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Red tide detection in the Strait of Hormuz (east of the Persian Gulf) using MODIS fluorescence data

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A monstrous red tide appeared on October 2008 and expanded to the west on November 2008 off the Iranian coasts in the Hormuz Strait (east of the Persian Gulf). MODIS satellite data, hydrographic and bio-optical field measurements were used to detect the red tide. MODIS fluorescence line height (FLH in \( \text{w m}^{-2} \text{\mu m}^{-1} \text{sr}^{-1} \)) data showed the highest correlation with near-concurrent \textit{in situ} chlorophyll concentration of 0.74 (100(FLH))\(^{1.23} \) \((r = 0.9, n = 44)\). In contrast, the band-ratio Chlorophyll product of MODIS showed more inconsistency with \textit{in situ} chlorophyll data due to the interference of other water constituents. High FLH value patches >0.18 were confirmed to be located at the medium to high \((10^4–10^6 \text{ cells l}^{-1})\) concentrations of \textit{Cochlodinium polykrikoides}, and also showed a chlorophyll anomaly >1 mg m\(^{-3}\), which means the potential of red tide occurrences. The FLH imagery also showed that the bloom started in early September along Bandar-Abbas port, and developed and moved to the west along the coastal regions. The results revealed that MODIS FLH and enhanced RGB (ERGB) imagery plus \textit{in situ} data are adequate tools for red tide monitoring.

1. Introduction

The occurrences of phytoplankton blooms are a regular phenomenon in the coastal waters of the Oman Sea and the Persian Gulf (Thangaraja \textit{et al.} 2007). Nevertheless, incidents of frequent occurrence of harmful algal blooms and mass kills of marine organisms create panic in the general public and are becoming common in the Persian Gulf and the Oman Sea (ROPME 1997, 2003, Thangaraja 1998). Published literature pertaining to occurrences of red tide in the Oman Sea and the Persian Gulf is very rare. Harmful Algal Blooms (HAB) occur every year in Persian Gulf waters. The presence of 38 taxa has been noted, which includes 18 identified to the species level, and the others have been identified to the genus level (Al-Hasan \textit{et al.} 1990, Rezai 1995, Rao \textit{et al.} 1998, Thangaraja \textit{et al.} 2001).

In the fall and winter of 2008, a monstrous red tide spanned from Muscat in Oman up to the UAE and on to the Iranian coasts. This bloom of the microorganism \textit{Cochlodinium polykrikoides} was associated with a large fish kill occurrence and hampered the marine industries and water desalination plants on the Persian Gulf coasts. In some of the affected areas, concentrations of \textit{C. polykrikoides} between 2 and

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8 million individual microorganisms per litre were recorded (Rezai and Sanjani 2009). *C. polykrikoides* is not new to the Persian Gulf environment. It is one of the indigenous microorganisms in this area (Savari 1984, Rezai 1995). *C. polykrikoides* is not toxic to people and cannot infect the water, but people should avoid eating shellfish from the area as they accumulate the algae’s toxins and can be extremely dangerous. It generates oxygen radicals that damage their gills, leading to suffocation (Shumway 1990, Kim 1998). However, to date the exact mechanisms causing *C. polykrikoides* blooms in the Persian Gulf remain unclear.

Temporal detection and observation of HABs is critical for environmental assessment, for ecological modelling, and for prediction and mitigation of red tide impacts. Significant efforts have been made using satellite ocean colour sensors, which provide synoptic coverage of the coastal ocean at near-daily frequencies or better. Multiple observations per day are possible using the two Moderate Resolution Imaging Spectroradiometer sensors (MODIS). Ocean colour sensors measure the amount of light reflected from the upper ocean at specific wavebands. Algal biomass, measured as the concentration of chlorophyll–a, can be accurately estimated from ocean colour data (Gordon *et al.* 1983, O’Reilly *et al.* 1998, Carder *et al.* 1999, 2004). The colour of the ocean is the combined result of the properties of various coloured constituents in the surface ocean, namely water molecules, phytoplankton, detritus, coloured dissolved organic matter (CDOM), suspended sediments, and bottom reflectance (if the water is optically shallow). However, it is difficult to determine whether high chlorophylls are due to non-toxic species or to an HAB.

These difficulties cannot be overcome with traditional bio-optical algorithms (Hu *et al.* 2005). New algorithms have been proposed based on *in situ* data to use the backscattering/chlorophyll ratio or the fluorescence/chlorophyll ratio to differentiate HABs from other blooms (Cannizzaro *et al.* 2008), but operational application of these new algorithms using satellite data still requires significant research (Hu *et al.* 2005).

The MODIS sensors are equipped with several bands that are specifically designed to measure the solar stimulated fluorescence of phytoplankton living in surface waters (Neville and Gower 1977, Gower and Borstad 1981, Hoge *et al.* 1986, Fischer and Kronfeld 1990, Letelier and Abott 1996). MODIS Bands 13, 14 and 15 are used to estimate fluorescence line height (FLH). A study of coastal run-off by Hu *et al.* (2004) used MODIS FLH to distinguish a phytoplankton bloom from a coastal dark water patch caused by riverine discharge. MODIS FLH data also have been used to detect the trace of HABs in the coastal waters west of Florida (Hu *et al.* 2005).

This research is an attempt to present the abilities of MODIS FLH data to detect a known algal bloom occurred in the Strait of Hormuz (east of the Persian Gulf) where the red tide formed and then extended to western parts of the area. Also, the phenomenon were monitored and sampled frequently on September and November 2008 during some *in situ* observations and field measurements. However, the main objective of this article is to assess whether MODIS FLH data can be used effectively to detect and evaluate the HABs such as used in the west of Florida by Hu *et al.* (2005).

### 2. Study area

The Persian Gulf is a semi-enclosed marginal sea about 1000 km long, about 200–300 km wide, with a mean depth of 35 m and a total volume of 6000 km³. At the east it is connected to the Gulf of Oman through the narrow Straits of Hormuz, which lead to the Arabian Sea. Freshwater inflow into the Gulf is estimated at 5–100 × 10⁶ m³
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(Grasshoff 1976). The adjacent rivers mainly in the north and northwest discharge annually about $1.1 \times 10^8$ m$^3$ of water and $4.8 \times 10^6$ tonnes of sediments (Reynolds 1993). Because of the surrounding arid desert and enormous loss of water due to evaporation that does not exceed the precipitation and river run-off, surface coastal waters attain a maximum temperature of 32°C and salinity of 44.30% (Saad 1976, Jacob and Al-Muzaini 1990). A northwest-to-southeast gradient exists, from high salinity and lower temperature in the northern Gulf to lower salinity and higher temperature at the Hormuz Strait (Halim 1984). The dense water formed by winter cooling and evaporation sinks to the bottom in the central Gulf and eventually flows out through the Straits of Hormuz as a thin layer into the Gulf of Oman (Grasshoff 1976, Halim 1984). This vertical mixing results in oxygenation down to the bottom (Siebold 1973).

2.1 Background pigment concentrations

Bio-cell abundances and chlorophyll-\(a\) data are not fairly available for the study area. Although the data are limited, a north-to-south gradient in cell abundance is suggested (Rao and Al-Yamani 1998). In the eastern part of the Persian Gulf and Strait of Hormuz, cell abundance varies widely. In November and September it is $1.4-42.0 \times 10^3$ cells l$^{-1}$ (Dorgham et al. 1987), and $0.07-449.1 \times 10^3$ cells l$^{-1}$ (Dorgham and Moftah 1989), respectively. In the Straits of Hormuz and the Gulf of Oman during September, cell densities are low, that is, $0.2-22.7 \times 10^3$ cells l$^{-1}$ (Dorgham and Moftah 1989). In the Strait of Hormuz and the eastern part of the Persian Gulf, the mean of phytoplankton ranges from $9.5$ to $18.7 \times 10^3$ cells l$^{-1}$ at the 10 m top level of depth (El-Gindy and Dorgham 1992). In contrast, cell abundance at the top 40 m depth of Oman Sea is about $3.7 \times 10^3$ cells l$^{-1}$ (El-Gindy and Dorgham 1992). In the Strait of Hormuz, chlorophyll-\(a\) concentration at the top 10 m of depth ranges from 0.96 to 1.18 mg m$^{-3}$ in September (El-Gindy and Dorgham 1992).

3. Data and methods

3.1 In situ data

Two surveys were conducted by the Iranian National Centre for Oceanography (INCO) from 16 to 18 November 2008. During these surveys, along-track hydrographic and bio-optical data were collected. The temperature and salinity data were collected using a CTD model Ocean-Seven 304 and chlorophyll concentrations were measured with a Seapoint Chlorophyll Fluorometer (SCF; Seapoint Sensors Inc., Exeter, NH, USA) sensor from surface to the maximum depth. At discrete stations, water samples were collected for quantitative analysis of chlorophyll to calibrate the underway fluorescence and the other water constituent measurements. Cell counts of \(C.\ polykrikoides\) were obtained from the Iranian Fisheries Research Institute (IFRI) from 3 to 7 October 2008. The IFRI samples were counted with a light microscope that was sometimes inverted, and some samples were preserved in non-acidic Lugol solution for subsequent counting.

3.2 Satellite data

MODIS data were collected from DAAC and processed with up-to-date algorithms and software (NASA SeaDAS 5.3). An iterative approach for sediment-rich waters, based on the Gordon and Wang (1994) algorithm, was used to correct for atmospheric interference in the six ocean colour bands in turbid coastal waters to obtain water-leaving radiance $L_w(\lambda)$ (Arnone et al. 1998, Stumpf et al. 2003), which were then used
in the OC4 band-ratio algorithm (O’Reilly et al. 2000) to estimate chlorophyll abundances in mg m$^{-3}$. A baseline subtraction algorithm (Letelier and Abott 1996) was used to estimate FLH, and a band ratio algorithm (O’Reilly et al. 2000) was used to estimate the chlorophyll concentration.

The corrected reflectance data of the MODIS medium resolution (250 and 500 m) bands (645, 555 and 469 nm) were used to derive composite red-green-blue colour (RGB) and enhanced RGB (ERGB) images. This type of image carries information from three MODIS bands, and therefore allows detection of more spatial features than the Chlorophyll imagery, which was derived from only two bands per pixel.

Rigorously, satellite data validation should be performed with in situ data collected within about 2 or 3 hours of the satellite overpass (Bailey et al. 2000). In practice, due to frequent cloud cover or other inconveniences, this often leads to very few matching data pairs. Hu et al. (2005) proposed that in the near-shore segment (within 10 m water depth) differences of up to 6 hours between satellite overpass and in situ data are primarily valid for FLH and Chlorophyll products.

To reduce errors from satellite sensor digitization noise, a median value from a 3 × 3 box was used to filter the image data (Hu et al. 2001). Similarly, for each satellite pixel (about 1 km × 1 km), a median value from the multiple in situ data points was used.

Proper interpretation of MODIS Chlorophyll changes is difficult, however. If we have confidence in the consistency of satellite estimates of chlorophyll, even if the accuracy is doubtful, then computing the difference between images to assess anomalies can help attribute changes to specific phytoplankton dynamics. Stumpf et al. (2003) proposed using the difference between an instantaneous satellite chlorophyll estimate and the mean value of chlorophyll over two previous months, with two weeks in between, as an index to detect suspicious patches that may be potential red tides. This method is now used operationally by NOAA NESDIS (CoastWatch) to issue HAB alerts for west Florida. However, the results are problematic when chlorophyll estimates are not consistent in time (Hu et al. 2005). This method has been performed as an index for chlorophyll anomalies in comparison with FLH and in situ data.

4. Results

In situ collected data within about 3 hours of the satellite overpass were selected for comparison. The chlorophyll fluorescence was converted to chlorophyll using selected water samples. Because samples were collected during the morning and from semi-identical water types (coastal waters), variations in chlorophyll fluorescence efficiency were not too much, and high correlation coefficients ($r = 0.96$, $n = 48$) for November 2008 cruises were obtained. The converted chlorophyll data were used to compare with the satellite estimates.

Figure 1 shows several MODIS/Aqua products and concurrent ship tracks. The images show large differences in the spatial distribution of detected features. Dark features have been differentiated on the ERGB images. These patches have been caused by high absorption of light due to chlorophyll and/or colour dissolved organic matter (CDOM) and could be separated from bright features which have been caused by either sediment resuspension (blue to green), or shallow bottom (green to cyan). The FLH images show detailed patchiness within the dark feature observed in the ERGB image at the centre (figure 1(a)). In contrast, the Chlorophyll images (figure 1(b)) display a continuous region of high concentration over the dark patches. The Chlorophyll
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Figure 1. MODIS/Aqua processed images for the Strait of Hormuz. (a) Fluorescence line height (FLH; \( \text{w m}^{-2} \text{µm}^{-1} \text{sr}^{-1} \)). (b) Band-ratio chlorophyll concentration (OC3M chl; mg m\(^{-3}\)). (c) enhanced RGB (ERGB) composite images from water-leaving radiance in three MODIS wavelengths: 645 nm (R), 555 nm (G) and 467 nm (B). MODIS data were collected on 16 November (9:30 GMT) (i) and 18 November (9:20 GMT) 2008 (ii). Water depth contour lines and near-concurrent ship survey transects overlaid on the FLH and chl images.

Images also mask any contrast between dark and bright water feature because all colour changes are interpreted by the band-ratio algorithm as changes in chlorophyll concentration.
On 16 November 2008, in situ data were collected along a cross-shelf transect (transect no. 1) (figure 1(a)). Figure 2 shows in situ chlorophyll, MODIS FLH and MODIS Chlorophyll along this transect for about 3 hours time window. FLH patterns matched the in situ chlorophyll patterns (Chlorophyll = 2.19(100(FLH))^{0.6}, r = 0.81, n = 48). The MODIS Chlorophyll also shows relatively good correlation with in situ chlorophyll for values lesser than 8 mg m^{-3}. For MODIS Chlorophyll values bigger than 8 mg m^{-3}, a bias of factor 4–9 times in situ chlorophyll were cleared.

For further processing the consistency between the MODIS parameters with in situ chlorophyll, data along a transect parallel to the coast near Qeshm Island (transect no. 2) were analysed for collected data on 18 November (figure 1(a(ii)) and (b(ii))) (figure 3). MODIS Chlorophyll shows better agreement with in situ chlorophyll (r = 0.83). Similar to figure 2, better correlation between in situ and MODIS chlorophyll were cleared for MODIS Chlorophyll values less than 8 mg m^{-3}, and for
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\[ \text{chl (mg m}^{-3}\text{)} \text{ and MODIS FLH (× 100 w m}^{-2}\text{µm}^{-1}\text{sr}^{-1}) \]

\[ \text{chl (mg m}^{-3}\text{)} \text{ and MODIS FLH (× 100 w m}^{-2}\text{µm}^{-1}\text{sr}^{-1}) \]

In situ chl

\[ \text{chl (mg m}^{-3}\text{)} \text{ and MODIS FLH (× 100 w m}^{-2}\text{µm}^{-1}\text{sr}^{-1}) \]

\[ \text{chl (mg m}^{-3}\text{)} \text{ and MODIS FLH (× 100 w m}^{-2}\text{µm}^{-1}\text{sr}^{-1}) \]

Figure 3. Similar to figure 2, but for the transect 18 November 2008 (figure 1(b)(i)).

bigger values an overestimated factor of 3–5 for MODIS Chlorophyll were observed.

The collected in situ chlorophyll along transect no. 2 have a better consistency with MODIS FLH and MODIS Chlorophyll \( (r = 0.90, r = 0.83 \text{ respectively} ) \) than collected data along transect no. 1.

Synoptic patterns seen in the MODIS FLH data showed better agreement with in situ chlorophyll than MODIS Chlorophyll. For the range of 0.4–8 mg m\(^{-3}\), the ratio between MODIS FLH and in situ chlorophyll was approximately 0.01 w m\(^{-2}\) µm\(^{-1}\) sr\(^{-1}\) per mg m\(^{-3}\) chlorophyll. For the range bigger than 8 mg m\(^{-3}\) this value was approximately 0.001 w m\(^{-2}\) µm\(^{-1}\) sr\(^{-1}\) per mg m\(^{-3}\) chlorophyll. Considering that the Persian Gulf red tide typically has more than \( 5 \times 10^6 \) cells l\(^{-1} \) of dinoflagellates (corresponding to 0.5 mg m\(^{-3}\) of chlorophyll), MODIS FLH should provide an adequate indication of the presence of red tides. However, satellite-derived Chlorophyll values exceeded the FLH along all analysed transects.

To illustrate the contrast between MODIS Chlorophyll and FLH more clearly, two arbitrary transects cross and parallel to the coast were selected for 25 November 2008 satellite imageries (figure 4). One of these transects crossed the shelf and pass from
dark coastal water (high absorption) to the brighter water (higher backscattering) (figure 4(a)) and the other crossed the pigment features at the middle of the Strait. Along these transects, bio-optical properties (FLH and Chlorophyll) from MODIS

Figure 4. Similar to figure 1. MODIS/Aqua imagery was obtained on 25 November 2004 (9:25 GMT). Overlaid on the images are two arbitrary along-coast and cross-shelf transect lines used to extract several parameters (shown in figure 5).
show relatively good agreement (figure 5). Along transect no. 3 (figure 4(a)), the agreement between FLH and Chlorophyll is \( r = 0.79 \) (\( n = 159 \)), and along transect no. 4 (figure 4(a)) the agreement coefficient is \( r = 0.72 \) (\( n = 108 \)). However, satellite-derived Chlorophyll values exceeded the FLH along these two transects. These trends are likely to be due to high concentrations of CDOM in coastal waters, where they are seen as dark patches in the ERGB images (figure 4(c)).

To determine the utility of the satellite-derived FLH images to identify suspicious blooms, the in situ data collected on early October 2008 (figure 6(c(ii))) were analysed against MODIS data. The concentrations of *C. polykrikoides* were determined in the selected stations along each transect at discrete dates. Several suspicious patterns were
identified in the FLH images of early October (figure 6). However, the FLH patches in the image series were confirmed by field sampling data of *C. polykrikoides* concentration along the transects. The FLH suspicious patterns were compared with Stumpf’s
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Figure 7. MODIS chl anomaly images for October and November 2008. Chl anomaly is defined as the difference between the current data and a two-month mean two weeks ago. Anomaly of > 1 mg m^{-3} indicates potential red tide, which could be compared with medium to high concentration of Cochlodinium over FLH patches in figure 6.

chlorophyll anomaly (figure 7). The results show a similar trend for high-FLH and chlorophyll anomaly in the images along the coasts.

From early October, the low concentration of bloom appeared along the east of Bandar-Abbas coast as discrete patches (figure 6(a(i))) and became bigger and moved towards the west (figure 6(a(ii))). The bloom drifted westward and formed a larger patch along the north and south of Qeshm Island (figure 6(b)). During the subsequent weeks until mid-November the bloom formed vast patches around Qeshm Island and along Bandar-Abbas shore with very high concentrations of C. polykrikoides (figure 1(a)). On November 25, the patches moved westward more. The Stumf chlorophyll anomaly images (figure 7) also show relatively similar trends.

Considering the much-larger and spatially coherent features identified by MODIS Chlorophyll data, the present study suggests that MODIS FLH data provide a better means to detect and trace the red tide patches. Clearly, FLH data are insufficient to identify whether a bloom is toxic or not.

5. Summary and conclusion
MODIS data were used to study the HAB event in the Strait of Hormuz coastal waters in October and November 2008. Comparison of analysed MODIS data with
observations collected during near-concurrent field surveys showed that MODIS fluorescence line height (FLH) data provided more reliable information than other traditional satellite products (e.g. chlorophyll concentration) on the relative distribution of the phytoplankton abundance in this complex coastal environment. Comparison of MODIS FLH with \textit{in situ} data collected within about 3 hours of the satellite overpass showed high correlation \((r = 0.9, n = 77)\) in coastal waters. In contrast, correlation between MODIS Chlorophyll and \textit{in situ} data was significantly lower. Estimation of chlorophyll with traditional remote-sensing techniques in optically complex waters will remain a great challenge to the ocean colour community, and it may prove to be an impossible task in many cases, particularly for waters where CDOM rather than phytoplankton dominates blue-light absorption. Therefore, the presence of CDOM and shallow bottom could often be misinterpreted as chlorophyll. The MODIS fluorescence bands were designed to overcome this difficulty by focusing on the red part of the spectrum, where chlorophyll fluorescence dominates the total signal, and therefore suffer little from other interference (CDOM, shallow bottom and atmosphere). Hence, MODIS FLH data can be used as a better index than the satellite-driven Chlorophyll to differentiate phytoplankton blooms from other suspicious features such as CDOM-rich plumes.

To test this concept, MODIS FLH image series were used to detect and trace a known red tide. Patches with high FLH values \((0.18 \ \text{w m}^{-2} \ \text{µm}^{-1} \ \text{sr}^{-1})\) were often found to contain medium-to-high concentrations \((10^4–10^6 \ \text{cells l}^{-1})\) of \textit{C. polykrikoides} in the region. The high FLH patches are also compared with Stumpf’s chlorophyll anomaly index on discrete dates. The results showed that the patches with FLH value >0.18 \text{w m}^{-2} \text{µm}^{-1} \text{sr}^{-1} were comparable with chlorophyll anomaly index >1 mg m\(^{-3}\), and for FLH \(\geq 0.25 \ \text{w m}^{-2} \ \text{µm}^{-1} \ \text{sr}^{-1}\) the chlorophyll anomaly index were >20 mg m\(^{-3}\). A chlorophyll anomaly >1 mg m\(^{-3}\) indicates potential red tide.

The results show the advantage of the MODIS FLH data over the traditional satellite Chlorophyll data in identifying and tracking blooms. MODIS level-2 products combined with the ERGB composite imagery data, and knowledge of local waters, can clearly identify whether a feature is shallow bottom, suspended sediment, phytoplankton bloom or CDOM-rich plume. Hence, MODIS FLH imagery, which is available daily, provides a tool to monitor the coastal regions for red tide blooms.

References


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