

## MULTI-TEMPORAL MODIS FOR DETECTION AND PUBLISHED LITERATURES FOR VALIDATION OF ALGAL BLOOMS IN SABAH AND SARAWAK, MALAYSIA

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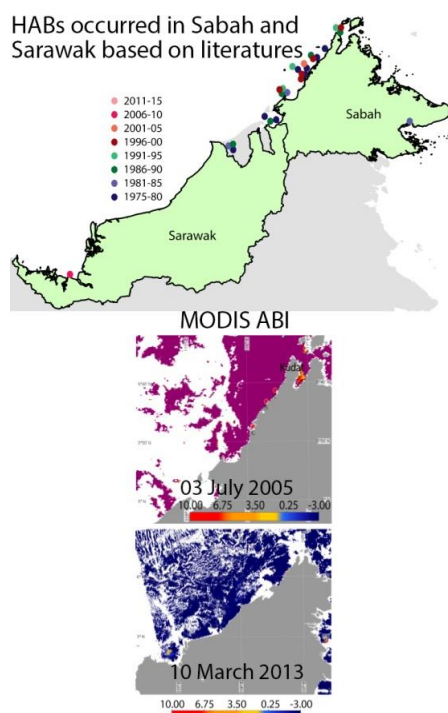
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### Graphical abstract



### Abstract

The coastal region of Sabah, Malaysia is mostly affected by harmful algal blooms (HABs) that often cause massive fish kills, and sometimes human casualties. Lack of a well-agreed, transparent and reproducible method, aperiodic nature and limited (technical) ability to monitor HAB at large regional scale, have all led to reinforced methodological improvement for bloom prediction, scientific management of coastal water resources, and regulatory attention. MODerate Resolution Imaging Spectroradiometer (MODIS), one of the well validated ocean colour sensors, enables acquiring high spectral resolution images, with short revisit time, freely accessible, and bay-wide coverage. Yet, the relative efficiency of MODIS-derived Chl-a (Chlorophyll-a), ABI (Algal Bloom Index), and nFLH (normalized Fluorescence Line Height) have not been compared in coastal regions of Malaysia. Fifteen MODIS Level 2 images acquired between 2005 and 2013 were considered as time series data that matched HAB events mentioned in previous studies. As historical real time in-situ data collection is often difficult (inaccessible), and thus unavailable; this project had to validate results obtained from literature, assuming that in-situ, would indicate HAB location at least during MODIS acquisition dates. Variations of HAB affected areas with temporal and spatial scales derived from bloom indices are shown in colour maps. Reliability of bloom information was measured by subjectively comparing HAB results provided by indices, and previously published in-situ results. ABI outperformed Chl-a and nFLH indices based on comparisons in both normal and HAB conditions occurring in the coastal waters of Sabah and Sarawak. The configuration and reliability retrieved from MODIS-ABI allowed their application in different likely tropical region as automated HAB monitoring systems and coastal water management programmes.

Keywords: Harmful phytoplankton bloom, MODIS, Chlorophyll-a, Algal Bloom Index, normalised Fluorescence Line Height, Malaysia

## Abstrak

Kawasan pantai Sabah, Malaysia kebanyakannya dipengaruhi oleh tumbuhan fitoplankton berbahaya (HAB) yang sering menyebabkan kematian ikan dengan jumlah yang besar dan boleh juga menyebabkan manusia. Kekurangan pada kaedah yang telus, berkala yang berkemampuan (teknikal) untuk memantau HAB pada skala serantau yang besar, telah menjadi faktor kepada peningkatan dan memperkukuh metodologi ramalan awal HAB, bagi pengurusan dan pemantauan sumber pesisiran pantai. MODIS (*Moderate Resolution Imaging Spectroradiometer*) adalah salah satu sensor satelit bagi warna lautan yang baik untuk memperolehi imej resolusi spektrum yang tinggi, dengan masa kutipan data yang singkat, boleh dicapai secara percuma dengan liputan yang luas. Walaubagaimanapun, kerberkesanan relatif Chl-a (Klorofil-a) yang dijana dari MODIS ABI (Algal Bloom Index), dan nFLH (normalized Fluorescence Line Height) belum pernah dikaji di pesisiran Malaysia. Lima belas set imej MODIS Tahap 2 yang diperolehi antara tahun 2005 dan 2013 semasa peristiwa HAB berlaku, telah digunakan dalam kajian ini. Sejarah kutipan data satelit masa hakiki adalah terbatas (tidak boleh diakses), oleh itu hasil kajian ini disahkan daripada hasil kajian literatur terdahulu, dengan anggapan data in-situ, menunjukkan lokasi HAB semasa tarikh kutipan data MODIS. Variasi kawasan yang terkena HAB dengan skala temporal dan spatial yang dijana dengan indeks mekar ditunjukkan dalam peta warna. Kebolehpercayaan maklumat mekar diukur dibuat dengan membandingkan hasil HAB yang dijana daripada indeks dan hasil di cerapan di lapangan. Hasil ABI mengatasi indeks Chl-a dan nFLH berdasarkan perbandingan di dalam keadaan normal dan pada Tarikh-tarikh HAB berlaku di perairan pantai Sabah dan Malaysia Sarawak. Konfigurasi dan kebolehpercayaan yang dijana dari MODIS-ABI mengesyorkan aplikasinya bagi rantau tropika lain bagi input ke sistem pengawasan HAB automatik dalam pengurusan pesisiran pantai.

*Kata kunci:* Harmful phytoplankton bloom, MODIS, Chlorophyll-a, Algal Bloom Index, normalized Fluorescence Line Height, Malaysia

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## 1.0 INTRODUCTION

Harmful phytoplankton bloom (HAB) is an outcome of the natural process of rapid and high biomass accumulation of phytoplankton (algae, blue green algae, or cyanobacteria) in the water column that can cause a negative impact on the aquatic ecosystem [1-3]. It can occur in any water bodies such as rivers, lakes and oceans, from freshwater or brackish waters to open ocean ecosystem around the world, and can cause mainly economic loss of aquaculture industries in a country.

In the coastal waters of Malaysia, HAB occurrences have been reported since 1976 [2, 4, 5, 6, 7, 8, 9, 10]. The first occurrence of HAB in the coastal waters of Kota Kinabalu (Sabah, Malaysia) in 1976 [11] and thereafter, their frequent occurrences almost every month in a year had caused massive fish kills and human casualties. Thus, HAB is considered as an increasingly serious problem in western Sabah and the coastal areas of the South China Sea [12]. The dinoflagellate *Pyrodinium bahamense* var. *compressum* is one of the most common HAB species found in the coastal waters of Malaysia [8, 13]. *Gymnodinium catenatum* is known as toxin producer, but not yet confirmed to cause paralytic shellfish

poisoning (PSP) in Sepanggar Bay occurred in 2003 [9]. *Cochlodinium polykrikoides* is known to cause PSP in Sepanggar Bay in 2005 [14]. As a result, west Sabah is identified as HAB persistent coastal area, affected by multiple algal species. Although reported, their detection, initiation of and departure from the blooms, spatio-temporal dynamics are often devised by in situ water sampling that only utilises an estimate of abundance at sparse spatial and temporal scales. Typically, cell densities counted from the in situ-based water column samples have been widely used to estimate algal abundance, and to be identified as harmful if it exceeds the threshold. As such, in situ sampling may not provide a precise estimate on the spatial extent and distribution, and abundance of HAB at required spatio-temporal scales, while ocean colour remote sensing can be used to synoptically identify and characterise spatial extent of the bloom.

Over the last three decades, researchers have been trying to develop and refine ocean colour algorithms to accurately detect and monitor phytoplankton blooms [15]. Using spectral properties and visualization capabilities of multi-spectral ocean colour remote sensors, such as CZCS (Coastal Zone Colour Scanner), SeaWiFS (Sea-Viewing Wide Field-of-View Sensor), MODIS (MODERate Resolution Imaging

Spectroradiometer), and MERIS (MEdium Resolution Imaging Spectrometer) HAB can be detected from the concentration of Chlorophyll-a (Chl-a), typically a proxy of phytoplankton biomass or growth. Using spectral properties of blue (440 nm), green (550 nm), yellow (570-580 nm), red (620-700 nm), or near-infrared (NIR; >700 nm) bands, HAB can be detected in many ways [15]. Chl-a concentrations, obtained from in-situ have an empirical relationships with water leaving reflectance, and therefore band ratios between blue and green are commonly used in Chl-a retrieval [16].

Water quality, i.e., turbidity and depth is the main hindrance to detecting aquatic vegetation [17-19] including phytoplankton by multispectral remote sensing. The multispectral sensor's capability, together with the algorithm used for the detection, analysis and mapping specific phytoplankton bloom, make this task challenging. These factors need to be considered when choosing a suitable ocean colour remote sensor and the classifier. Among these factors are thickness of bloom layer, reflectance received by the sensor, suspended particles, dissolved organic matter, water turbidity, etc. that may influence HAB detection individually, or in combination. Investigating the relative performance of HAB algorithm through assessing accuracy is a prerequisite for answering the question – combination of which ocean colour sensor and algorithm is appropriate for HAB distribution mapping?

There is a lack of a well-agreed, transparent and reproducible method, likely due to intrinsic aperiodic nature of HAB, and limited (technical) ability to monitoring it at large regional scale [20, 21]. All these have led to reinforced methodological improvement for bloom prediction, scientific management of coastal water resources, and regulatory attention.

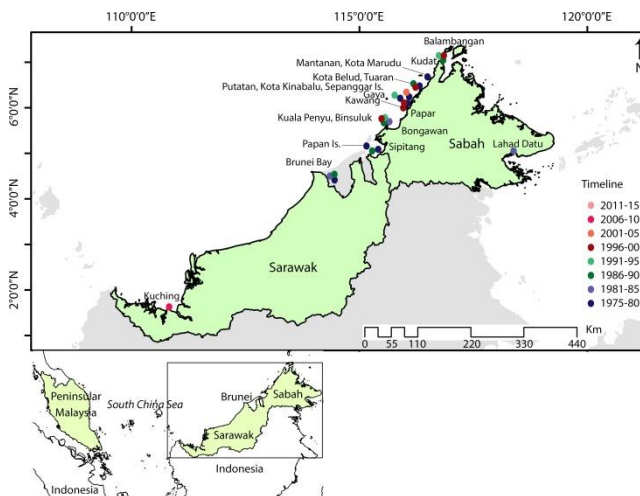
MODIS, one of the well validated ocean colour sensors, enabled acquiring high spectral resolution images, with short revisit time, freely accessible and bay-wide coverage [15]. Yet, the relative efficiency of MODIS-derived Chl-a, ABI (Algal Bloom Index), and nFLH (normalized Fluorescence Line Height) have not been compared in coastal regions of Malaysia. Therefore, the main objective of this research was to investigate the relative ability of those algorithms to differentiate HAB from non-HAB, across western Sabah and Sarawak, Malaysia were considered as test sites.

## 2.0 METHODOLOGY

### 2.1 Study Site

The coastal waters of Malaysia have been experiencing outbreaks of HABs for the past four decades, and the frequency of these blooming events were more intense along the coastline of east (Sabah and Sarawak) compared to the west (Peninsular Malaysia) [2]. Figure 1 shows the location and frequency of HAB which occurred between 1975

and 2015. Previous studies had identified the cause of the HABs was mainly due to the presence of *Pyrodinium bahamense* and *Cochlodinium polykrikoides* in the coastal waters of Sabah [2]. As such, coastal waters in Sabah and Sarawak (see Figure 1) were considered as suitable test sites for investigating the effectiveness of algal bloom detection algorithms that allowed higher frequency of potential HAB observations.



**Figure 1** Spatial distribution and frequency of HAB occurrence in the coastal waters in Sabah and Sarawak from 1975 to 2015 [13,14,22–24]; each circle is HAB frequency

### 2.2 MODIS Data and Image Processing

MODIS daily Level 2 data covering the study areas of East Malaysia (0°S, 9°N, 97°W, 108°E) were downloaded from the NASA ocean colour website (<https://oceancolor.gsfc.nasa.gov/cgi/browse.pl?sen=am>). The three data product types: a) chl-a, b) remote sensing reflectance (R<sub>rs</sub>), and c) nFLH were chosen prior to downloading. The thirty two cloud free images acquired on different dates for the years 2005, 2006, 2009, and 2013 were finally selected from available images (see Table 1). [Next, was an exhaustive literature search, and documentation of relevant HAB information. As no algal bloom was reported for the study areas in 2013, it was thus considered as a non-HAB period.

Using SeaWiFS Data Analysis System (SeaDAS version 7.3 under Linux OS), MODIS Level-2 containing radiometric and bio-optical products of Chl-a (retrieved by MODIS OC3M standard algorithm), ABI, and nFLH were derived.

The MODIS OC3M, a global standard ocean colour band ratios, was adapted to the MODIS spectral bands from the SeaWiFS OC4 [25]. The algorithm used for Algal Bloom Index (ABI) retrieval, was developed by Ahn and Shanmugam [29].

**Table 1** MODIS image acquisition dates used in this study, and HAB occurrence period and location reported in previous studies

MODIS acquisition dates	HAB dates	Location	HAB Species	Impact	Reference
01/01/2005 26/01/2005 25/02/2005 27/02/2005 02/03/2005 11/03/2005 13/03/2005 15/03/2005 18/03/2005 31/03/2005 19/06/2005 03/07/2005 10/07/2005 12/07/2005	January 2005 to June 2006	Sepanggar Bay, off Kota Kinabalu, Sabah	<i>Cochlodinium polykrioides</i>	Fish mortalities in cage-cultures red discolouration of coastal water	[14,26]
03/04/2006 17/04/2006 19/04/2006 01/05/2006 05/05/2006 10/05/2006 21/05/2006 30/05/2006 02/06/2006 06/06/2006 13/06/2006	2006	Kuching, Sarawak, and Kota Kinabalu, Sabah	<i>Cochlodinium polykrioides</i>	Water discolouration and some fish kills	
19/03/2009 24/03/2009 31/03/2009 02/04/2009 11/04/2009 15/04/2009 25/04/2009 27/04/2009	8 Sept 2009 7 May 2009 9 Sept 2009	Santubong, Sarawak Muara Tebas, Sarawak Kudat, Sabah  Kota Kinabalu, Sabah	<i>Pseudo-nitzschia pugens</i>   <i>Pyrodinium bahamense</i>	Amnesic Shellfish Poisoning (ASP)   Paralytic shellfish poisoning (PSP)	[27,28]   [2]
13/02/2013 26/02/2013 03/03/2013 10/03/2013	Non-HAB	Non-HAB	Non-HAB	Non-HAB	Nil

**Table 2** Summary of the level of agreement (%) between MODIS products and literature supported HAB occurrence in coastal areas in Sabah and Sarawak

Location	Year	Level of agreement (%)		
		Chl-a	nFLH	ABI
Sabah				
Sepanggar Bay, off Kota Kinabalu	2005, 2006, and 2009	6.25	75.00	84.38
Kudat	2009	12.50	62.50	87.50
Sarawak				
Santubong and Muara Tebas, Kuching	2009	25.00	50.00	75.00

The ABI was calculated based on the normalised water-leaving radiance at three wavelengths in the visible domains (i.e., 443, 488, and 555 nm), and is defined as follows:

$$ABI = 10 \left[ \left( \frac{nLw_{488}}{nLw_{555}} \right) - \left( \frac{nLw_{443}}{a} \right) \right] / \left[ \left( \frac{nLw_{448}}{nLw_{555}} \right) + \left( \frac{nLw_{443}}{a} \right) \right] \quad (1)$$

where  $a$  is assumed unity, allows the calculation of phytoplankton absorption and it is an important driver of reflectance in the blue (443 nm), and other factors that regulate reflectance at 555 nm [30];  $nLw$  represents normalised water-leaving radiance, and it was obtained from the product of the mean solar radiance ( $F_0$ ) for the respective  $R_{rs}$  at wavelengths 443, 488 and 555 nm (Equation 2).

$$nLw(\lambda) = F_0(\lambda) \times R_{rs}(\lambda) \quad (2)$$

The ABI values ranged from 0 to 10; greater ABI represent higher possible HAB events in the pixel location. ABI does not necessarily mean an obvious impact as 'harmful' on other organisms or the environment, but is indicative of a bloom event.

Passive phytoplankton concentration can be estimated from fluorescence measure (FLH), which was first developed by Neville and Gower [31], and



spectral band properties of MODIS allow for FLH retrieval [32]. The general form of FLH algorithm is as below:

$$FLH = L_{14} - L_{baseline} \quad (3)$$

where

$$L_{baseline} = L_{15} + (L_{13} - L_{15}) \times [(r_{15} - r_{14}) / (r_{15} - r_{13})] \quad (4)$$

The subscript refers to the MODIS band number,  $L$  refers to the radiance, and  $r$  refers to the band center wavelength ( $r_{13}$  = 665.1 nm,  $r_{14}$  = 676.7 nm, and  $r_{15}$  = 746.3). Compared to a standard Chl algorithm, MODIS FLH has the ability to provide a more precise fluorescence that can be used for the detection of algal blooms tested in this study [33].

### 2.3 HAB Data

In-situ data on HAB occurrence (timing and location) in the coastal waters of Sabah and Sarawak were obtained from published research articles (see Table 1). *Cochlodinium polykrikoides* blooms were found along the Sabah and Sarawak coasts between 2005 and 2006, while *Pyrodinium bahamense* bloom occurred in waters off Kota Kinabalu, Sabah in 2009. The ASP causing diatom *Pseudo-nitzschia pungens* was found in Sabah and Sarawak in different sampling dates of 2009. The information of bloom was used as the ground truth data to validate HAB detection ability on MODIS imagery. In this study, the level of accuracy was measured from comparison between MODIS provided, and literature supported HAB locations. There was a 'full' level of agreement, i.e., 100% when the condition was true for all image dates. This means that the higher the level of agreement, the more acceptable was the MODIS algorithm.

## 3.0 RESULTS AND DISCUSSION

The effectiveness of MODIS algorithms were assessed by counting the number of images that enabled HAB condition match up of documented information (literature), and their percent values represented as the level of agreement. Table 2 shows that ABI algorithm produced HAB images with higher level of agreement (>75%), followed by nFLH, whereas Chl-a produced the lowest reliable HAB predicting images, regardless of spatio-temporal variations.

Overall, the spatial extent and HAB presence or absence characteristics retrieved from the ABI were comparable with published research information. ABI provided satisfactory and relatively accurate results with better HAB prediction images than Chl-a, and nFLH algorithms. The colour maps shown in Figure 2 and results in Table 2 were consistent with HAB trends observed in respective studies (references in Table 1). Hence ABI was an ideal algorithm to MODIS for

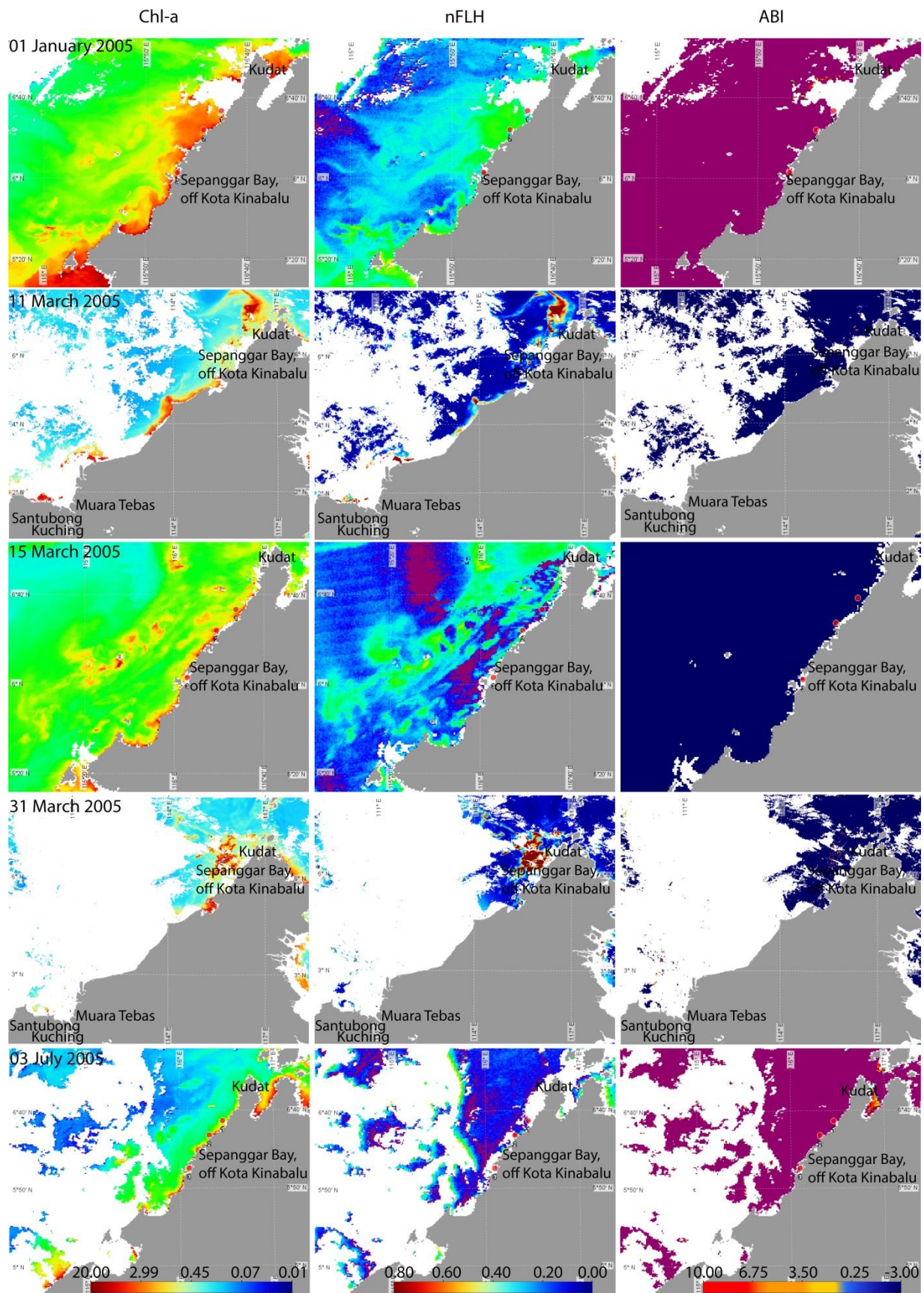
characterising HAB blooms from different water types. Similarly, using ABI, PHBs in the Arabian Sea and Gulf of Oman were better detected from a MODIS-Aqua [30].

This study used published HAB research data for subjective validation check in terms of level of agreement (see Table 2). This was due mainly to the absence of near and real time quality data on HAB spatial occurrence and distribution [34]. As it was difficult and sometimes impossible to get a perfect match between HAB occurrence period and project logistics, this research project experienced a major constrain i.e., failed to accumulate in-situ derived scientific data on the spatio-temporal dynamics of HAB for the study sites. In-situ observations were mostly performed in the near-shore areas because they are accessible and it was easy to collect water samples from those areas. Being MODIS data with coarse spatial resolution (250 – 500 m per pixel), this data was less useful for satellite-based HAB model development, when HAB typically occurred far away from the shore. This limitation, however, was offset by the approach suggested in this study (MODIS ABI), could be advantageous over the in-situ or the other two algorithms in a sense that it allowed near real-time bloom occurrence data in automated manner (without building empirical relationship between in-situ and satellite data) at large spatio-temporal scale.

It was found that most of the Chl-a products showed overestimated areas with high chlorophyll concentrations (see Figure 2). This could be due to high water turbidity (class II) along the coastal areas of Borneo. Similar to this study, the commonly used global ocean colour band ratios overestimated Chl-a, and found uncertainty of 35% [35]. Given that Chl-a concentration alone was unable to discriminate HAB from non-HAB, algorithm which is less affected by the backscattering of HAB-producing phytoplankton has been proposed [36]. ABI has shown greater ability to detect *P. bahamense* and *C. polykrikoides* compared to Chl-a or nFLH (see Figure 2). Species specific detection ability of MODIS has been a topic of recent research [37].

Although MODIS spectral position was within the 670-690 nm range that allow the computation of nFLH, Zhao *et al.* [38] had reported better performance of MERIS in HAB detection. The application and use of MODIS ABI to detect HAB have been found to be successful in many studies [30].

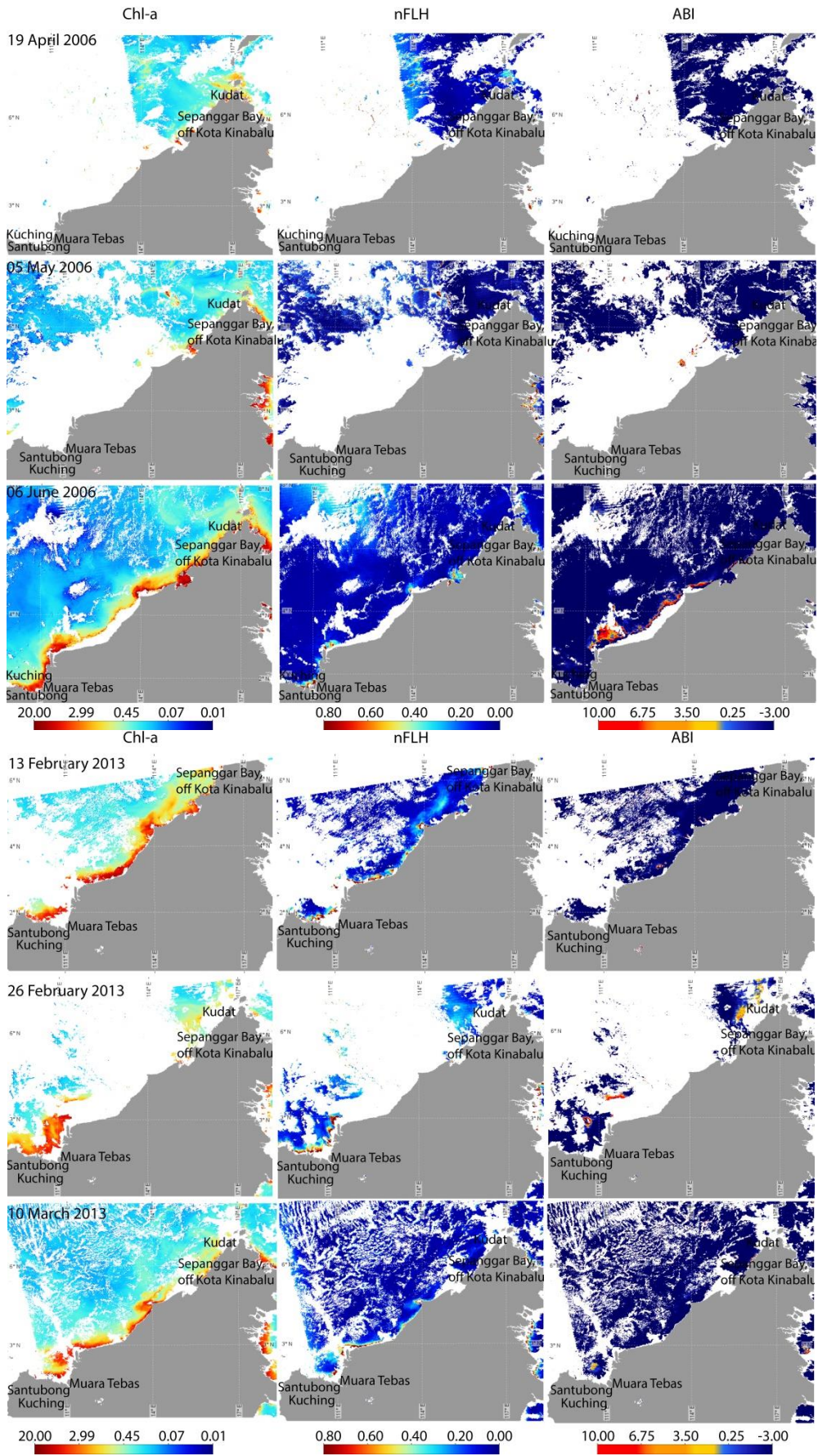
However, it is important to note that the HAB spatio-temporal distribution maps obtained from MODIS, followed in this study relied on first optical depth, phytoplankton concentrations occurring in the deep water column were not sensed by ocean colour remote sensors [39]. While blooms may had occurred in deep water [40] with significantly low Chl-a concentration (<0.1 mg m<sup>-3</sup>), they (blooms) remained undetected. Therefore, the combination of in-situ observations for deep water Chl-a concentration, and ABI or any other suitable method can improve HAB detection ability.



**Figure 2** Example MODIS standard Chl-a (first panel), nFLH (second panel) and ABI (third panel) derived from image acquired on different dates (indicated in upper left of each image row) of years 2005, 2006 and 2013. The approximate locations of HAB occurring areas are labeled based on published research information (Table 1)



Figure 2. (Continued).



## 4.0 CONCLUSION

The recurrent and spreading trend of HAB occurrences in the coastal region of Malaysia should be given proper attention by the marine management authorities. MODIS-based high spectral resolution with daily image capturing mission would enable real time HAB detection and early warning. Compared to MODIS Chl-a, and nFLH, ABI provided greater reliable products in this study. Although the validation check was subjective and thus, a quantitative analysis of and comparison of HAB algorithms with regard to behaviour and intensity could not be assessed in this study. At least, the usefulness of published research data provided the opportunity to test reliability of the results, and its worthiness, which was the focus of this study. Configuration and reliability was assessed by the degree of agreement derived from MODIS-ABI, which would enhance its application in the tropical region as real time HAB monitoring systems, and coastal water management programmes.

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