Evaluating the Performance of MODIS FLH Ocean Color Algorithm in Detecting the Harmful Algae Blooms in the Arabian Gulf and the Gulf of Oman

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Abstract— **Detecting and monitoring harmful algae blooms (HABs) outbreaks are facing significant challenges at both local and regional scales. Red tide outbreaks in the Arabian Gulf and Gulf of Oman have caused a number of negative effects during the last few affecting therefore the daily human life. The objective of this project is to validate the existing MODIS ocean color algorithm (FLH and nFLH) to detect and monitor red tide outbreaks in the Arabian Gulf and Gulf of Oman Therefore, the model can be used as early warning and daily monitoring tools of red tide outbreaks in the Arabian Gulf. The results show that, the correlation between FLH, normalized FLH and in situ chlorophyll show R^2 of 0.58 and 0.57, respectively. The FLH performance is affected by the impact of bottom on the blue and green reflectance, high turbidity of the atmosphere caused by the suspended aerosol particles that increase the reflectance detected by the satellite and water sediments.**

Keywords— red tide, algae, Arabian Gulf, Gulf of Oman, MODIS, FLH, nFLH,

I. INTRODUCTION

Harmful Algal Blooms (HABs), commonly called red tide, occur frequently in the Arabian Gulf and Gulf of Oman mainly during winter seasons (2000-2001; 2006, 2008-2009). This phenomenon transforms the water color to red, green or brown due to the dense batches of the HABs formed in oceans. These HABs may cause death/poison of the fish and birds which affect the food cycle, affect human health by irritating the eyes and the respiratory systems, damage the filtration and the membrane systems of the desalination plants which are the main source of fresh water in this arid region, and affect the recreational activities in the affected areas [1]. Recently, In February and March, 2013, intensive batches of HABs have been found in the Gulf of Oman which caused the spread of the bad smell and shutting down one of the desalination plants in Sharjah, United Arab Emirates (UAE) to protect the units of the desalination plants. They have been observed first in Oman and then they moved toward the eaten coastline of UAE where it reached Kalba, Khor Fakhan and Fujairah.

The parameters used to characterize and quantify these HABs are: chlorophyll and Fluorescence. These parameters can be measured by the conventional water quality monitoring techniques which are expensive and time consuming. However, remote sensing is a very applicable alternative technique at large-scale where low and medium resolution data are openly available to users through different space agencies and programs free of charges [2][3].

Satellites (MODIS, MERIS) data have been successfully used for water quality monitoring and mapping (chlorophyll concentration, seas surface temperature, dissolved organic matter, etc.) using several ocean color algorithms (OC3, FLH, etc.) [2]. In spite of their good accuracy over some regions (California, Florida, China, Mexico, Korea, etc.), most of these algorithms failed when applied over the Arabian Seas [1][4][5][6]. The disagreements may be caused by several factors which are improper atmospheric correction and physiological changes in the algal species. Specifically, the FLH algorithm was not tested well over the region.

The objective of this study is to validate and improve the performance of the Fluorescence line height (FLH) MODIS ocean color algorithm in the Arabian Gulf and the Gulf of Oman.

II. STUDY SITE AND DATA SETS

A. Study site

- Arabian Gulf

The Arabian Gulf is a semi enclosed shallow basin located between latitude 24°N and 30°N and longitude 48°E and 57°E with Iran covering most of the northern coast and Saudi Arabia most of the southern coast as shown in Figure 6 [7][8][9]. . It is considered as one of the most complicated ecosystem in the world [49]. It occupies a surface area of 8630 km^3surrounded by a very arid and dry region. The Arabian Gulf width varies from 75 to 370 km, it is more shallow in the southern region near the coastline of the United Arab Emirates where the depth is generally lower than 20 m, however, the depth increases toward the northern part of the Gulf in front of the Iranian offshore where the depth reaches its maximum value of about 80 m [7]. The length of the Arabian Gulf is around 990 km extended from the Shatt Al-Arab in Iraq to the Strait of

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Hurmuz which connect the Arabian Gulf is to the Gulf of Oman [8] [10], [9]. It stretched 280 km and width of 56 km.

There are two major flows in the Arabian Gulf, the first one is the inflow towards the northern Iranian region from the strait of Hurmuz and the second one flows by the density difference force southwards against the other flow which leads to salinity rise in the southern region of the Gulf [8]. It was reported by Richlen et al. (2008) that the Arabian Gulf has two major circulations currents. The first one is located in the western area of the Gulf with clockwise movements while the second one is located in the eastern area where water moves in counter clockwise direction. As a result, water upwelling behavior is observed in the Iranian coast[8] (Figure 1) .

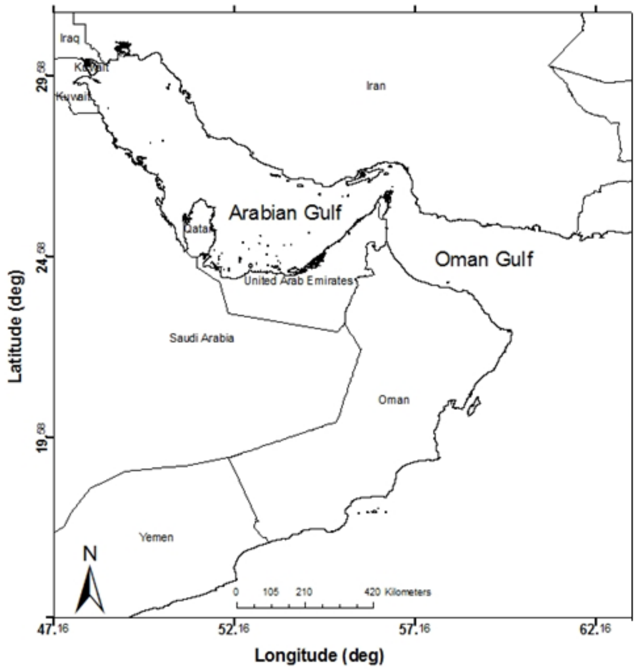

FIGURE 1. The study site (Arabian Gulf and Gulf of Oman)

- Gulf of Oman

The Gulf of Oman is located between 22°N to 26°N latitude and 56°E to 60°E longitude.. It has a width of about 370 km and it is extended along 545 km [11]. The Gulf of Oman is characterized with high precipitation rate in the northern part (150-200 mm/year) and low precipitation rate in the southern part (45 to 60 mm/year). The productivity of HABs in Oman Sea is high especially in the summer season which is mainly caused by gravitational settling of aerosol particles, upwelling currents and convection during the cold season [12][13] (Figure 1).

B. Data Sets

A considerable dataset was used to validate the FLH algorithm. This dataset is constituted by *in situ* chlorophyll data and MODIS images collected between 2001 and 2011 over our study region.

- *In situ data*

In situ data were collected to validate the FLH algorithm for better adaptation to the environmental conditions of the Arabian Gulf and Gulf of Oman. Chlorophyll in situ measurements were extracted from an intensive field measurement campaign organized by different organizations from 2006 to 2011 as following:

- ✓ The Regional Organization for the Protection of the Marine Environment (ROPME) [14] has sampled 66 stations spread uniformly over the Gulf of Oman and the Arabian Gulf,. Chlorophyll concentrations were measured at three depths (Surface, middle and very deep) starting from the third of February until the ninth of March, 2006.

- ✓ National Institute of Oceanography (NIO) in India has collected chlorophyll data from SK 209 cruise organized over three-week period from the 4th to 25th of September 2001.The collected data were in the Arabian Sea and Gulf of Oman at 33 different stations.

- ✓ Sultan Qaboos University (Oman) has collected few chlorophyll measurements in 2008.

- ✓ The Marine Research and Resources Center (MRRC) in Umm Al Quwain (UAE) has collected recently chlorophyll, salinity, oxygen and temperature measurements in April and May 2011 from six stations located in the western and eastern coasts of UAE.
- ✓ The British Oceanographic Data Centre (BODC) of the UK National Oceanography Centre (www.bodc.ac.uk) has collected measurements during sampling campaigns of 1994 (143 stations) and 2001 (18 stations) that includes: chlorophyll concentration, oxygen concentration, calculated salinity, turbidity and temperature with different depth.

- ✓ Marine science and Fisheries Center (MSFC) in Oman has collected chlorophyll data in 2010 and 2011 in three stations in Dibba, Suhar and Sur with several depths that reach a maximum of 28 m.

- ✓ NASA Ocean Biology Processing Group (OBPG) has collected few chlorophyll measurements in 2009 in Gulf of Oman (http://seabass.gsfc.nasa.gov).

- *MODIS data*

MODIS (Moderate Resolution Imaging Spectroradiometer) is one of NASA's Earths observing System (EOS). It is a key instrument onboard of Terra (EOS AM) and Aqua (EOS PM) satellites which were launched in December 1999 and May 2002, respectively. The entire earth can be viewed by MODIS Aqua and Terra within one day. Spatial, temporal and spectral resolutions are more developed in MODIS satellite compared to others similar missions. MODIS has 36 bands with different spatial resolutions: 250 m, 500 m and 1 km. The bands with lower resolutions (250 m and 500 m) are designed for land-related applications because they have low sensitivity, but it is very interesting to apply them in ocean applications. More than forty high quality science products of MODIS were developed during the ten years of operation [15].

MODIS level 1A images (not calibrated values) that coincide with the shortest time interval to in situ measurements were considered for this study considering temporal a and spatial variance lower than 40%. All available images were collected from NASA data portal and preprocessed to get the calibrated radiance and reflectance measurements. They were geo-located into standard map projection after performing the atmospheric correction. All these corrections were performed using SEADAS Software which is open source Linux software developed and validated by NASA ocean color group. The reflectance and radiance values of the available stations were extracted from the nearest pixels to the sampling locations (within a radius of 3 km).

MODIS water leaving radiance L_w and normalized water leaving radiance nL_w of the pixels covering the ground measurements were extracted for three red wavelengths: band 14 (678 nm), bands 13 (667 nm), and band 15 (748 nm) after processing the raw images (level 1A). This processing includes the calibration, atmospheric and georeferencing corrections undertaken using SEADAS software.

III. LITERATURE REVIEW

A. Red Tide Outbreaks in the Arabian Gulf and The Gulf of Oman

Red tide is a cyclical phenomenon, so it occurred periodically with few years of time gab [5].

In the Arabian Gulf, Oman was the first country that has encountered extensive blooming activities in the seventies killing thousands of fish. These blooming activities were followed by another severe red tide event in 1986 which affected UAE coastline and caused fish mortalities [5]. In September 1999, huge amounts of fish died because of red tide outbreak in Kuwait. Dinoflagellate *Gmnodinium* were the most phytoplankton species observed at that period, this kind of specie were found previously in New Zealand off shore [16]. Recently, high rate of red tide outbreaks has started in UAE during 25-28 August 2008. It extended along the coastline of the country until December 23rd [1]. Blooming activities have increased again in February 2009 along UAE coastline. Most of fish mortalities were in Umm Al Quwain, Sharjah and eastern coastline [17].

Gulf of Oman exposed to the first algal blooms in 1970's where the presence of phytoplankton species *Prednium, Dionophysis* and Prorocentrum was recorded. It was reported that there was a high fish mortality because of those species associated with bacterium that depleted the oxygen in the water. Another fish moralities episode occurred in 2000 because of the lack of oxygen but no toxic phytoplankton were observed in Gulf of Oman. In October 13 2005, blooming activities were observed in Masirah Island off shore killing significant amounts of fish and turning the water to orange color [18].

B. Causes of red tide

Red tide can be caused by several reasons:

- High water temperature especially in the Arabian Gulf where the water is warm and can reach temperature of 30-35°C. This temperature range is very favorable to grow the phytoplankton species such as C. polykrikoides.
- High nutrients content in the water which can be inflow in the Arabian Gulf naturally from the discharge of Shat Al Arab or the Indian rivers through the Strait of Hurmuz or anthropogenic caused by the human activities such as brine and sewage discharge (e.g. near Musafah Industrial area (UAE) where the sewage, and industrial water, rich with phosphate and nitrogen, are dumped to the Arabian Gulf water). .
- Wind driven dust (aerosols) which can transfer the dust particles which can settle later on in the sea and cause red tide.

Phytoplankton can be transferred by the discharge of ballast water, which is used to balance the ships and oil tankers. For instant, phytoplankton species, such as "cochlodinium polykriokoides, gymnodiniumcatenatum and pseudo-nitzschia", that caused the red tide are not from the Arabian Gulf region. These species are common in Mexico Gulf and Korea which might be transferred from other areas. Phytoplankton species can be also transferred by water currents [5].

C. FLH algortihm

Fluorescence is considered as a good indicator of the chlorophyll in the water. It is re-emission of a portion of the solar radiation absorbed at all visible wavelengths by the phytoplankton chlorophyll in frequencies other than the infra-red. In 1997, it was found that chlorophyll concentrations can be derived from sun simulated fluorescence [3]. Later, Hu et al. (2005) have demonstrated that the FLH approach can be efficiently used to detect areas affected by harmful algal boom in the coastal water of West Florida (Gulf of Mexico) based on MODIS bands: band 13 (667 nm), 14 (678 nm) and 15 (748 nm). The maximum chlorophyll fluorescence is measured at band 14. Bands 13 and 15 are used for backscattering correction. It is expressed as follow,

$$FLH = L_{14} - L_{baseline}$$

$$L_{baseline} = L_{15} + (L_{13} - L_{15}) \times [(748 - 678)/(748 - 667)]$$

Normalized FLH (nFLH) was also used in this paper, which is a function of nL_w instead of L_w.

The results obtained by Hu et al. (2005) have shown that FLH was highly correlated with the in situ chlorophyll data ($R^2 = 0.92$). The authors expected that by combining MODIS FLH, remotely sensed chlorophyll, and true color image (RGB) can enhance the detection of red tide and differentiate phytoplankton species[19]. However, in another study performed by Tomlinson et al. (2008), the authors found that FLH model was unsuccessful in classifying K.brevis blooms, where only 71% of the blooms were properly identified by FLH in some scenes. The authors have also observed that the FLH method overestimate blooming concentrations in other scenes. Tomlinson et al. (2008) have recommended further assessment of the FLH method [1].

FLH can be affected by several factors, which are atmospheric scattering and absorption, physiological changes in the algal species and the performance of the instrument and sun radiations. Gases and water vapor in the atmosphere can be absorbed and affect the satellite data but fortunately, the narrow range of the three bands (10 nm each) make them less vulnerable to atmospheric absorption [3].

IV. RESULTS AND DISCUSSIONS

This section presents the analysis of the results using MODIS data coincides with the in situ data described earlier.

A. Analyzing the water spectrum using MODIS data

Seawater characteristics change when it contains additional substances, such as colored dissolved organic matters (CDOM), and phytoplankton. Therefore, it affects the reflectance spectrum of the water at different wavelengths. Figure 2 shows how the presence of algae (Chl = 27.7 mg/m^3) affect the reflectance spectrum compared to clear water (Chl = 1.02 mg/m^3). It is obvious that the reflectance of algae contaminated water is lower than clear water reflectance at 400-500 nm. However, it increases at 500-600 nm and it reaches the peak at 550 nm because of the low absorption of green light. Similarly, there is another small peak between 645 and 750 nm because of the interaction of algal cell scattering and the lowest combined impact of pigments and water absorption. Therefore, the spectral signature of the seawater changes significantly with the presence of algae. Chlorophyll has strong absorption of the blue light between 400 and 500 nm. It also has strong absorption of red light at 675 nm [20].

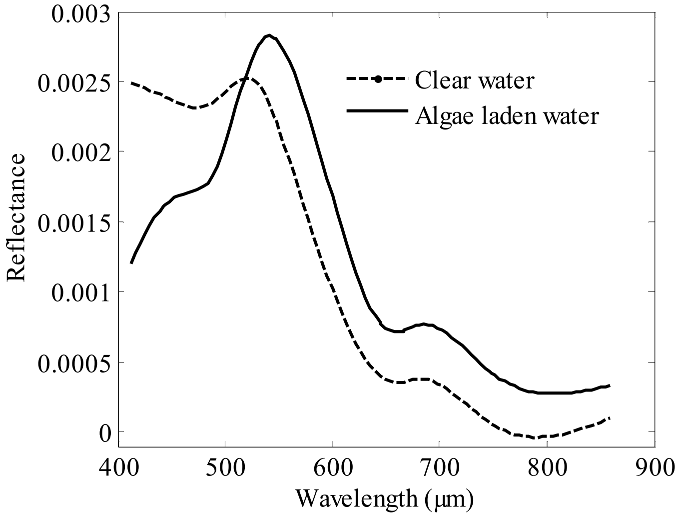

FIGURE 2. The spectrum of clear water and algae laden water using MODIS image

B. Correlation of FLH and nFLH with chlorophyll concentration.

There is a high correlation between the FLH and in situ chlorophyll concentration as shown in Figure 3. As the chlorophyll concentration increases, the FLH increases. The linear relationships between FLH/normalized FLH and in situ chlorophyll show R^2 of 0.58 and 0.57, respectively as shown in Figures 3 and 4.

FLH performed well in some points, however, in other points the performance was low in estimating the chlorophyll concentration which may be caused by some of the following factors such as the impact of bottom on the blue and green reflectance which increases the bias, specially over the shallow western part of the Arabian Gulf, high turbidity of the atmosphere caused by the suspended aerosol particles that increase the reflectance detected by the satellite and water sediments.

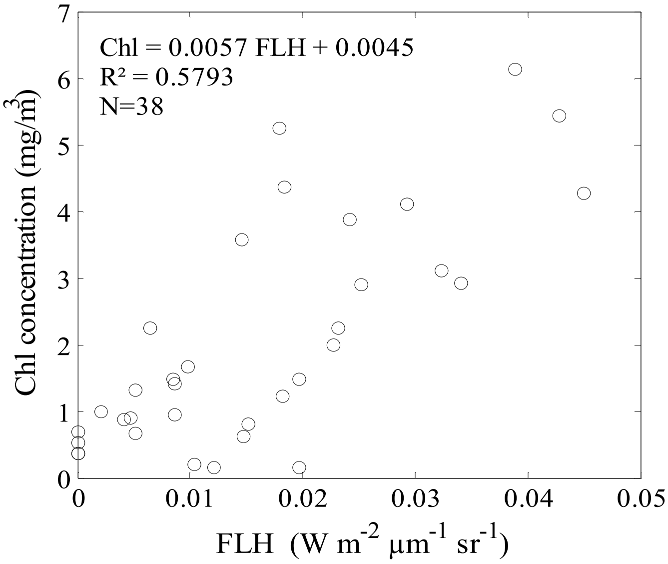

FIGURE 3. Chlorophyll concentration versus FLH.

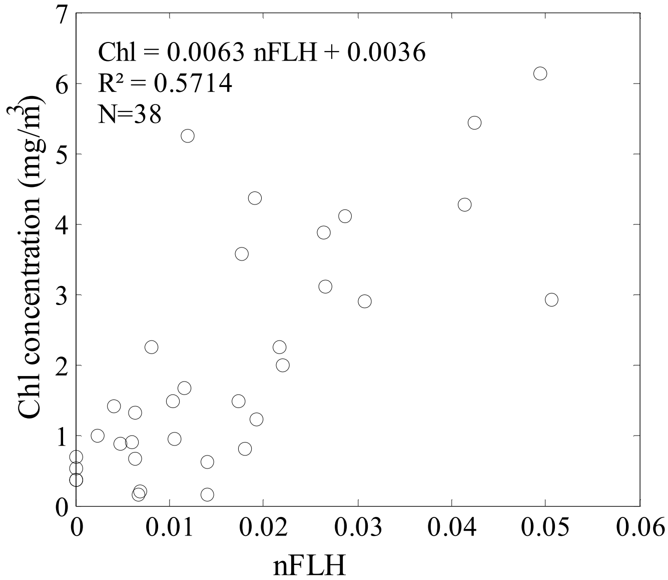

FIGURE 4. Chlorophyll concentration versus nFLH.

FLH is designed to overcome the effect of the suspended solids in the blue absorption by focusing on the red part of the spectrum where chlorophyll fluorescence controls the total signal. However, , it might be affected slightly by other factors such as suspended solids, shallow water and the atmosphere [19].

FLH and nFLH show similar performance. However, the increasing trend is more obvious in nFLH correlation with the in situ data. Most of the data used in the match up are from ROPME cruise and most of the other in situ data were masked because of the atmospheric correction failure. This masking occurred because the ocean color tools conclude that the atmosphere is very turbid, so no water parameters can be retrieved from space.

FLH, and nFLH were mapped for the seventh of November, 2008. This day was selected because the concentrations of phytoplankton blooms were very high which reached around 267 mg/m^3 in the Gulf of Oman.

Enhanced RGB (ERGB) was created using the composite of nL_w at 547 (R), 488 (G), and 443 nm (B). The ERGB (Figure 5) shows the batches of the algae blooms spreading mostly in the Gulf of Oman. The water circulation in this period (summer monsoon) has shaped the flow of the algae blooms (shown in dark red color) as shown in the ERGB. High values of FLH were found in the algae blooms area as well which ranged between 0.1 to 0.3 $Wm^{-2}\mu m^{-1}sr^{-1}$.

In the literature, it was found that the chlorophyll concentration equal 10 times the FLH values. So, we can say that the chlorophyll range is between 10 to 30 mg m^3. The values of nFLH were also high in the algae blooms area. However, the variation of the algae concentrations was not very obvious in the nFLH map (Figures 6 and 7).

The backscattering at 667 mn (bb 667 nm) was also mapped for the same day to make sure that the high FLH was caused by the dense algae bloom not the high sediments of the water as shown in Figure 8. It is observed that bb 667 nm is very high in the coastal area where the sediments concentration is high; however, it is relatively low in the algae blooms area which supports the real reason of the high FLH which is the presence of algae not the sediments.

So, it can be stated that FLH and nFLH performance is affected by the turbid atmosphere and the complex features of the Arabian Gulf.

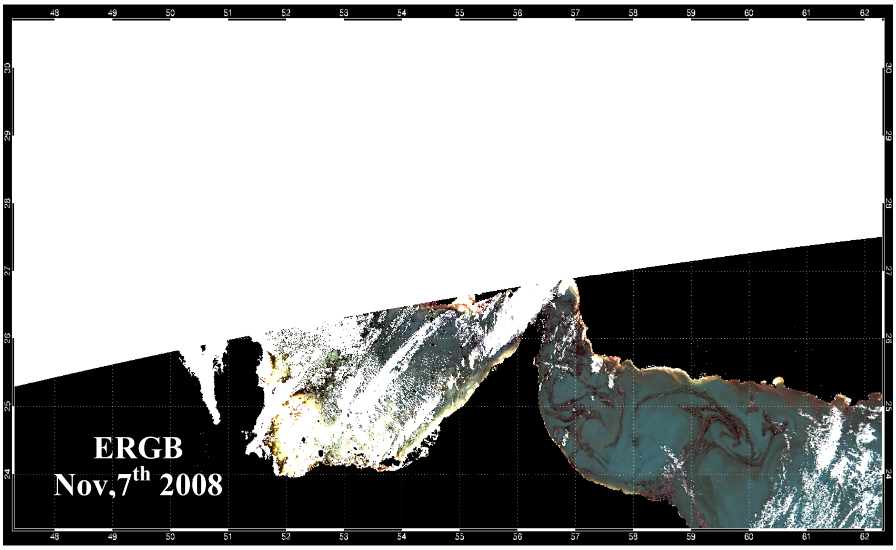

FIGURE 5. Enhanced true color (RGB) MODIS image of Nov,7th 2008

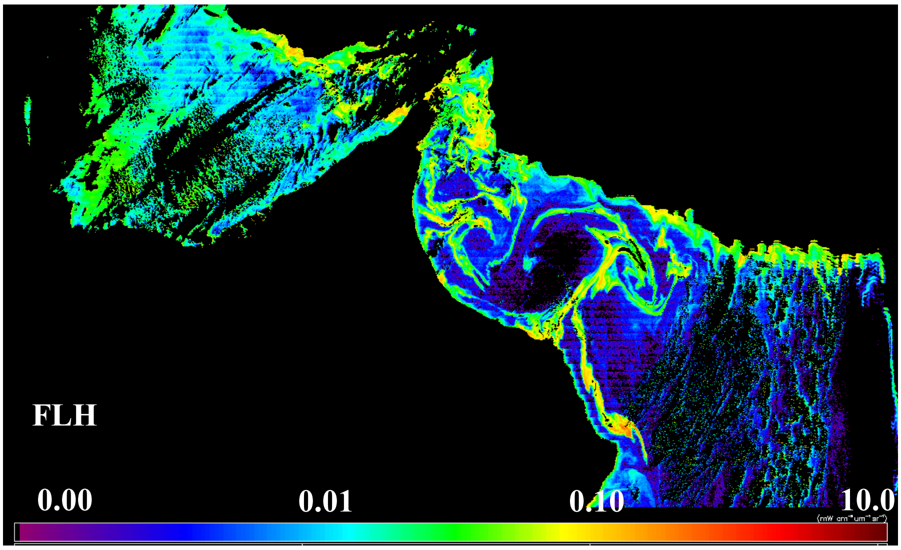

FIGURE 6. FLH of Nov,7th 2008

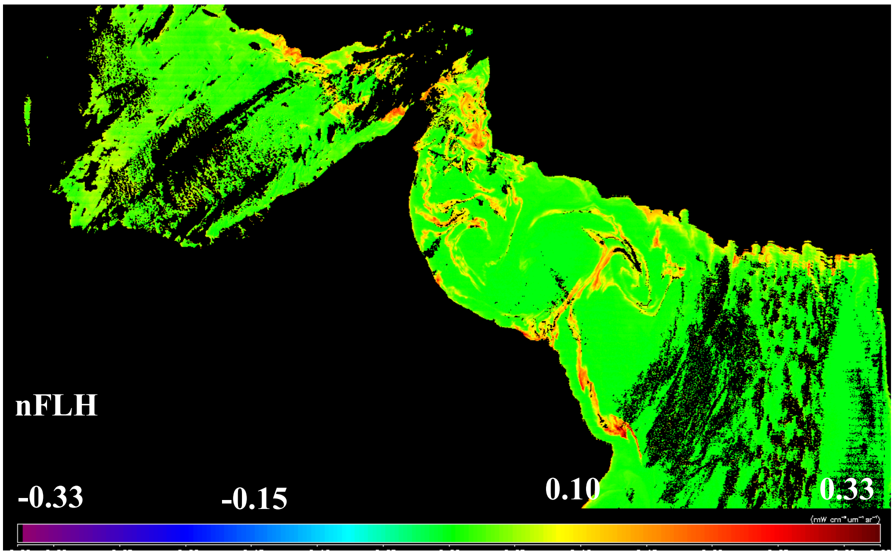

FIGURE 7. nFLH of Nov,7th 2008

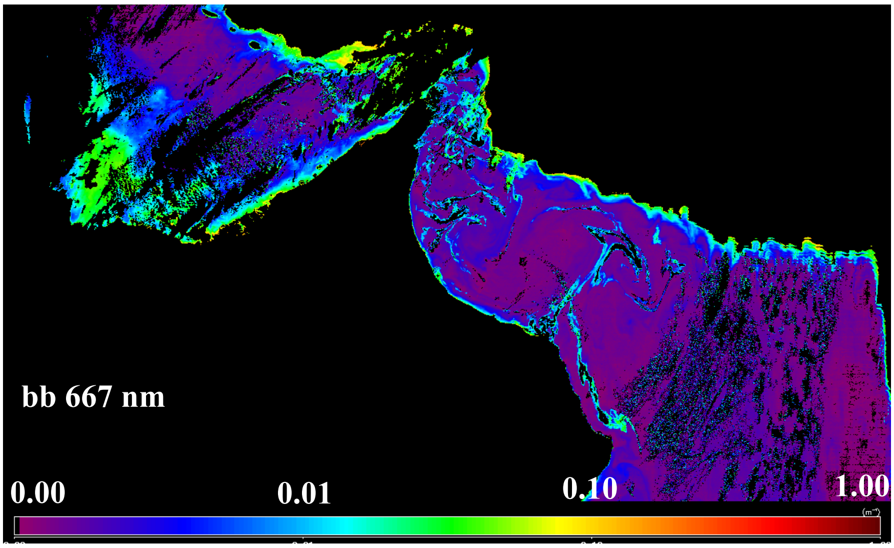

FIGURE 8. bb at 667 nm of Nov,7th 2008

V. CONCLUIOSNS

Detecting and monitoring harmful algae blooms (HABs) outbreaks are facing significant challenges at both local and regional scales. Many MODIS models were tested to detect and monitor red tide outbreaks in the Arabian Gulf. In this paper, FLH algorithm was validated to examine its performance in detecting the algae blooms in the Arabian Gulf and Gulf of Oman. The validation was done using in situ data collected in the Arabian Gulf and Gulf of Oman from 2001 to 2011.

Several conclusions were found as follow:

1. FLH was successful in detecting the red tide in some of the locations.
2. The correlations between FLH/normalized FLH and in situ chlorophyll measurements show low R^2 of 0.58 and 0.57, respectively
3. The obtained low performance of FLH algorithm in estimating the chlorophyll concentration was low in some locations may be caused by the impact of bottom on the blue and green reflectance which increases the bias specially over the shallow western part of the Arabian Seas, high turbidity of the atmosphere caused by the suspended aerosol particles that increase the reflectance detected by the satellite and water sediments.
4. Large areas of the Arabian Gulf and Gulf of Oman were masked even under cloud free conditions because of SEADAS atmospheric correction models failure. This failure is caused by the high aerosol

condition in the region and SEADAS is designed for the clear atmosphere

VI. ACKNOLWGMENT

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