Jurnal
Teknologi

Full Paper

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

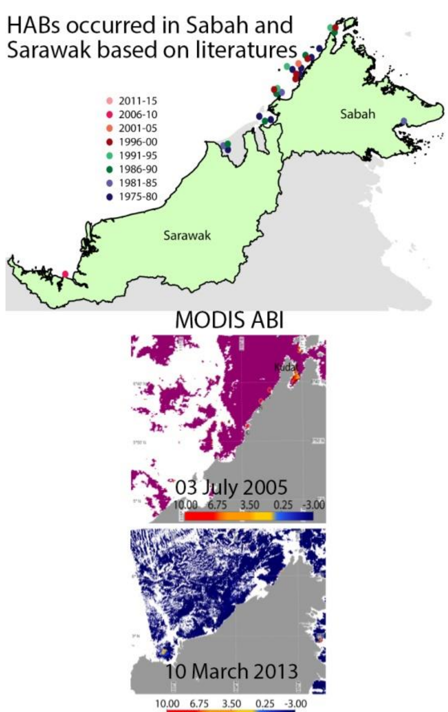
Mohammad Shawkat Hossain[a], Mazlan Hashim[b,c]*, Aidy Mohamed Muslim[a]

[a]Institute of Oceanography and Environment (INOS), University Malaysia Terengganu (UMT), 21030 Kuala Nerus, Terengganu, Malaysia
[b]Geoscience and Digital Earth Centre (INSTeG), Research Institute for Sustainable Environment (RISE), 81310 UTM Johor Bahru, Malaysia
[c]Faculty of Built Environment & Surveying, Universiti Teknologi Malaysia (UTM), 81310 UTM Johor Bahru, Malaysia

Article history
Received
8 July 2018
Received in revised form
1 March 2019
Accepted
5 March 2019
Published online
18 April 2019

*Corresponding author
mazlanhashim@utm.my

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 faktur 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 untok 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 persisiran 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 applikasinya bagi rantau tropika lain bagi input ke sistem pengawasan HAB automatik dalam pengurusan persisiran pantai.

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

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.

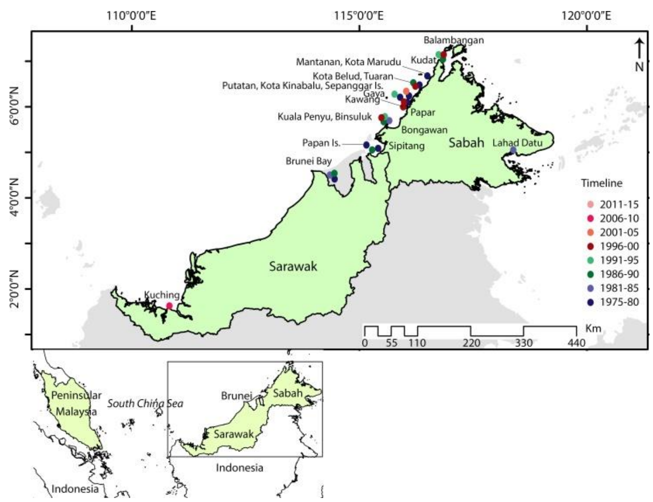


Figure 1 Spatial distribution and frequency of HAB occurrence in the coastal waters in Sabah and Sarawak from 1975 to 2015 [13,14,22–24]; each circle is HAB frequency

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 (Rrs), 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	January 2005 to June 2006	Sepanggar Bay, off Kota Kinabalu, Sabah	*Cochlodinium polykrikoides*	Fish mortalities in cage-cultures red discolouration of coastal water	[14,26]
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					
03/04/2006	2006	Kuching, Sarawak, and Kota Kinabalu, Sabah	*Cochlodinium polykrikoides*	Water discolouration and some fish kills	
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					
19/03/2009	8 Sept 2009	Santubong, Sarawak	*Pseudo-nitzschia pugens*	Amnesic Shellfish Poisoning (ASP)	[27,28]
24/03/2009	7 May 2009	Muara Tebas, Sarawak			
31/03/2009	9 Sept 2009				
02/04/2009		Kudat, Sabah		Paralytic shellfish poisoning (PSP)	
11/04/2009					
15/04/2009		Kota Kinabalu, Sabah	*Pyrodinium bahamense*		[2]
25/04/2009					
27/04/2009					
13/02/2013	Non-HAB	Non-HAB	Non-HAB	Non-HAB	Nil
26/02/2013					
03/03/2013					
10/03/2013					

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:

$$ABI = 10\left[\left(\frac{nLw488}{nLw555}\right) - \left(\frac{nLw443}{a}\right)\right] / \left[\left(\frac{nLw448}{nLw555}\right) + \left(\frac{nLw443}{a}\right)\right] \quad (1)$$

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

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

The subscript refers to the MODIS band number, L refers to the radiance, and ? refers to the band center wavelength ($?_{13}$= 665.1 nm, $?_{14}$= 676.7 nm, and $?_{15}$= 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 pugens* 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^{-3}), 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.

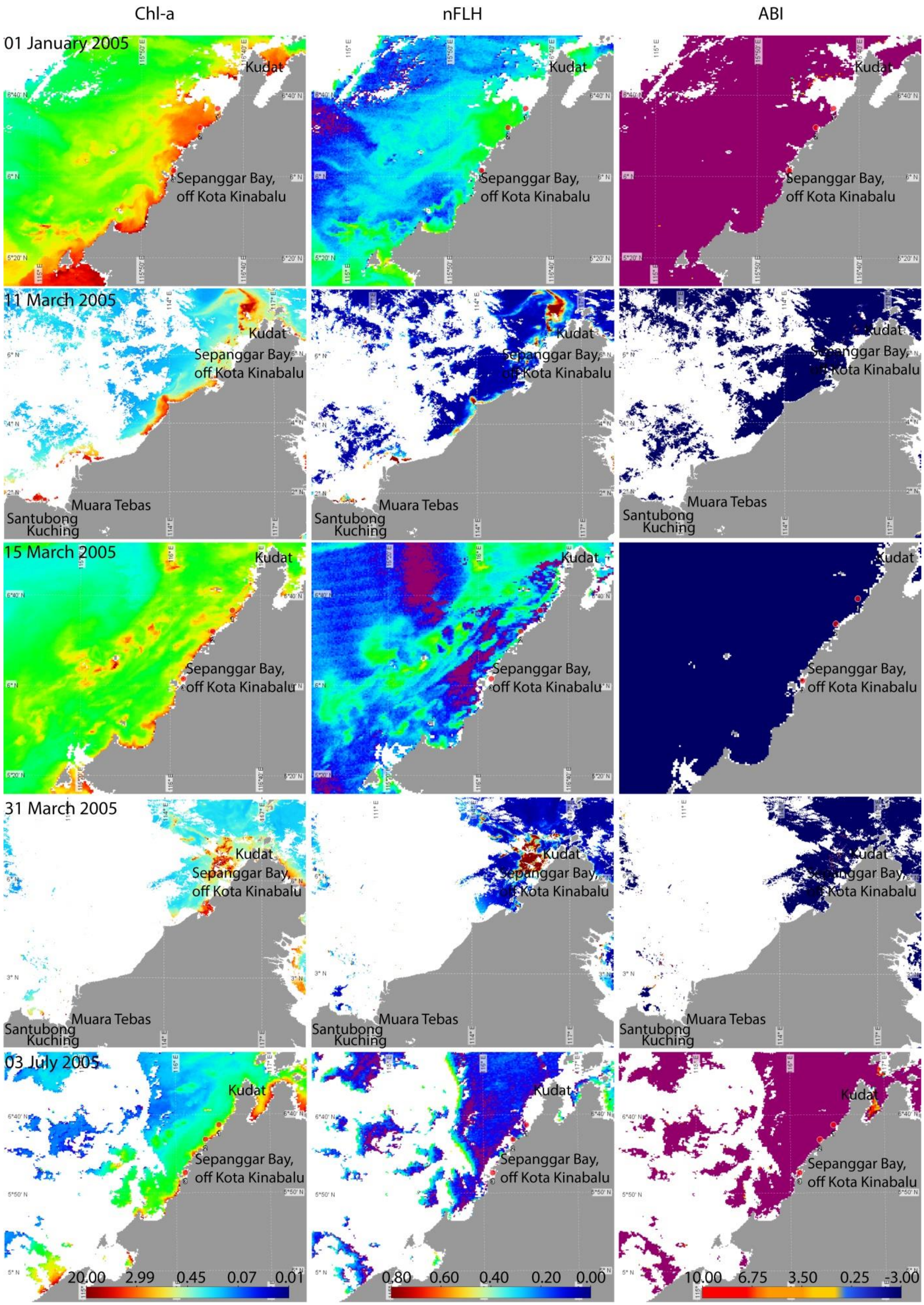
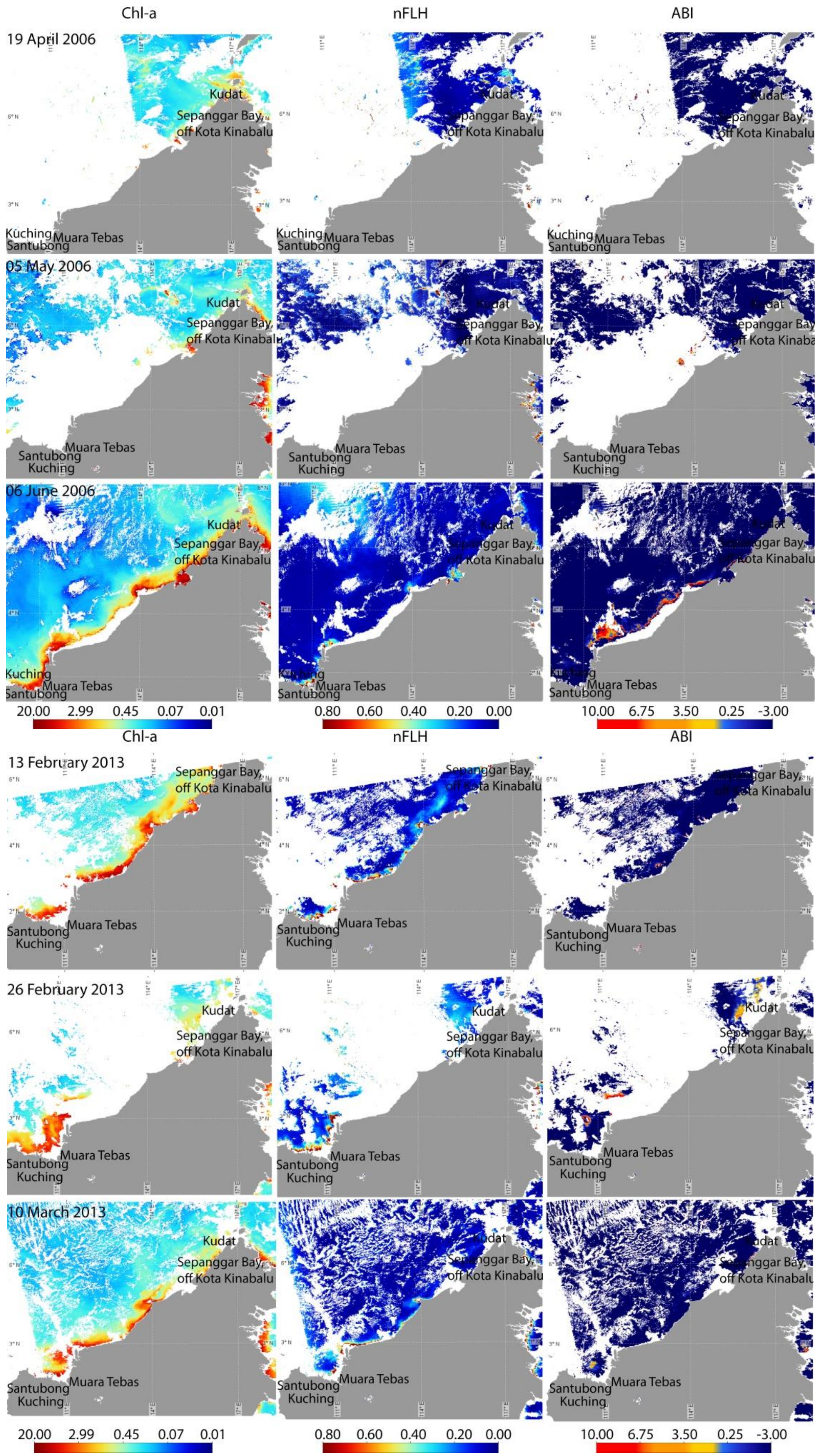


Figure 2 Example MODIS standard Chl-a (first panel), nFLH (second panel) and ABI (third panel) derived from image acquired on different dates (indicated in upper left of each image row) of years 2005, 2006 and 2013. The approximate locations of HAB occurring areas are labeled based on published research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

Acknowledgement

This work was supported by the Trans Disciplinary Research Grant Scheme (TRGS) [Project Code: PY/2016/05999 R.J130000.7809.4L851] from the Ministry of Higher Education, Malaysia; and the PDRU [Project Code: PY/2016/07808 Qj130000.21A2.03E41] by the Universiti Teknologi Malaysia (UTM).

References

[1] Anderson, D. M., and Maguire, J. 2016. Forecasting the Risk of Harmful Algal Blooms. *Harmful Algae.* 53: 1-7. DOI: https://doi.org/10.1016/j.hal.2015.11.005.

[2] Lim, P. T., Usup, G., and Leaw, C. P. 2012. Harmful Algal Blooms in Malaysian Waters. *Sains Malaysiana.* 41(12): 1509-1515.

[3] Assmy, P., and Smetacek, V. 2009. Algal Blooms. *Encyclopedia of Microbiology*. 27-41.

[4] Lim, P. T., Leaw, C. P., and Usup, G. 2004. First Incidence of Paralytic Shellfish Poisoning on the East Coast of Peninsular Malaysia. *Marine Science into the New Millennium: New Perspectives and Challenges*. Phang, S. M., Chong, V. C., Ho, S. S., Mokhtar, N., and Ooi, J. L. S. (eds.). University of Malaya Maritime Research Centre: Kuala Lumpur, Malaysia. 661-667.

[5] Usup, G., Leaw, C. P., Lim, P. T., and Ahmad, A. 2002. Probable Toxin Producer Responsible for the First Occurrence of Paralytic Shellfish Poisoning on the East Coast of Peninsula Malaysia. *Malaysia Appllied Biology.* 31(2): 29-35.

[6] Lim, P. T., Leaw, C. P., and Ogata, T. 2007. Morphological Variation of Two *Alexandrium* Species Responsible for Paralytic Shellfish Poisoning in Southeast Asia. *Botanica Marina***.** 50(1): 14-21. DOI : https://doi.org/10.1515/BOT.2007.003.

[7] Usup, G., and Azanza, R. V. 1998. Physiology and Bloom Dynamics of the Tropical Dinoflagellate *Pyrodinium Bahamense*. In *Physiological Ecology of Harmful Algal Blooms*. Anderson, D. M., Cembella, A. D., and Hallegraeff, G. M. (eds.) Berlin: Springer-Verlag. 81-94.

[8] Usup, G., Ahmad, A., Matsuoka, K., Lim, P. T., and Leaw, C. P. 2012. Biology, Ecology and Bloom Dynamics of the Toxic Marine Dinoflagellate *Pyrodinium* Bahamense. *Harmful Algae***.** 14: 301-312. DOI: https://doi.org/10.1016/j.hal.2011.10.026.

[9] Mohammad-Noor, N., Adam, A., Franco Soler, J. M., Anton, A., and Muhamad Shaleh, S. R. 2010. First Record of Toxic *Gymnodinium Catenatum* off the West Coast of Sabah, Malaysia. In *Proceedings of 13th International Conference on Harmful Algae*. Ho, K. C., Zhou, M. J., Qi, Y. Z. (eds.). International Society for the Study of Harmful Algae, Hong Kong. 25-29.

[10] Lim, H. C., Leaw, C. P., Tan, T. H., Kon, N. F., Yek, L. H., Hii, K. S., Teng, S. T., Razali, R. M., Usup, G., Iwataki, M., and Lim, P. T. 2014. A Bloom of *Karlodinium Australe* (Gymnodiniales, Dinophyceae) Associated with Mass Mortality of Cage-Cultured Fishes in West Johor Strait, Malaysia. *Harmful Algae.* 40: 51-62. DOI : https://doi.org/10.1016/j.hal.2014.10.005.

[11] Roy, R. N. 1997. Red Tide and Outbreak of Paralytic Shellfish Poisoning in Sabah. *Medical Journal of Malaysia.* 31(3): 247-251.

[12] Wang, S., Tang, D., He, F., Fukuyo, Y., and Azanza, R. V. 2008. Occurrences of Harmful Algal Blooms (HABs) Associated with Ocean Environments in the South China Sea. *Hydrobiologia.* 596(1): 79-93. DOI: https://doi.org/10.1007/s10750-007-9059-4.

[13] Azanza, R. V., and Taylor, F. J. R. 2001. Are *Pyrodinium* Blooms in the Southeast Asian Region Recurring and Spreading? A View at the End of the Millennium. *Ambio***.** 30(6): 356-364. DOI : https://doi.org/10.1579/0044-7447-30.6.356.

[14] Anton, A., Teoh, P. L., Mohd-Shaleh, S. R., and Mohammad-Noor, N. 2008. First Occurrence of Cochlodinium Blooms in Sabah, Malaysia. *Harmful Algae*. 7(3): 331-336. DOI : https://doi.org/10.1016/j.hal.2007.12.013.

[15] Blondeau-Patissier, D., Gower, J. F. R., Dekker, A. G., Phinn, S. R., and Brando, V. E. 2014. A Review of Ocean Color Remote Sensing Methods and Statistical Techniques for the Detection, Mapping and Analysis of Phytoplankton Blooms in Coastal and Open Oceans. *Progress in Oceanography.* 123: 123-144. DOI : https://doi.org/10.1016/j.pocean.2013.12.008.

[16] Matthews, M. W. 2011. A Current Review of Empirical Procedures of Remote Sensing in Inland and Near-Coastal Transitional Waters. *International Journal of Remote Sensing.* 32(21): 6855-6899.

[17] Hossain, M. S., Bujang, J. S., Zakaria, M. H., and Hashim, M. 2015. The Application of Remote Sensing to Seagrass Ecosystems: An Overview and Future Research Prospects. *International Journal of Remote Sensing.* 36(1): 61-114. DOI : https://doi.org/10.1080/01431161.2014.990649.

[18] Hossain, M. S., Bujang, J. S., Zakaria, M. H., and Hashim, M. 2016. Marine and Human Habitat Mapping for the Coral Triangle Initiative Region of Sabah Using Landsat and Google Earth Imagery. *Marine Policy***.** 72: 176-191. DOI : https://doi.org/10.1016/j.marpol.2016.07.003.

[19] Hashim, M., Ito, S., Numata, S., Hosaka, T., Hossain, M. S., Misbari, S., Yahya, N. N., and Ahmad, S. 2017. Using Fisher Knowledge, Mapping Population, Habitat Suitability and Risk for the Conservation of Dugongs in Johor Straits of Malaysia. *Marine Policy***.** 78: 18-25. DOI : https://doi.org/10.1016/j.marpol.2017.01.002.

[20] Anderson, D. M., Cembella, A. D., and Hallegraeff, G. M. 2012. Progress in Understanding Harmful Algal Blooms: Paradigm Shifts and New Technologies for Research, Monitoring, and Management. *Annual Review of Marine Science***.** 4(1): 143-176. DOI: https://doi.org/10.1146/annurev-marine-120308-081121.

[21] Shen, L., Xu, H., and Guo, X. 2012. Satellite Remote Sensing of Harmful Algal Blooms (HABs) and A Potential Synthesized Framework. *Sensors***.** 12(6): 7778-7803. DOI: https://doi.org/10.3390/s120607778.

[22] Ting, T. M., and Wong, J. T. S. 1989. Summary of Red Tide

and Paralytic Shellfish Poisoning in Sabah, Malaysia. *Biology, Epidemiology and Management of Pyrodinium Red Tides*. Hallegraeff, G. M., and Maclean, J. L. (eds.). ICLARM. 19-29.

[23] Razali, R. M., Leaw, C. P., Lim, H. C., Nyanti, L., Ishak, I., and Lim, P. T. 2015. Harmful Microalgae Assemblage in the Aquaculture Area of Aman Island, Northen Strait of Malacca. *Malaysian Journal of Science*. 34(1): 24-36.

[24] Tan, T. H., Leaw, C. P., Hii, K. S., and Lim, P. T. 2012. Morphology of Two Harmful *Prorocentrum* (Dinophyceae) from Malaysian Borneo. *Proceedings of the 12th Symposium of the Malaysian Society of Applied Biology*. Kuala Terengganu, Terengganu. 294-300.

[25] Chen, J., and Quan, W. 2013. An Improved Algorithm for Retrieving Chlorophyll-A from the Yellow River Estuary Using MODIS Imagery. *Environmental Monitoring and Assessment.* 185(3): 2243-2255.
DOI: https://doi.org/ 10.1007/s10661-012-2705-y.

[26] Sidik, M. J., Rashed-Un-Nabi, M., and Azharul Hoque, M. 2008. Distribution of Phytoplankton Community in Relation to Environmental Parameters in Cage Culture Area of Sepanggar Bay, Sabah, Malaysia. *Estuarine, Coastal and Shelf Science*. 80(2): 251-260.
DOI : https://doi.org/10.1016/j.ecss.2008.08.004.

[27] Lim, H. C., Lim, P. T., Su, S. N. P., Teng, S. T., and Leaw, C. P. 2011. Genetic Diversity of *Pseudo-Nitzschia Pungens* (Bacillariophyceae) in Borneo, Malaysia. *Coastal Marince Science*. 35(1): 58-63.

[28] Lim, H. C., Lim, P. T., Teng, S. T., Bates, S. S., and Leaw, C. P. 2014. Genetic Structure of *Pseudo-Nitzschia Pungens* (Bacillariophyceae) Populations: Implications of A Global Diversification of the Diatom. *Harmful Algae*. 37: 142-152.
DOI: https://doi.org/10.1016/j.hal.2014.06.004.

[29] Ahn, Y.-H. and Shanmugam, P. 2006. Detecting the Red Tide Algal Blooms from Satellite Ocean Color Observations in Optically Complex Northeast-Asia Coastal Waters. *Remote Sensing of Environment.* 103(4): 419-437.
DOI: https://doi.org/10.1016/j.rse.2006.04.007.

[30] Shanmugam, P. 2011. A New Bio-Optical Algorithm for the Remote Sensing of Algal Blooms in Complex Ocean Waters. *Journal of Geophysical Research: Oceans.* 116: 1-12.
DOI: https://doi.org/10.1029/2010JC006796.

[31] Neville, R. A., and Gower, J. F. R. 1977. Passive Remote Sensing of Phytoplankton Via Chlorophyll A Fluorescence. *Journal of Geophysical Research.* 82(24): 3487-3493.
DOI : https://doi.org/10.1029/JC082i024p03487.

[32] Letelier, R. M., and Abbott, M. R. 1996. An Analysis of Chlorophyll Fluorescence Algorithms for the Moderate Resolution Imaging Spectrometer (MODIS). *Remote Sensing of Environment.* 58(2): 215-223.
DOI : https://doi.org/10.1016/S0034-4257(96)00073-9.

[33] Frolov, S., Kudela, R. M., and Bellingham, J. G. 2013. Monitoring of Harmful Algal Blooms in the Era of Diminishing Resources: A Case Study of The U.S. West Coast. *Harmful Algae*. 21-22: 1-12.
DOI: https://doi.org/10.1016/j.hal.2012.11.001.

[34] Babin, M., Roesler, C. S., and Cullen, J. J. 2008. *Real-Time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms: Theory, Instrumentation and Modelling*. Paris, France: Unesco.

[35] Moore, T. S., Campbell, J. W., and Dowell, M. D. 2009. A Class-Based Approach to Characterizing and Mapping the Uncertainty of the MODIS Ocean Chlorophyll Product. *Remote Sensing of Environment*. 113(11): 2424-2430.
DOI: https://doi.org/10.1016/j.rse.2009.07.016.

[36] Cannizzaro, J. P., Carder, K. L., Chen, F. R., Heil, C. A., and Vargo, G. A. 2008. A Novel Technique for Detection of the Toxic Dinoflagellate, *Karenia Brevis*, in the Gulf of Mexico from Remotely Sensed Ocean Color Data. *Continental Shelf Research.* 28(1): 137-158.
DOI: https://doi.org/10.1016/j.csr.2004.04.007.

[37] Siswanto, E., Ishizaka, J., Tripathy, S. C., and Miyamura, K. 2013. Detection Of Harmful Algal Blooms Of Karenia Mikimotoi Using MODIS Measurements: A Case Study Of Seto-Inland Sea, Japan. *Remote Sensing of Environment.* 129**:** 185-196.
DOI: https://doi.org/10.1016/j.rse.2012.11.003.

[38] Zhao, D., Xing, X., Liu, Y., Yang, J., and Wang, L. 2010. The Relation of Chlorophyll-A Concentration with the Reflectance Peak Near 700 Nm in Algae-Dominated Waters and Sensitivity of Fluorescence Algorithms for Detecting Algal Bloom. *Internationa Journal of Remote Sensing.* 31(1): 39-48.
DOI: https://doi.org/10.1080/01431160902882512.

[39] Huisman, J., Pham Thi, N. N., Karl, D. M., and Sommeijer, B. 2006. Reduced Mixing Generates Oscillations and Chaos in the Oceanic Deep Chlorophyll Maximum. *Nature*. 439(7074): 322.
DOI: https://doi.org/10.1038/nature04245.

[40] Villareal, T. A., Adornato, A., Wilson, C., and Schoenbaechler, C. A. 2011. Summer Blooms of Diatom-Diazotroph Assemblages and Surface Chlorophyll in the North Pacific Gyre: A Disconnect. *Journal of Geophysical Research: Oceans*. 116: C03001.
DOI: https://doi.org/10.1029/2010JC006268.