawau waters at ±0.06. Variability of Chl-a concentration in Kota Kinabalu and Kudat was moderate at ±0.23 and ±0.11, respectively. Five regions in Sabah waters were analyzed separately and some regularities were observed. Table 3 summarizes the anomalies, ψ of Chl-a concentration in the ratio over the five regions in Sabah waters. The anomalies were determined with reference to a normal Chl-a concentration value established using 14-year time series data from 2002 to 2015. Indicator ↑ represents

Table 1 — Specifications of data sets obtained

Parameter	Sensor & Product	Resolution	Compositing period	Products downloaded
SeaSurface Temperature (SST), $_o$C	Aqua MODIS Sea Surface Temperature (11μ daytime)	9km	Monthly	July 2013 – June 2016
			Annual Composite	2002-2016
Chlorophyll-a levels, mg m^{-3}	Aqua MODIS Chlorophyll Concentration, OCI Algorithm	9km	Monthly	July 2013 – June 2016
			Annual Composite	2002-2016

Table 2 — Dimensions of research areas. Coordinates refer to the centre points of research areas

Point	Place	Lat	Lon	Length of sides , km
LBU	Labuan	5.28	115.23	100
BKI	Kota Kinabalu	5.98	116.07	100
KUD	Kudat	7.07	117.02	140
SDK	Sandakan	6.11	118.57	200
TWU	Tawau	4.28	118.56	200

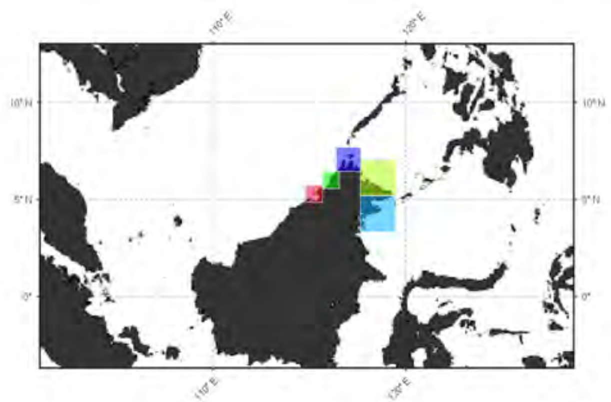

Fig. 1 — Map of Sabah with the location of Labuan (red), Kota Kinabalu (green), Kudat (blue), Sandakan (yellow), and Tawau (cyan).

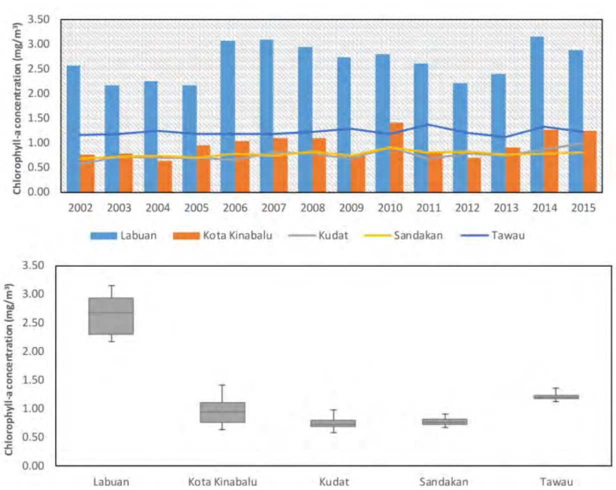

Fig. 2 — Satellite-derived Chlorophyll-a concentration in clustered column bar chart (upper) and box plot (lower) over the five study areas in Sabah coastal waters measured from 2002 to 2015.

positive anomalies of Chl-a concentration and ↓represents negative anomalies, while the highlighted indicator represents the three most significant increase or decrease over the years. In Labuan waters, some major upwelling events were recordedin 2006, 2007, and 2014 with an average Chl-a concentration of >3.00 mg/cm^3 was recorded. In Kota Kinabalu and Kudat waters, three highest mean Chl-a concentration of >1.30 mg/cm^3 (KK) and >0.80 mg/m^3 (KDT) were recorded in 2010, 2014, and 2015. In Sandakan and Tawau waters, the upwelling events were not significantly observable because there was no specific unusual high or low Chl-a concentration measured over the years. In other words, the trend of Chl-a concentration over east coast region in Sabah was rather consistent with little to insignificant fluctuations. On the other hand, unusually low Chl-a concentration of <2.20 mg/cm^3 was recorded in 2003, 2005, and 2012 in Labuan waters. In Kota Kinabalu and Kudat waters, low Chl-a concentration of <0.70 mg/cm^3 was recorded in 2002, 2004, 2006, 2009, 2011 and 2012.

In order to understand the seasonal variation of Chl- a concentration in Sabah waters throughout the year, we selected three most recent years from July 2013 to June 2016 to examine the variability of Chl-a concentration. On spatial analysis, the highest mean Chl-a concentration was recorded in Labuan waters (>2.00 mg/m^3), followed by Tawau(>1.00 mg/m^3), and Kota Kinabalu (~1.00 mg/m^3). Meanwhile, low mean Chl-a concentration was consistently recorded in Kudat and Sandakan waters at approximately 0.80 mg/m^3. Figure 3 shows the monthly mean Chl-a concentration off the main five study areas in Sabah measured from July 2013 to June 2016. In Sabah waters, there are two major monsoon seasons experienced throughout the year. The first is northeast monsoon (NEM) which starts from November until February, while the second is southeast monsoon (SWM) which spans from May to August. During the NEM, strong northeasterly wind is expected over the west coast and northern coast of Sabah. In winter, northeasterly cold winds blowing along the coast induce the cooling and hence a densification of the surface water resulting in strong vertical mixing. The mixed layer depth reaches the bottom in most of the region, therefore contributing to the nutrient enrichment of the surface layer, therefore favoring the photosynthetic activity [16]. However, the southeastcoast off Tawau receives relatively weak NEM wind in contrast to other regions. During the SWM, weak southeasterly wind is expectedover Labuan, Sandakan, and Tawau but relatively higher speed is expected at the northwest part off KK and the northern tip off Kudat. A consistent bell-curved pattern was observed for the variability of Chl-a concentration in Labuan waters where the concentration often peaks during the NEM (Nov – Feb). Within the 3 consecutive years, the

Table 3 — Anomalies of Chl-a concentration (mg/m^3) in ratio over the five regions in Sabah waters from 2002 to 2015. Indicator↑ represents positive anomalies and ↓represent negative anomalies. Red highlighted indicators are three most significant increase or decrease of Chl-a concentration over the years.

Year	Labuan			Kota Kinabalu			Kudat			Sandakan			Tawau		
	Chl-a	ψ		Chl-a	ψ		Chl-a	ψ		Chl-a	ψ		Chl-a	ψ	
2002	2.57	0.97	↓	0.75	0.78	↓	0.57	0.76	↓	0.67	0.87	↓	1.16	0.95	↓
2003	2.17	0.82	↓	0.79	0.82	↓	0.72	0.96	↓	0.72	0.94	↓	1.19	0.97	↓
2004	2.26	0.85	↓	0.64	0.66	↓	0.70	0.94	↓	0.73	0.95	↓	1.24	1.02	↑
2005	2.16	0.82	↓	0.95	0.99	↓	0.70	0.93	↓	0.70	0.91	↓	1.18	0.96	↓
2006	3.07	1.16	↑	1.03	1.07	↑	0.65	0.87	↓	0.79	1.02	↑	1.18	0.97	↓
2007	3.10	1.17	↑	1.10	1.14	↑	0.81	1.07	↑	0.73	0.95	↓	1.18	0.97	↓
2008	2.94	1.11	↑	1.09	1.14	↑	0.78	1.04	↑	0.82	1.07	↑	1.23	1.01	↑
2009	2.73	1.03	↑	0.74	0.77	↓	0.68	0.91	↓	0.73	0.95	↓	1.29	1.06	↑
2010	2.80	1.06	↑	1.41	1.47	↑	0.90	1.20	↑	0.90	1.17	↑	1.17	0.96	↓
2011	2.61	0.99	↓	0.82	0.85	↓	0.68	0.90	↓	0.80	1.05	↑	1.36	1.11	↑
2012	2.22	0.84	↓	0.69	0.72	↓	0.79	1.05	↑	0.82	1.06	↑	1.19	0.98	↓
2013	2.39	0.90	↓	0.91	0.95	↓	0.74	0.98	↓	0.75	0.98	↓	1.13	0.92	↓
2014	3.15	1.19	↑	1.27	1.32	↑	0.87	1.15	↑	0.78	1.01	↑	1.34	1.09	↑
2015	2.89	1.09	↑	1.25	1.30	↑	0.98	1.31	↑	0.81	1.05	↑	1.23	1.01	↑
Avg	2.65			0.96			0.75			0.77			1.22		
STD	0.35			0.23			0.11			0.06			0.07		

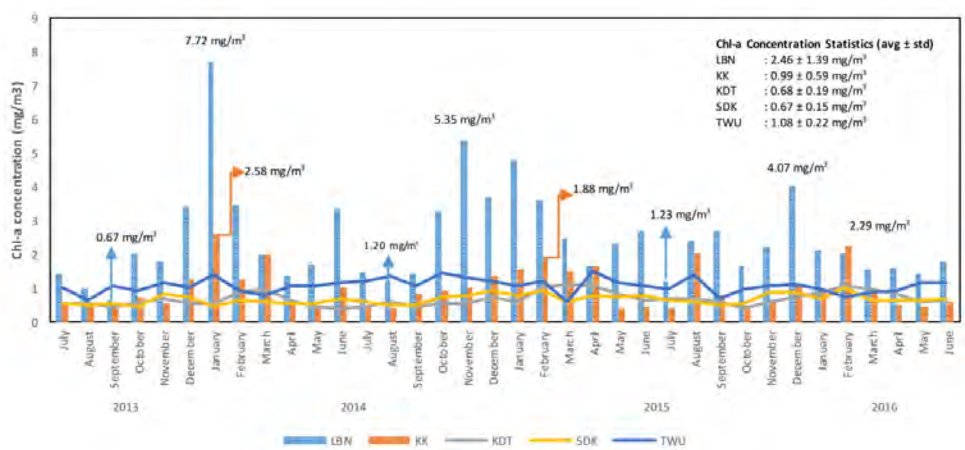

Fig. 3 — Monthly mean Chl-a concentration off the main five study areas in Sabah measured from July 2013 to June 2016. Maxima values are labeled to highlight extreme occurrence of Chl-a concentration.

Chl-a concentration over Sabah coastal areas is the most abundantin Labuan waterswhich peaks in Jan’14 (7.72 mg/m^3), Nov’14 (5.35 mg/m^3), and Dec’15 (4.07 mg/m^3). For Kota Kinabalu waters, the Chl-a concentration often peaks in the late NEM in Jan’14 at 2.58mg/m^3, Feb’15 at 1.88 mg/m^3, and Feb’16 at 2.29 mg/m^3. In contrast, the Chl-a concentration in Kudat, Sandakan, and Tawau waters is quite consistent where no significant seasonal pattern was observable. The coefficient of variation in std. dev. was less than <0.20 mg/m^3 for all regions in Kudat, Sandakan, and Tawau. On the other hand, the low Chl-a concentration over Sabah coastal regions normally occurs during the SWM or transition period between NEM-SWM. In Labuan waters, three significant low Chl-a concentration events were recorded in Sept’13 at 0.67 mg/m^3, Aug’14 at 1.20 mg/m^3, and Jul’15 at 1.23 mg/m^3. In a similar pattern, for Kota Kinabalu waters, the three lowest Chl-a concentration events were recorded in Sept’13 at 0.41 mg/m^3, Aug’14 at 0.40 mg/m^3, and May’15 at 0.40 mg/m^3.

Satellite-derived data observed by MODIS radiometer was used to determine the anomalies of chlorophyll-a (Chl-a) concentration in the surface sea layer and sea surface temperature (SST). The anomalies were determined with reference to thenormal value established using 14-year time series data from 2002 to 2015. We selected Labuan and Kota Kinabalu region to demonstrate the effects of SST on thedensity of chlorophyll due to its significant variability in Chl-a concentration over the years. Figure 4 presents the monthly mean Chl-a concentration and SST recorded in Labuan waters (upper) and Kota Kinabalu waters (lower) together with its corresponding anomalies, ψ from July 2013 to June 2016. Within the 3 consecutive years, maxima concentration of Chl-a in Labuan and Kota Kinabalu waters were consistently recorded during the NEM. Looking at these maxima, the behavior of SST exhibits a consistent pattern where high Chl-a concentration is often associated with low SST. The evolution pattern between Chl-a concentration and SST was not completely direct but a sturdy high Chl-a concentration is often entailed with low SST especially during NEM. In contrast, the low Chl-a concentration occurred for high SST consistently especially during SWM. The high SST was normally recordedin the month May – August for approximately higher by 2°C from the normal SST. Looking at the statistics on SST, we believed that theincrease of 2°C is beyond normal fluctuation. The annual composite of SST in Labuan and Kota Kinabalu waters is 30.0°C and expected to fluctuate of not more than 0.3~0.4°C. More specifically, the monthly composite of SST exhibits the similar average value but slightly higher fluctuation of 1.0°C. In Kota Kinabalu waters, two maxima SST of >32°C were recorded in Jun'15 and May'16. The corresponding Chl-a concentration recorded was relatively low at 0.48 mg/m^3 and 0.45 mg/m^{3}which is below the average value by 0.50 mg/m^3.

The area coverage of high Chl-a and low SST is a good indicator of upwelling event, which changed notably in the westerncoastof Sabah waters in January 2014. Variability is shown by the areal extent of eutrophic waters for the study regions in Figure 5, which was higher in early-January (J008) and late-January (J032)than the previous or subsequent days. In mid-January (J016 and J024), the extent of eutrophic water decreased considerably where most of the areas have no data. Missing data was probably due to

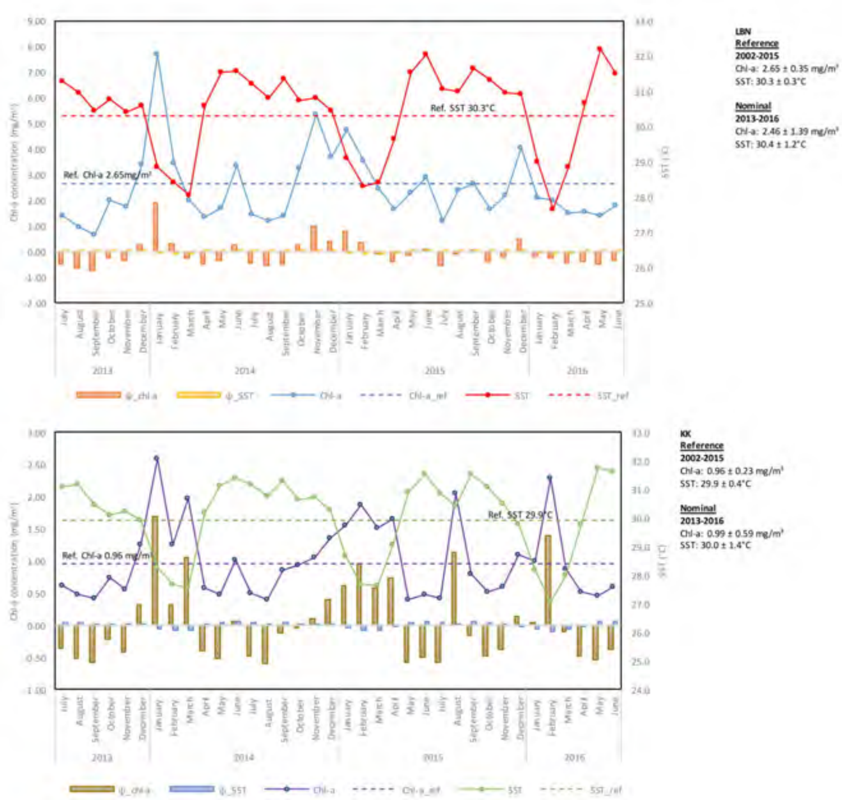

Fig 4 — Monthly mean Chl-a concentration and SST in Labuan waters (upper) and Kota Kinabalu waters (lower) from July 2013 to June 2016. The clustered column shows the anomalies, ψ of Chl-a concentration and SST with reference to a normal value established using 14-years data series from 2002 to 2015.

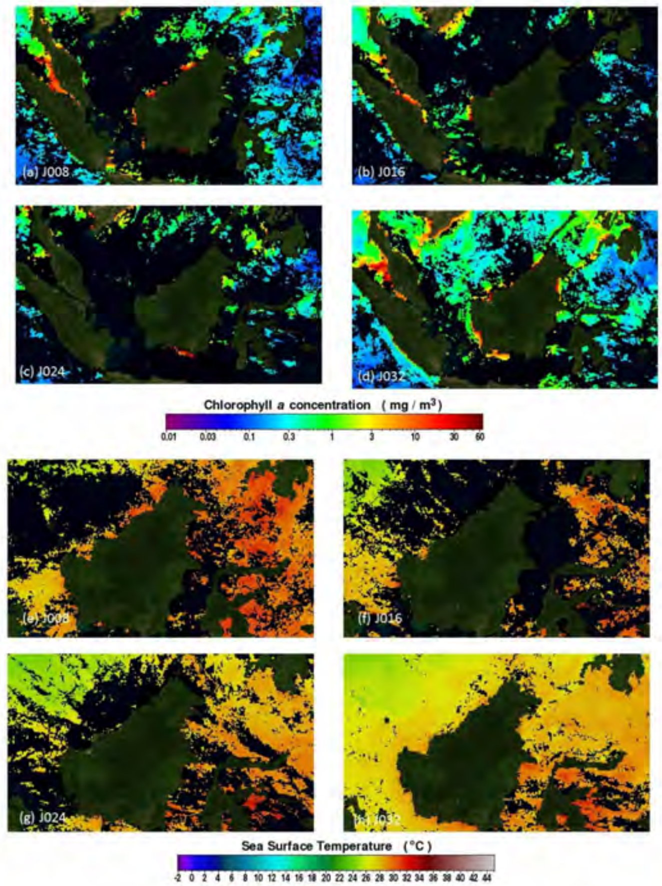

Fig. 5 — Aqua MODIS chlorophyll concentration and SST 8-days composite images of Sabah coastal region in January, 2014. Upwelling event occurred on J032 and before characteristics were shown on J008, J016, and J024.

abundant cloud cover and insignificant ocean color detectable via satellite remote sensing. From January 01-08, eutrophic waters were observable in the western coast of Sabah, where high phytoplankton productivity was expected in Labuan and Kota Kinabalu waters. From January 09-16, a significant decrease in the areal extent of eutrophic waters was detected and continuously decreased to a minimum in January 17- 24. However, a sudden increase in the chlorophyll concentration was detectedin January 25-31, where the abundant eutrophic waters was detected in all Sabah coastalregions. The most intense upwelling effect was observed in Labuan waters with a sudden increase of 4.53 mg/m^{3}was observed within 16 days. Besides, its variability on chl-a concentration in terms of spatial distribution was also the highest in J032, which may also suggest a good indicator of upwelling characteristics. The concurrent high dispersity on chl-a concentration in thewestern coast of Sabah waters is one reason to support this observation (see Table 4). In overall from J001 to J032, the chl-a concentration in Sabah waters remarked an increment of 6.0 mg/m^3 with the highest increment observed in Labuan waters (+4.53 mg/m^3), followed by Kota Kinabalu (+1.56 mg/m^3), and Tawau (+0.94 mg/m^3). When the upwelling effect is represented by aremarkable increase in chl-a concentration in these regions, but Kudat and Sandakan waters seem weakly related. The concentration has neither significant increment nor the variability on spatial distribution is insignificant. In fact, instead of showing anincreasein chl-a concentration, both these regions observed decrement from J008 to J032 though the magnitude was not significant large < 1.0 mg/m^3.

To further look into the upwelling characteristics, we examine on the evolution pattern of SST before, during and after the upwelling event. Figure 5 shows the evolution pattern of SST before and during the upwelling event where an inverse correlation was observed against the surface Chl-a concentration. The increase of the concentration is highly associated with the decrease in SST. Since the 8-days composite satellite images from J016 to J024 are always

Table 4 — Mask pixels extraction of Aqua MODISchlorophyll-a concentration and SST on 8-days composite images of Sabah coastal region in January and February, 2014. NaN represents no data.

	LBU	BKI	KDU	SDK	TWU
			Chlorophyll-a concentration in mg / m^3		
J008	6.19 ± 4.79	1.07 ± 0.74	0.68 ± 0.47	1.25 ± 0.34	0.63 ± 0.72
J016	NaN	2.63 ± 3.95	NaN	NaN	NaN
J024	NaN	NaN	NaN	0.26 ± 0.07	0.98 ± 0.69
J032	10.72 ± 9.05	2.63 ± 3.95	0.59 ± 0.85	0.35 ± 0.49	1.57 ± 2.32
Δ J032 / J008	+4.53	+1.56	-0.09	-0.90	+0.94
J040	3.97 ± 5.18	0.94 ± 1.04	0.58 ± 0.67	0.61 ± 0.95	0.94 ± 1.22
J048	1.29 ± 1.27	1.00 ± 0.00	0.44 ± 0.05	0.48 ± 0.91	0.33 ± 0.21
J056	3.82 ± 5.32	1.10 ± 0.65	1.13 ± 2.94	0.21 ± 0.17	0.54 ± 0.64
Δ J032 / J056	-6.90	-1.53	+0.54	-0.14	-1.03
SST in °C					
J008	29.90 ± 0.72	29.80 ± 0.73	28.90 ± 1.00	29.10 ± 1.06	29.70 ± 0.80
J016	NaN	NaN	28.20 ± 0.74	28.10 ± 0.49	NaN
J024	NaN	25.90 ± 0.00	27.90 ± 0.22	28.20 ± 0.59	28.30 ± 1.05
J032	28.30 ± 0.73	27.60 ± 0.35	27.70 ± 0.42	27.70 ± 0.28	27.80 ± 0.55
Δ J032 / J008	-1.60	-2.20	-1.20	-1.40	-1.90
J040	28.70 ± 0.94	28.00 ± 0.42	27.80 ± 0.51	27.70 ± 0.44	28.30 ± 0.52
J048	28.30 ± 0.59	28.00 ± 0.44	27.20 ± 0.64	28.30 ± 0.58	28.70 ± 0.53
J056	28.30 ± 1.13	27.70 ± 0.75	27.40 ± 0.65	27.90 ± 0.45	28.10 ± 0.76
Δ J032 / J056	0.00	+0.10	-0.30	+0.20	+0.30

subjected to heavy cloud cover, the comparison was only made between J008 and J032. Warmer SST extent was clearly observed for J008 as compared to J032 (Figure 5). Cold SST on J032 was evenly distributed along the coastal regions especially in the western part of Sabah waters indicating the foster of phytoplankton productivity. In Labuan waters, a reduction of SST by -1.60°C was observed after 16 days and this corresponds to an increment in Chl-a concentration by +4.53 mg/m^3. The second intense upwelling effect was observed in Kota Kinabalu waters where SST decreasedby-2.20°C for Chl-a concentration increased by 1.56 mg/m^3. The weakest upwelling effects occurred in Tawau waters where SST decreased by - 1.90°C for Chl-a concentration increased by 0.94 mg/m^3. We believe that this variability was the evidence of the occurrence of upwelling characteristics that brought the low SST and high-nutrient water from thedeep sea towards the coastal regions. For Kudat and Sandakan waters, the variability of SST was less than < -1.50°C and the corresponding Chl-a concentration has no significant increment but a relatively small magnitude of negative forcing was observed. In open ocean upwelling systems, phytoplankton Chl-a was strongly influenced by the observed upwelling event and circulation pattern by two means: new nutrient input enhancing growth and by passive advection/accumulation of the existing phytoplankton biomass[17]. Phytoplankton in the investigated area move offshore and concentrate at some distance from the coast during the upwelling event. Upwelling regions indicated by areas of low temperature and high Chl-a were mainly found in the central basin off Labuan, and north of the Kota Kinabalu during the northeast monsoon prevailing in winter. Phytoplankton production in the study area was clearly related to the coupled physical-chemical-biological oceanographic processes, but the most dominant ones are the oceanic dynamics driven by the monsoonal season variability [18].

After the upwelling event on J032, the SST from J040 to J056 remained stable with aninsignificant variation of less than < ±0.30°C in all regions of Sabah waters (see Figure 6 and Table 4). From what we observe on Figure 4 and 5, the coldest SST panel was on J032 which we presumed the occurrence of upwelling event. The evolution pattern of SST is quite straightforward that before upwelling event, SST was warmwith an average temperature of ~29.0-30.0°C but during the period when the upwelling event was the most intense, the average temperature dropped to~27.0°C. Thereafter, the SST rose back to

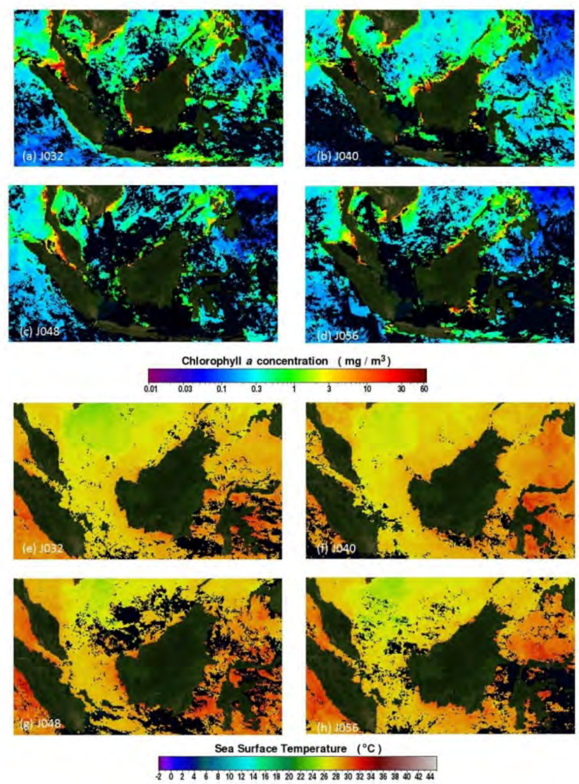

Fig. 6 — Aqua MODIS chlorophyll concentration and SST 8-days composite images of Sabah coastal region in February, 2014. Upwelling event occurred on J032 and after characteristics were shown on J040, J048, and J056.

thenormal average temperature of ~28.0°C in all regions of Sabah waters. However,in the SST image, the location of the coldest upwelled water is not observed to be very close to the coast in Sabah waters. Instead, the coldest pane was detected far in the deep ocean South China Sea (see Fig.6(e)). In the chlorophyll image, the dramatic effect of the nutrients provided by the upwelling process can be seen by the color change from J032 to J056. The high concentration pane in the image decreased abruptly from J032 to J040 with the most significant decrease was observed in Labuan waters (- 6.75 mg/m^3), followed by Kota Kinabalu waters (-1.69 mg/m^3), and Tawau waters (-0.63 mg/m^3). January is NEM season (wintertime) in the Borneo region, and SST in the South China Sea are expectedwarmerin SWM season (summertime) due to less rainfall and lower wind speed. It has been shown in previous studies that a significant proportion of nutrients used in primary production after an upwelling pulse may be supplied by the regeneration of the phytoplankton biomass in the same area where upwelling occurs [17]. Looking at the normal anomalies of SST, an average SST of ~30.0°C was expected throughout the years in Sabah waters, but during the NEM season, the SST could drop to a minimum of ~27.0°C and for SWM season the SST could be higher at ~32.0°C.In the context for upwelling event Jan'2014, the upwelled waters appear to be one or two degrees colder than the normal SST but have not dropped beyond the normal anomalies in NEM. It is hard to discern a large difference in the SSTdata, especially in this region as it is located near the equator with constant temperature throughout the year. Besides, the surface distribution of temperature in the region can be weak indicator of upwelling activity as vertical profiles of temperature within smaller area of persistent upwelling is more significant [19].

On the distribution of chl-a concentration, in thesummertime of SWM, the concentrations were relatively low and distributed uniformly throughout the basin with a narrow belt of high chlorophyll concentration along the coastal waters, particularly the coasts of Borneo [20]. In wintertime of NEM, chl-a concentration increasedthroughout the entire basin due to the higher wind speed and colder SST. However, the dramatic change of chlorophyll concentration has provided solidevidence on the occurrence of upwelling event in this region. This is because the unusual high chlorophyll concentration observed in Jan'2014 was beyond the normal seasonal fluctuation and in fact measuredthe highest concentration in the past 14 years from 2002 to 2015. Besides, the upwelling characteristics were also well demonstrated by the evolution pattern of the chlorophyll concentration and SST in the region.

Conclusion

It has beendetermined that from all the five research regions, Labuan recorded the highest mean Chl-a levels regardless of the strength of upwelling taking place. Labuan and Kota Kinabalu recorded peaks in their Chl-a levels during the Northeast Monsoon (NEM) that takes place from November to February. The peaks during NEM can be attributed to the strong northeasterly winds NEM brings to Sabah's western and northern coasts, which increase the strength of upwelling occurrences in the region. Likewise, the southwestern monsoon (SWM) and the transition period between NEM and SWM causes upwelling to be weak, and hence causes a decrease in Chl-a levels in all regions, with an especially noticeable drop in Kota Kinabalu and Labuan. It is also to be noted that the NEM and SWM saw a drop and rise in average SST levels respectively throughout all five research areas.

Strong upwelling events were noticed through a sudden spike in Chl-a levels in the eutrophic waters with the strongest upwelling effects noted in Labuan. SST levels recorded small differences (within 1~2^{O}C) regardless of Chl-a levels leading to the inference that SST levels did not play a huge role in upwelling events in Sabah coastal regions. Reason behind the minor changes in SST can be attributed to the tropical location of the research area, which means that variations in SST due to environmental factors are small.Improvements that can be made in future studies in this area include taking readings of parameters more frequently (eg. daily) to provide a more accurate visualization of the relationship betweenupwelling and Chl-a levels. The effect of other factors (ie – river discharge) on this study can also be the subject of further investigation as well.

Acknowledgement

This research was supported by the Malaysian Ministry of Education under the research grant number RAG0071-SG-2015, and is greatly acknowledged.

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