5th SASTech Iran | Mashhad May 12 - 17 | 2011
5th Symposium on Advances in Science & Technology

Detection and monitoring of algal blooms in Persian Gulf using MODIS images

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Paper Reference Number: 1812-471
Name of the Presenter: Elham Tayebi

Abstract

Persian Gulf is susceptible to occurrence of Algal bloom phenomenon. As an example, the Red tide phenomenon occurred in the region from autumn 2008 to spring 2009. The aim of this research is to detect the Red tide phenomenon in the Persian Gulf waters and its monitoring during specific period of time using remote sensing data.
Detection of Red tide phenomenon in waters of the region was accomplished using chlorophyll anomaly monitoring method. By using values of water leaving reflectance in visible and near infrared bands, regression analysis and also field measurements, an experimental bio-optical model was produced to estimate chlorophyll-a density of water using data gathered by MODIS sensor. This model explains %93 of the chlorophyll-a variation for chl-a ranging from 5 to 30 $mg\ m^{-3}$ and can be used to estimate chl-a density with a normalized root mean square error (RMSEN) of %9.8 and mean normalized bias (MNB) of %0.4.
To determine areas where Red tide phenomenon is occurred in specific dates, values of chlorophyll-a density estimated at that date using the produced chlorophyll model is compared with the thresholds extracted from chlorophyll map of the same area related to a normal year (*i.e.* the previous year). Through this method, areas with intensive changes in chlorophyll-a density which are apt to bloom occurrence are determined. As the produced chlorophyll model does not provide the desirable accuracy in Case 1 waters, a filter is considered to omit the Case 1 waters from the final Red tide map. The obtained results show that the produced regional chlorophyll model is effectively capable of detecting bloom occurrence areas compared to OC3M model of MODIS sensor.

Key words: Detection, Algal bloom, chlorophyll density, Persian Gulf, MODIS

1. Introduction

A harmful algal bloom (HAB) is an algal bloom that causes negative impacts to other organisms via production of natural toxins or by other means and are often associated with large-scale marine mortality events. The red tide seen in Persian Gulf and Oman Sea in the years 2008 and 2009 is originated from a phytoplankton named "Cochlodinium Polykrikoides" (CP) (Richlen et al., 2008).

The vast environmental, economical and health damages resulted from red tides and susceptibility of Persian Gulf waters for this phenomenon, urges the precise and continual monitoring of waters of the region for early detection of the phenomenon in order to confront and prevent the subsequent harmful effects. There are some restrictions when using in situ observation techniques due to their spatial and temporal coverage. They are also highly expensive and time consuming. Therefore it is necessary to use ocean color observations by utilizing remote sensing techniques. Such techniques can be effective tools for early detection and monitoring red tide phenomenon in seas and oceans considering its wide synoptic coverage, frequent revisit capability, rapidness and low cost.
Red tide occurrence resulting from changes in one of the main optical components of waters which are phytoplanktons, effects on the optical features and color of waters and so it can be studied by observation of changes in the reflection spectrum of waters. By increasing use of satellite images for water environment studies in recent years and development of new satellite sensors with better spectral, radiometric, temporal and spatial effectiveness; their use for optical detection of red tide in waters has been noticed by researchers. Different efforts have been made to consider the possibility of using chlorophyll products of ocean color sensors in order to detect affected regions by kinds of blooms in different parts of the world (e.g. Stumpf, 2003). Other different methods for detection of special kinds of algal blooms based on their unique optical features have been developed (Cannizzaro et al, 2002). There have also been studies based on the use of classification techniques in order to separate regions infected by algal blooms from other waters with distinct optical features (Pasterkamp et al., 2002).
The main aim of this study is to detect occurrence of algal blooms in Persian Gulf waters by using optical methods and through MODIS sensor images. To achieve this, red and near infrared spectral bands of this sensor are used. In this research, the method of chlorophyll anomaly monitoring in satellite images is performed to detect CP blooms in Persian Gulf waters. Also, in order to monitor the red tide phenomenon, a relation between MODIS bands or their combinations with chlorophyll density in water as a quantitative parameter to show the intensity of the phenomenon is found.

2. Data and Material

2.1. Data

The satellite data used are the Level 1B images of MODIS sensor of Terra and Aqua satellites. This level of MODIS products includes calibrated radiances for all bands of the sensor. However, there are some noises in this product that must be omitted.
One of the important and essential issues in this research is to collect necessary field data for the calibration of the considered chlorophyll model to estimate chlorophyll density and to assess the results. Field data includes chlorophyll density and water turbidity together with geographical coordinates of the sampling locations. The data has been collected by "Persian Gulf and Oman sea ecological research institute" from 31 sampling stations located around Hormuz Strait and its east and west in 3 consecutive days during the red tide occurrence (i.e. February 26 to February 28, 2009).
Those field data which are very near to land, cloud obscured pixels, very near to cloud pixels or near to the image sides pixels are not used for modeling. The proper time difference that is maximum 2 or 3 hours between sampling time and the time when satellite passes over the region is also considered.

2.2. Study area

The study area includes some parts of Persian Gulf and Oman Sea situated between 54.5883° and 57.7213° geographical longitude, 24.8039° and 27.5427° geographical latitude.

2.3. Preprocessing of Satellite Data

The received raw images have many different errors. In order to make them usable to produce bio-optical models, first these errors must be removed or their effects must be reduced. Generally, the image preprocessing steps include geometric, radiometric and atmospheric corrections. In addition to common geometric errors, Bowtie error is also one of the existing geometric errors in MODIS images. Striping is another error which is among the radiometric errors. The preprocessing steps of satellite data is explained below.

2.3.1. Bowtie Error correction

When the viewing angle of the sensor increases related to nadir, the width of the pixels increases. The increasing amount in the sides of the image is almost doubled. This causes a raise in frame overlaying in the sides of the image along satellite movement which is known as Bowtie error. This effect is quite considerable in MODIS sensor because of its high viewing angle (- 55 to 55 degree). To correct this error, Modistools software package which is installed on ENVI software, has been used.

2.3.2. Destriping

The Striping error occurs because of the unequal functioning of sensor's detectors. In order to omit this error we usually need to know the accurate gain and offset of each detector. But, because of inaccurate calibration and also change in calibration coefficients by increasing sensor's age, these coefficients are not available and we have to use other methods. The method used to reduce this error in this research is matching the detectors' histograms with a reference histogram. This was tested for two reference histograms including histogram of detector with the most variance and the whole image histogram, while better results achieved when using whole image histogram. However, before doing this step, the cloud and land pixels of the image were masked so that produced signals by detectors of a band are statistically the same and no considerable changes in image details exist.

2.3.3. Land and Cloud Masking

The method used in this research to separate water regions from other regions is the use of NDVI vegetation index as relation 1 (Marcos et al., 2004). In MODIS sensor, bands 1 and 2 are used to calculate NDVI. As for water regions, the value $\rho(859)$ is less than the value $\rho(645)$, so NDVI value will be negative.

$$NDVI = \frac{\rho(\lambda_{NIR}) - \rho(\lambda_R)}{\rho(\lambda_{NIR}) + \rho(\lambda_R)} \qquad (1)$$

In order to detect pixels obscured with clouds in MODIS images, according to the method by Wang and Shi (2006), SWIR bands of MODIS sensor in 1240nm and 1640nm are applied. Considering much stronger absorption of water in SWIR wavelengths, the ocean is black even for waters with high turbidity and then it is possible to ignore the amount of reflection resulted by water from the total reflectance measured by the sensor. On the other hand, the amount of reflection by small size aerosols with less absorption is also considerably less in these wavelengths. So, by using a threshold in SWIR band, the efficiency of cloud mask algorithm of MODIS in coastal waters is considerably improved compared to using the NIR bands.

2.3.4. Atmospheric Correction

The aim of atmospheric correction is to gain the normalized water leaving reflectance $[\rho_w]_N$ or the normalized water leaving radiance $[L_w]_N$ that just measured above the water surface and is not affected by atmosphere or light condition of the region and sensor's position. For this, the absorption and scattering effects related to air molecules and aerosols must be omitted from the total reflectance measured by the sensor. The method used in this research for atmospheric correction in turbid and coastal waters, is the method represented by Ruddick et al. (2000). In this method the assumption of zero water-leaving radiance for the near-infrared bands at 765 and 865 nm is replaced by the assumptions of spatial homogeneity of the 765:865-nm ratios for aerosol reflectance and for water-leaving reflectance. These assumptions are based on the simplicity of optical features of waters in infrared bands. In this spectral range, the absorption of water is almost completely determined by absorption of pure water and scattering has also little spectral changes (Ruddick et al., 2000). In this research, the atmospheric correction of ocean data of MODIS sensor was done by using SEADAS software.

3. Research Methodology

3.1. Chlorophyll anomaly monitoring in MODIS images

It is almost impossible to use MODIS sensor bands to detect CP phytoplankton based on its unique optical features because of its very few spectral bands. But as the increase of chlorophyll-a density in a region can be a sign for increase of phytoplankton cells, the chlorophyll anomaly monitoring is used. The monitoring is based on the abnormal changes in chlorophyll density of water in bloom period compared to normal conditions. This is a common method for detection of different kinds of phytoplankton blooms. As the base of this method is on chlorophyll density, it is necessary to estimate the chlorophyll density with a high precision in order to achieve high accuracy in detection of algal bloom regions. In order to detect abnormal changes in chlorophyll density, it is necessary to compare the values of chlorophyll density to a threshold. The threshold is chosen differently in different researches. According to Ruddick et al (2007), the chlorophyll map of the region belonging to previous year when there was no bloom, is applied as the threshold chlorophyll map. By comparing the values of chlorophyll density in any location with the threshold obtained from the threshold chlorophyll map, algal bloom affected regions are detected.

3.2. Development of bio-optical algorithms for chlorophyll density estimation

Bio-optical algorithms are based on the relation between the electromagnetic waves reflection leaving from water with those dissolved and suspended materials in the water. Most remote sensing studies on chlorophyll of water are based on empirical relations between the radiations in narrow bands or band ratios and chlorophyll density. To model the chlorophyll density of water through empirical bio-optical models, chlorophyll density is taken as a dependant variant and reflections are taken as independent variants and then regression analysis is applied. To do this, two independent data sets are required which include training data needed for production of regression model and test data for assessment of the model. Statistical tests are used to analyze the significance of the regression. In order to assess the suitability of the models, the parameters R^2

(determination coefficient), MNB (Mean Normalized Bias), RMSEN *(*Normalized Route Mean Square Error), Skewness and Kurtosis are used.

4. Results and Analysis

4.1. Modeling of chlorophyll density in study area

The standard chlorophyll products of MODIS sensor are produced through models with global coefficients which are almost suitable for case 1 waters while the Persian Gulf waters show bio-optical characteristics of case 2 waters in most regions. Comparison of the chlorophyll values obtained from OC3M algorithm of MODIS (O'Reilly, 2000) which is defined by relations 2 and 3 with chlorophyll values resulted from the sampling of the region, shows a RMSEN equal to %47 for this model. This RMSEN is too high and therefore lacks the required accuracy level to estimate the chlorophyll. This implies that the standard chlorophyll product of MODIS is not suitable for the desirable accuracy level in case 2 waters of the region. Therefore it is necessary to produce a suitable regional chlorophyll model.

$$chl - OC3M = 10^{(0.2830 - 2.752X + 1.457X^2 + 0.659X^3 - 1.403X^4)} \tag{2}$$

$$X = log_{10}[max(R_{rs}(488)/R_{rs}(551) \quad , \quad R_{rs}(443)/R_{rs}(551))] \tag{3}$$

To produce a model for estimation of chlorophyll-a density in waters of the region, a relation between the chlorophyll density and remote sensing reflectance values (*Rrs*) in one band or a combination of some sensitive bands by using empirical methods and regression analysis must be found. To do this, two kinds of independent variants, including *Rrs* values and their band ratios in visible and near infrared wavelengths are separately used in regression analysis. These values are extracted from MODIS images after preprocessing. The bands or band ratios which are sensitive to chlorophyll density changes are identified through calculating of the Spearman correlation coefficient between each of the independent variants and dependent variant (chlorophyll density).

In this modeling, the univariate and multivariate linear regressions are considered. Also, as the relation between dependant and independent variables may follow a nonlinear manner, the polynomial models of order two or higher assessed as well. Therefore, by assessment of different models resulted from regression analysis, the model with relation 4 has been chosen as the optimum regional model for estimation of chlorophyll-a density. This model is a polynomial of order 4 with 5 independent variables consisting log-scaled values of remotely sensed reflectance. It has a determination coefficient of %93, RMSEN of %9.8 and MNB of %0.4 for chlorophyll-a density ranging from 5 to 30$mg\ m^{-3}$.

$$\begin{aligned} \text{Log(chlorophyll)} = & -10.868 + 0.014\,(\log(R_{rs}469))^4 - 1.185\log(R_{rs}555) + 4.716\log(R_{rs}645) + \\ & 0\,.06\,(\log(R_{rs}678))^4 - 9.201\log(R_{rs}748) - \\ & 0.123\,(\log(R_{rs}748))^4 \end{aligned} \tag{4}$$

In Figure 1 the scatter plot of chlorophyll values calculated through this model against chlorophyll values obtained by field observations is shown.

4.2. Detection of Algal bloom in study area

In chlorophyll anomaly monitoring method, the regions with bloom occurrence are detected by comparing the chlorophyll density of water with a threshold. The first phase is to estimate the chlorophyll density of waters of the region and produce the chlorophyll map of the related date. According to Ruddick and Park (2007), the threshold is extracted from the chlorophyll map of the previous year of the same date of the region when there was no bloom. So, it is also necessary to produce chlorophyll map of waters of the region at that date.

The chlorophyll anomaly map on February 27, 2009 was produced through subtraction of chlorophyll density of water at that date and chlorophyll density of water of the previous year of the same date (February 27, 2008) in a pixel by pixel basis. After that, obtained differentiation values were compared with an 80 percent threshold according to Ruddick

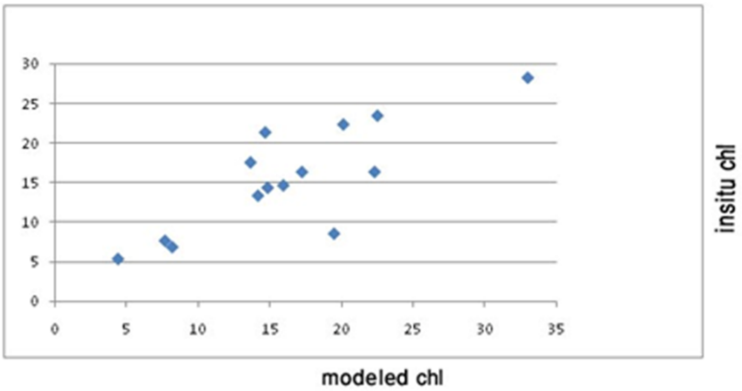

Figure 1: Scatter plot of modeled chl with relation 4 against insitu chl.

and Park (2007). So, when the chlorophyll density of water in a point is increased 80 percent or more compared to the previous year, it can be regarded as the occurrence of algal bloom in that point.

There were few measured field samples for chlorophyll modeling. They were situated in red tide occurrence regions with very high chlorophyll density and turbidity and also optical specifications similar to case 2 waters. The mentioned reasons have resulted in the fact that the obtained regional model based on these samples overestimating the chlorophyll values when compared to the real ones in waters with similar specifications in case 1 waters.

As mentioned, case 1 waters cannot be considered for the region showing red tide occurrence. In order to omit unreal results caused by applied chlorophyll model, according to Petrenko and Ouillon (2005), those pixels which do not comply with the relation 5 are detected as case 1 waters. Therefore these pixels are omitted from the obtained chlorophyll anomaly map of the previous phase. As a result, the remaining pixels which comply with %80 threshold are identified as the region with algal bloom occurrence.

$$\max\left(\frac{R_{rs}(443)}{R_{rs}(555)}, \frac{R_{rs}(488)}{R_{rs}(555)}\right) < 1 \tag{5}$$

The red tide maps resulted from chlorophyll anomaly method are shown in Figure 2, A and B**.** These maps have been produced based on two chlorophyll estimation approaches. The first approach is based on relation 4 to produce the chlorophyll density maps for the specific day (i.e. inside bloom occurrence period) and for the same day in the previous year, while the second one is based on the standard chlorophyll model OC3M for the same days.

4.3. Assessment of the results

In order to quantitatively assess the results obtained by using chlorophyll anomaly monitoring method, samples from 15 stations that situated in red tide occurrence regions were taken. It was observed that amongst these 15 stations, chlorophyll anomaly monitoring using first approach (Figure 2-A) detected 10 stations as bloom occurrence while the second approach (Figure 2-B) detected 5 stations as bloom occurrence. In addition, many red tide regions which can be identified even visually in RGB image (shown in Figure 3) cannot be detected by the second approach. This implies the weakness of standard chlorophyll model of MODIS (i.e. OC3M) in detection of algal bloom in the region. It seems chlorophyll anomaly monitoring using method proposed in this study which is based on a regional chlorophyll model is relatively more appropriate in detecting

A B

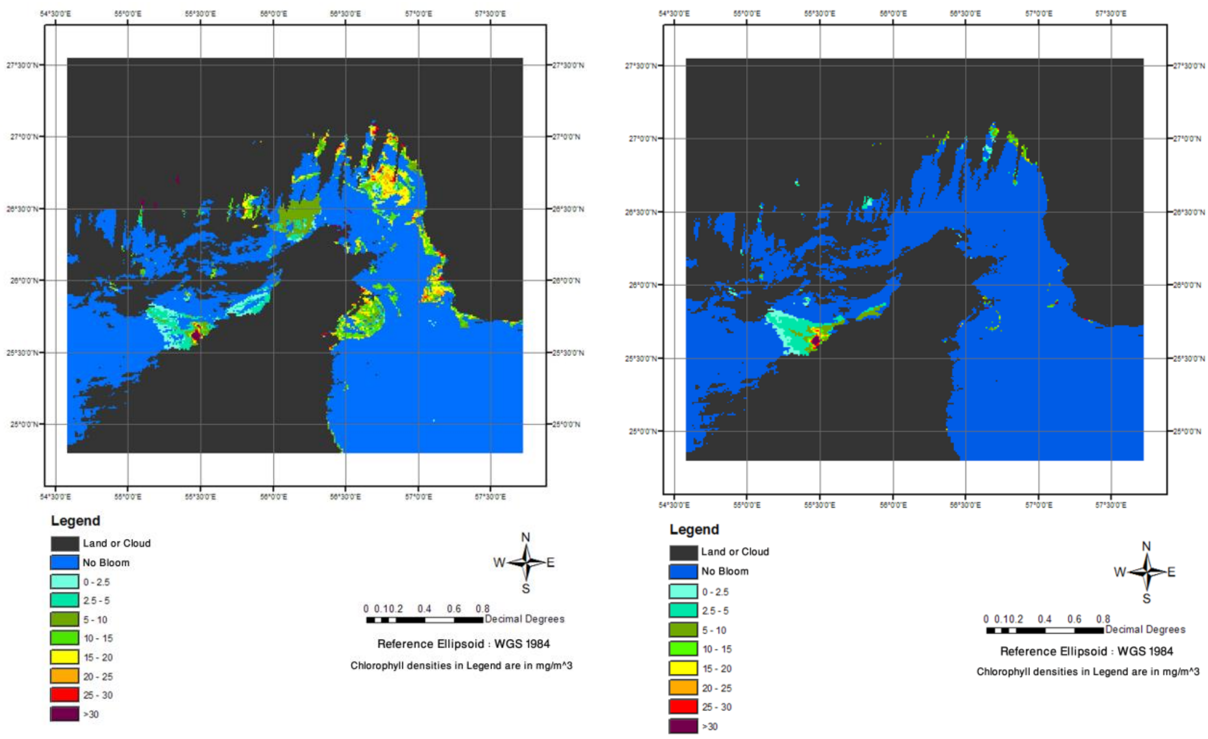

Figure 2: Red tide map of Persian Gulf and Oman Sea on Feb 27, 2009 produced through chlorophyll Anomaly monitoring based on A) first approach, B) second approach.

algal bloom occurrence when compared with OC3M method. The proposed method also has less omission error. However, in this study it was not possible to identify the regions mistakenly detected as red tide by this algorithm and also it was not possible to assess the results pixel by pixel due to the lack of sufficient field data of the region in red tide occurrence period.

5. Conclusions

MODIS imagery has been used in this study for optical detection of red tide because of its suitable spectral bands, frequent revisit capability and simple accessibility. The results of this research show that the implementation of chlorophyll anomaly monitoring method in MODIS images leads to detection of the overall distribution of algal bloom occurrence in the waters of the region and therefore the early detection of the phenomenon is possible by using satellite images. Also quantitative assessment of the results using available field data shows that produced regional chlorophyll model can detect red tide regions more accurately in Case 2 waters compared to standard chlorophyll model (OC3M) of MODIS. Regional chlorophyll model was produced using empirical method and through regression analysis. The assessments show that applying multivariate regression and considering higher order variables in modeling, improve the results considerably and reduce systematic and random errors of modeling. In general, the algorithms were based on the chlorophyll-a red absorption feature, the green peak and/or the red/NIR peak, given their location in spectral regions of low sensitivity to CDOM (Colored Dissolved Organic Matter) and detritus absorption and strong sensitivity to cell scattering demonstrated to be more reliable to quantify C. P in Case 2 waters of the region.

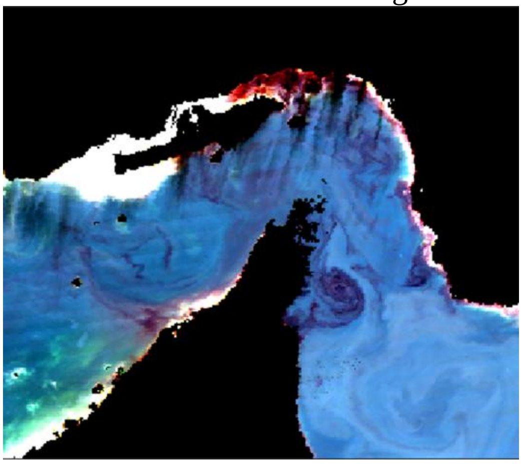

Figure 3: RGB image of study area on Feb 27, 2009 (Blue: 443 nm, Green: 488 nm, Red: 551nm).

Acknowledgments
The in situ data was supplied by "Persian Gulf and Oman sea ecological research institute" for this study. We thank for this support. Also we thank NASA MODIS project for providing MODIS processing algorithms and ocean color data products.

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