An improved MODIS standard chlorophyll-a algorithm for Malacca Straits Water

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Abstract. The Malacca Straits has high productivity of nutrients as a result to potential primary production. Yet, the Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua has shown an overestimation of Chl-a retrieval in the case-2 water of Malacca Straits. In an update to the previous study, this paper presents the second validation exercise of MODIS OC3M algorithm using the reprocessed MODIS data (R2013) and locally tuned the algorithm with respect to two in-sit stations located at northern and southern part of Malacca Straits. The result shows the OC3M retrieved in the case-2 (south station) water remarkably overestimated in-situ Chl-a, but it is underestimated in the case-1 (north station). Local tuning was employed by iterative regression at the fourth-order polynomial to improve the accuracy of Chl-a retrieval. As a result, locally tuned OC3M algorithm give robust statistical performance and can be applied best for both case-1 and case-2 water in Malacca Straits.

1. Introduction

In recent years, study in phytoplankton diversity has increased due to its important role in regulating climate by production and consumption in greenhouse gases. Phytoplankton biomass philosophically defined as (Chlorophyll-a, hereafter Chl-a) is useful to delineate potential fishing ground based on high correlation between the total primary production and the fisheries production. The Malacca Straits (MS) has been found to have high productivity because of high nutrient inputs were discharged from the rivers, [1].

Ocean colour remote sensing has been proved to be a useful tool for mapping the Chl-a concentration. However, the retrieval of Chl-a in the coastal region such as MS is usually challenging due to the other in-water constituents regardless of Chl-a (e.g., gelbstoff, suspended sediment, etc.) hence resulting in satellite-retrieved Chl-a overestimation. Indeed, highly overestimated satellite Chl-a retrieved using NASA standard algorithm was found in the MS [1]. Previous studies mentioned that NASA standard Chl-a algorithm used in the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) data such as SeaWiFS OC4 and MODIS OC3M respectively can retrieve Chl-a well in the case-1 water (i.e., open ocean) but not in the case-2 water (such as that in the coastal region). MODIS validation carried out by Sun [2] showed that the MODIS Chl-a was overestimated to the in-situ Chl-a in coastal region of China and the same results regarding case-2 water were also obtained by Cannizarro[3], Moses [4] and Darecki [5].
Siswanto[6] found that modification of standard NASA ocean color algorithms is necessary to improve the retrieval of in-water bio-optical constituents in the Yellow and East China Seas using satellite remote sensing and other studies by Hu [7] and Le [8] also suggested the need of regionally tuned algorithms for better retrieval of in-water bio-optical constituents. However, no study was conducted to validate and calibrate the NASA standard ocean color algorithm as well as to perform algorithm modification to improve the accuracy of Chl-a estimation especially in the Malacca Straits. Thus, a preliminary exercise was carried out to evaluate the performance of MODIS OC3M algorithm and later locally tuned the algorithm that yield high accuracy Chl-a retrieval in the MS water. Despite of the fact that the revised OC3M for the MS has been devised, NASA recently announced the reprocessed MODIS Aqua (MODIS-A) data [9] and as a result, this paper aims to validate this new data and yet to update the existing OC3M algorithm so as to have regionally tuned and improved quality of the current satellite retrieved Chl-a.

2. Materials and method
Validation of satellite retrieved Chl-a requires in-situ data measured at higher degree of coherent in space and time. Therefore, simultaneous data acquisition for both satellite and in-situ derived Chl-a is pertinent and description on each data was presented as follows. The data has been collected from October 2011 until August 2012.

2.2 In-situ data
In-situ Chl-a data were collected by the Japan International Research Centre for Agriculture Sciences (JIRCAS) and Penang Fisheries Research Institute (FRI) at two stations in the northern and southern parts of the MS as shown in Figure 1. The in-situ Chl-a was measured based on the method proposed by Suzuki and Ishimaru [10]. The method is based on fluorescence profiles measured by fluorometer and converting the range-dependent fluorescence into Chl-a estimates by using the conversion factors obtained from linear regression analysis.

2.3 Satellite data
This study uses MODIS-A Level 2 from the latest reprocessed MODIS (hereafter referred as MODIS-A R2013) at the spatial resolution of 1km which can be downloaded at Ocean Color website [11]. Yet, this is a consecutive study of the preliminary one conducted using the previous MODIS-A Level 2 with R2010 variant (hereafter denoted as MODIS-A R2010). The match-up data of satellite and in-situ were chosen based on approximately simultaneous temporal with 1 or 2 hours interval. In the both exercises, the remote sensing reflectance of MODIS data (MODIS-A Rrs) is extracted and used as inputs to the revised OC3M algorithm, as formulated in Eq.(2), using the SeaWiFS Data Analysis System (SeaDAS version 6.3) and applying standard atmospheric correction or black pixel assumption method[12].

2.4 Regionally tuned MODIS standard Chl-a algorithm
The regionally tuned of empirical MODIS OC3M algorithm is devised in the basis of maximum band ratio, MBR (in this paper denoted as \(R_{3M}\)) of the Rrs at 443, 488 and 547 nm [9]. The functional form of the OC3M algorithm is as below.

\[
\log[Chl] = c_0 - c_1 R_{3M} + c_2 (R_{3M})^2 + c_3 (R_{3M})^3 - c_4 (R_{3M})^4
\]  

(1)

where,

\[
R_{3M} = \log_{10} \left( \frac{R_{rs} \, 443 > R_{rs} \, 488}{R_{rs} \, 547} \right)
\]  

(2)

and the original polynomial coefficients of \(c_0, c_1, c_2, c_3, c_4\) are 0.283, -2.753, 1.457, 0.659, and -1.403 respectively. This study applies an iterative regression technique by recursively fitting the logarithmic
satellite retrieved and the logarithmic in-situ derived Chl-a in the fourth-order polynomials. This iterative fitting technique is based on the objective function to achieve a slope of 1 and an intercept of 0.000, maximum $R^2$ and minimum RMS [13]. The most optimum coefficients (that met the limit of the objective function) were achieved by employing Type-2 linear regression [6].

3. Results and discussion
The study obtained 18 coincident points out of 300 data sets where the data are matched in time and space. This study has more Chl-a data than the preliminary one which used 13 out of 58 available match-up points as some satellite data were contaminated by clouds and there was less in-situ data provided.

The match-ups point selection was based on approximate time and date of measurement for both sea-thruthing and space-borne acquisition. Since match-up data in case-2 water were very few in the previous exercise the sensibility of the algorithm toward the case-2 water is rather weak. Therefore, by adding more match-up data in case-2 water, and using the reprocessed MODIS data, a new verification is needed to update the previous work.

The in-situ Chl-a and Chl-a retrieved using OC3M (MODISA R2013) were plotted with the line chart of nLw555, which is commonly used as an index of suspended sediment concentration or turbidity(see Figure 2). Previous study mentioned that the waters having nLw555 lower and higher than 1 mW cm$^{-2}$ μm$^{-1}$ sr usually optically belongs to case-1 and case-2 waters, respectively [6] and therefore, we defined the case-1 and the case-2 waters is associated with the ST.1 and the ST.2, respectively. Figure 2, it is obviously show that the OC3M-retrieved Chl-a of the case-2 water remarkably overestimated in-situ Chl-a and this overestimation trend is relatively caused by high suspended sediment concentrations which is shown by the nLw555 line chart.

The R2013 variant employs the calibration of MODIS Aqua bands 8 and 9 (412nm and 443nm) to adjust the temporal trends in the response versus scan angles (RVS)[14]. These temporal adjustments details explanation can be found in ocean color website [15]. Unfortunately, the SeaWiFS mission was ended in late 2010 due to a terminal spacecraft anomaly. The objective of MODISA R2013 is to implement a new instrument calibration that is fully independent of the SeaWiFS mission.

3.1 Validation and regionally tuned OC3M algorithm and its applicability in the MS water
Before the local tuning, the Chl-a retrieved by improved MODISA R2013, from the Eq.(1), was plotted against the in-situ Chl-a collected from both stations, and the statistical parameters were calculated to evaluate algorithm performance as shown in Figure 3. The Chl-a retrieved by the locally-tuned OC3M
(namely OCms) also been plotted in black dashed line, so the trend of Chl-a estimation can be clearly seen in Figure 2.

Figure 2. Temporal variations of in-situ Chl-a, OC3M-retrieved Chl-a and MODIS nLw555 in ST.1 and ST.2 waters.

In the preliminary study the $R^2$ value of the regression of in-situ Chl-a against the original OC3M-retrieved Chl-a (MODISA R2010) was remarkably low (0.031) if both case-1 and case-2 water data were combined, while for OC3M (MODISA R2013) the $R^2$ value has been improved from 0.031 to 0.276, but both data has resulted approximately the same high absolute percentage difference (APD) result which is ± 89%. The high APD value means the applicability of OC3M algorithm in the MS was not reliable. In global scale, NASA has targeted that the APD value should be less than 35% to consider the algorithm is reliable [13]. In this case, we had conducted the verification and locally-tuned of the algorithm separately for case-1 and case-2 water.

Based on the statistical analysis done for both MODISA R2010 and R2013, the performance of OC3M in MS is trivial. In the case-1 water the OC3M was underestimate the in-situ Chl-a while in the case-2 water the in-situ Chl-a was overestimated (see Figure 2). Indeed, this result was supported by the relative percentage difference (RPD) value which is very low for case-1 water and very high for case-2 water (see Table 1).

The improved and locally-tuned OC3M algorithm for MS water is referring to OCms (ms stands for Malacca Straits) and for using the latest reprocessed (MODISA R2013) data, the updated version of locally-tuned algorithm for case-1 and case-2 waters are namely OCms1.v2 and OCms2.v2, respectively. However, the result produced by OCms1.v2 shows just slight improvement of $R^2$ and RPD value over the result produced by OCms_1 (MODISA R2010), but surprisingly the APD value is higher than the OCms_1. For the case-2 water the performance of OCms2.v2 is significant in which more match-up points are added and as a result, the $R^2$ is higher than the one by OCms_2 (MODISA R2010) (see Table 1).

The study found that by using the reprocessed MODISA R2013 data shows greater improvement than data of MODISA R2010 with the higher $R^2$ for Case-1 and Case-2 waters. Theoretically, the validation for MS water has slightly improved because of the recalibration at band 9 (443nm) which involved in the MBR used for OC3M algorithm. This suggests that the improved MODISA R2013 provides high correlation of Chl-a in time and space with the in-situ.

The algorithm is therefore best to map the Chl-a over the MS regardless of the condition for Case-1 and Case-2 water as shown in Figure 3. Though, the same problem that was in previous exercise still occur if applying both locally tuned algorithm OCms1.v2 and OCms2.v2 in the MS water where the map of Chl-a shows unrealistic estimation as depicted in Figure 3 (b). Therefore, we are using the
same alternative where the original OC3M was applied for case-1 and the locally-tuned OC3M (OCms2.v2) for case-2 water. Figure 3(c) shows the impact of overestimation has been reduced.

Table 1. Statistical analysis of the OC3M retrieved Chl-a against the in-situ Chl-a. The 4th and 5th column shows the locally-tuned of OC3M (R2010) and OC3M (R2013) for case-1 water, respectively. The 6th column shows the locally-tuned of OC3M (R2010) and OC3M (R2013) for case-2 water, respectively.

| Bio-optical algorithms | OC3M (R2010) | OC3M (R2013) | OCms1 | OCms1.v2 | OCms2 | OCms2.v2 |
|------------------------|--------------|--------------|-------|----------|-------|----------|
| RPD                    | 2.075        | 174.801      | 1.470 | 1.020    | 0.003 | 0.230    |
| APD                    | 89.225       | 89.880       | 23.920| 26.000   | 5.930 | 11.000   |
| RMSE                   | 0.547        | 0.025        | 0.130 | 0.130    | 0.032 | 0.060    |
| $R^2$                  | 0.031        | 0.276        | 0.674 | 0.676    | 0.321 | 0.877    |
| $N$                    | 13           | 18           | 9     | 9        | 4     | 9        |

Figure 3.(a), (b) and (c) is the map of Chl-a distribution on November 17, 2011 using the MODISA R2013 data. (a) Map of Chl-a retrieved by using original OC3M, (b) combined OCms1.v2 (in case-1 water) and OCms2.v2 (in case-2 water)and (c) combined OC3M (in case-1 water) and OCms2.v2 (in-case-2 water).

4. Conclusion
An updated locally-tuned OC3M algorithm has shown some improvement for Chl-a estimation in case-2 water. However, the statistical robustness of these algorithms is trivial due to the fact of in-situ points are not sparsely distributed over the MS. This shows that the improved MODIS 2013 with iterative fitting method is only reliable for certain and limited part of MS. Therefore, it is a need for an alternative to be undertaken to improve the area coverage aspect of the algorithm. As a solution, there is a new version of standard OC3M (OCv6) which has been updated using comprehensive in situ data of NOMAD version 2 and by applying the different coefficient in the OC3M algorithm, it therefore gives different result or improvement to the applicability of OC3M in MS. Moreover, in algorithm development, it will be more helpful if the in-situ $Rrs$ data was used. This could give other option of optimum MBR as inputs to improve the regionally tuned algorithm in the MS water. However, this update of the algorithm validation can contribute to the development of regionally-tuned algorithm in MS for more reliable Chl-a retrieval.
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