Red Tide Monitoring in the Persian Gulf and Gulf of Oman Using MODIS Sensor Data

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ABSTRACT: Satellite imaging sensors are one of the safest, least expensive and easiest ways to monitor marine pollutions. Recently, both Persian Gulf and Gulf of Oman are experiencing several types of pollution including oil spills and heavy metal pollutions as well as Harmful Algal Bloom (HAB) caused by biological and environmental changes. Their occurrence of the red tide or harmful algal bloom during fall and winter 2008-2009 caused numerous unknown factors in the Strait of Hormuz. Persian Gulf and Gulf of Oman which left many destructive effects on fishery, aquaculture, tourism and environmental conditions of the region as some of them have not vanished absolutely yet. This paper deals with the analysis of application of the marine satellite imaging sensors to study and monitor the adverse environmental factors, particularly those associated with algal bloom occurred in 2008-2009. Data obtained by the MODIS sensors have been used to monitor the relevant environmental factors of the red tide. Our results show that the occurred algal bloom was the result of seawater temperature drop, water circulation and the adverse environmental pollutions caused by industrial and urban sewages entering the coastal waters in this region of the Persian Gulf. This red tide phenomenon was started in the Strait of Hormuz and eventually covered about 140,000 km² of the Persian Gulf and total area of Strait of Hormuz and it survived for 9 months which is a record amongst the occurred algal blooms across the world.

Keywords: Persian Gulf, marine pollution, red tide, MODIS data

INTRODUCTION

Recently, marine pollutions have increased considerably and put the marine ecosystems under the influence of their adverse effects; these types of pollutions can destroy most of the marine species and endanger healthiness of the sea creatures and even human beings. Given its proximity to an oil-rich and industrial zone, the Persian Gulf has been affected by such adverse effects which have recently increased very quickly.

The increase of urban and industrial sewages, oil spill from oil wells and tankers, loading heavy metals and chemicals from seaports located across the Persian Gulf coasts and daily passage of over 18 million barrels of oil from the Strait of Hormuz are some of the adverse factors which menace the environmental life cycle of the Persian Gulf and Gulf of Oman. Recently, some phenomena such as harmful algal bloom have been considerably increased in this region and have become the most critical problem of the Persian Gulf and Gulf of Oman. Precise identification of the phenomenon in association with qualitative and quantitative examinations of its main causes can be very helpful towards solving this problem; however, unfortunately not only it has not been realized so far because of managerial inconsistency among various Persian Gulf states, but the failure of these countries to comply with the environmental standards has put the local waters under the warning conditions.

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.
The red tide seen in Persian Gulf and Oman Sea in the years 2008 and 2009 is originated from a phytoplankton named “Cochlodinium Polykrikoides” (Richlen et al., 2008). The event of 2008-2009 harmful algal bloom in Persian Gulf, Gulf of Oman and Strait of Hormuz is studied in this paper. Persian Gulf is categorized as a semi-closed sea with 37 m mean depth and high salinity levels as its southern coasts salinity can reach up to 42 psu\(^1\). Its temperature varies very markedly during the year in contrast with other gulfs, seas and oceans of the globe. Persian Gulf acts as a reverse estuary due to intense evaporation and small precipitation, as a result less salty waters of the Indian Ocean enter the Persian Gulf from northern coast and after touching the axis of Gulf, in an area between Iranian Nayband Gulf and Qatar Peninsula, they flow toward southern coasts of the Persian Gulf, and becoming saltier and hence eventually moving out of the Gulf as a dense deep outflow (Figure 1, e. g. Hamzei, 2007).

![Figure 1. The study area of this research considering inflow and outflow currents of the Persian Gulf inspired by the general circulation pattern (Reynolds, 1993)](image)

**METHODOLOGY**

As a medium resolution imaging spectroradiometer equipped with coastal zones color scanner, a satellite imaging sensor, so called Moderate-resolution imaging spectroradiometer (MODIS), locating on the Nimbus 7 and Landset satellite was used in this study. This sensor has been designed to collect data with 0.25-1 km resolution on 36 visible and infrared bands. Both orbit and geometry of this imaging sensor are designed so that any point on the earth becomes visible everyday or once every two days. A wide range of the oceanic, atmospheric and terrestrial processes have come to be observed using this satellite. A number of 21 spectral bands of the sensor are used for oceanic algorithms.

The red tide phenomenon or harmful algal blooms (HABs) can be detected through discovering discoloration of the surface water and/or observing the concentrations of chlorophylls accumulated in water. MODIS sensor is used in this study to detect changes of marine parameters including chlorophyll concentration changes, seawater temperature and discoloration of the surface water across the Persian Gulf, Strait of Hormuz and Gulf of Oman and they will be used in turn to analyze changes in both density and concentration of algae caused by the red tide event. Also, their extension mode is evaluated given daily changes of this parameter and evaluation of the movement path.

<table>
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<th>Table 2. OC2 and OC3M algorithms for detecting chlorophyll density, used by MODIS sensor inspired by the Reilly equation (O’Reilly, 1998)</th>
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<tr>
<td><strong>OC3M</strong></td>
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<tr>
<td>( \text{chl} \ a \ (\mu g/L) = 10^a (R_443 + a R_488 + a R_551) )</td>
</tr>
<tr>
<td>( R = \log((\text{max}(R_{443}, R_{488}))/R_{551}) )</td>
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<tr>
<td>( a = [0.28, -2.78, 1.46, 0.66, -1.42] )</td>
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\(^1\) Practical salinity unit (PSU)
Field data for this study has are collected through cruises conducted by the Persian Gulf and Oman Sea Ecological Research Institute, before as well as after occurrence of the red tide phenomenon. This data was compared with the satellite data. The standard algorithms of chlorophyll and temperature and then the best possible results were obtained from the satellite data after applying local corrections.

By adjusting the coefficients of OC2 and OC3M algorithms, the measuring accuracy of seawater chlorophyll during harmful algal bloom, caused by Cochlodinium polykrikoides, was acceptably matched with the real concentrations. Eventually, SeaWiFS Data Analysis System (SeaDAS) software was used to convert the obtained result into images.

Figure 2. dual-chain and octa-chain phytoplankton, Cochlodinium polykrikoides, causes the HAB in the Strait of Hormuz (Seraji, 2008)

RESULTS

A Cochlodinium polykrikoides (figure 2) initiated harmful algal bloom that occurred in the Persian Gulf, Gulf of Oman and Strait of Hormuz since the end of summer 2008 to spring 2010. The red tide in the north of the Strait of Hormuz survived for 9 consecutive months which is considered as a unique red tide in terms of duration among those which have been reported so far. According to the first observations, the red tide was first observed in southern coasts of the Gulf of Oman in Muscat Seaport in August 17, 2008 and afterwards was stretched out to southwestern banks of Gulf of Oman near Ras-al Diba in September 11, 2008. Apparently, after being surrounded by midscale marine eddy, it has turned its way to northern banks of the Strait of Hormuz; so, this HAB was recorded for the first time in Iranian water in September 30, 2008 at the coasts of the Hormuz Island by the Persian Gulf and Sea of Oman Ecological Research Institute and Hormuzgan Province Department of Environment. By matching the initial observations with the satellite images, it can be found that the initial observations and report of the red tide show a 10-day delay in contrast with the occurrence date of the phenomenon recorded by the satellite. Relying on the current information and interpretation of the satellite images, it seems that the red tide has been started from Oman’s banks in the Arabian Sea and has speeded towards the northern part of the Gulf of Oman and north banks of the Strait of Hormuz by sea currents, caused by water discharge of mesoscale eddies, after departing for southern Sea of Oman, and also probably by the flow due to mesoscale eddies and the inflow from the Oman Sea into the Persian Gulf. Concerning the domination of the necessary condition for HAB, i.e. temperature drop and increased nutrients supplied by urban and industrial sewages, this phenomenon has succeeded to extend and to survive for 9 months up to spring 2009.

Figure 3. Formation of streaks of HAB in the northern part of the Strait of Hormuz in Sep.22, 2008 (left) and in Sep. 26, 2008 (right)
Satellite data which are collected on the initial days of the red tide developed in Sep. 22, 2008 at the northern Strait of Hormuz indicate the prompt extension of the phenomenon across the northern Strait of Hormuz up to its southern banks.

Data of chlorophyll-a density that are collected by MODIS sensor in October 2008 indicate the density increase of the marine chlorophylls, as the whole areas of the northern part of the Strait of Hormuz have been overwhelmed by this chlorophylls. By considering the climatic condition and seasonal currents of the Strait of Hormuz, it seems that growth of Cochlodinium polyrikoide planktons has been prompted by seawater temperature drop in this area.

Satellite images during this period show the stretchiness of a dense algal band along the northern banks and central area of the strait; there, for more tendencies of the algae to gather along the coastline, more population density of the algae in the central parts of the Strait is a major characteristic of this event. Mesoscale marine eddy in the Gulf of Oman has directed the algal patch from south to north sides of the sea which is seen along the northern Gulf of Oman coastline. Seawater temperature drop below 28 °C and average salinity as 37 psu over northern and central areas of the Strait are the main physical specifications of the northern Strait of Hormuz.
Figure 6. Monthly averaged values of chlorophyll a and temperature in November 2008 using data of MODIS sensor of Aqua satellite.

Images on Dec.1, 2008 shows a considerable monthly growth of algal density. Approximately the total coastal areas of the Hormuzgan Province in Iran are overwhelmed by the algal density of Cochlodinium polyrikoides during this period. A wide range of this area including central, southern and northern banks of Sea of Oman, most parts of Strait of Hormuz and Hormuzgan Province banks in the Persian Gulf are covered by Cochlodinium polyrikoides planktons during November and December. Plankton density decreases gradually from the northern banks of the Strait of Hormuz (highest density) to the west and east sides of the Strait. Growth of algae is fueled by temperature decrease from 28°C to 26°C. Proliferation and the extension of phytoplankton population towards the axis of the Persian Gulf in the early December leads to the movement of a part of this population to the area near the Qatar and Bahrain peninsulas the return current and another part along with the entry current continues to move along the Iranian coasts to the northern parts of the Persian Gulf.

Figure 7. Monthly averaged values of chlorophyll a and temperature in December 2008 using data of MODIS sensor of Aqua satellite.

Satellite images during January 2009 indicate more extension of the algal bloom up to most parts of the northern regions of the Persian Gulf and Strait of Hormuz as well as the northern and southern regions of Gulf of Oman. Plankton concentration has progressed up to the central regions of Bushehr Province coasts and it seems to be less in comparison with that in December. This can be explained by the decrease of speed inflow current into the Persian Gulf comparison to the return currents from the Persian Gulf northern end. Algal density has been expanded from northern coasts of the Persian Gulf to the southern coast which is seen up to vicinity of the Qatar Peninsula.
Figure 8. Monthly averaged values of chlorophyll a and temperature in January 2009 using data of MODIS sensor of Aqua satellite.

The short-term bloom in the southern part of the Gulf of Oman takes place in late February which is larger than that of the southern areas. This bloom is extended to the central parts of Gulf of Oman because of the effects of the mesoscale eddies; it can be initiated with suitable environmental and temperature condition of the region rather close to the Persian Gulf with less than 20°C.

Figure 9. Monthly averaged values of chlorophyll a and temperature in February 2009 using data of MODIS sensor of Aqua satellite.

March 2009 is associated with the intense weakness of the plankton bloom along the entire area of the Persian Gulf (Fig. 8); covering the northern Strait of Hormuz where it has had high algal density within the total period of the bloom; HAB has been vanished in other parts of the Persian Gulf, however, some parts of the Gulf of Oman still suffer from it.
Figure 10. Monthly averaged values of chlorophyll a and temperature in March 2009 using the data of MODIS sensor of Aqua satellite.

Figure 9 shows same area in April 2009 when the highest density is seen in the northern part of the Strait of Hormuz; however, generally its density has decreased or vanished completely across the Persian Gulf in this period. The algal density has also decreased dramatically in the Gulf of Oman. Temperature of the seawater begins to increase in April that till this time has had little effect on the algal bloom.

The plankton density is decreased enormously from May to June 2009 and only scattered plankton spots are seen in Bandar Abbas coasts of Iran; hence, it appears that the red tide has been removed and the plankton density has decreased to its lowest level by this time. Such trend prevails till September 2009 and no algal in considerable density was seen in this area.

Figure 11. Monthly averaged values of chlorophyll a and temperature in April 2009 using data of MODIS sensor of Aqua satellite.

Field studies and satellite images show that the extension path and the increasing trend of the red tide (Cochlodinium polykrikoides) across the Persian Gulf and Gulf of Oman have been exactly consistent with the general circulation of water in the Persian Gulf. Structure of the oceanic mesoscale eddies has been effective in transferring the algae over the Sea of Oman. Algae move from Gulf of Oman towards the northern and central parts of Strait of Hormuz and they reach the Persian Gulf along with Iranian coastal waters, and they continue the same path until they reach the axis located in boarders between Hormozgan and Bushehr Provinces of Iran. At this point the algae patch is split into two parts, one continues the above-mentioned path and the other one shifts its path to the central part of the Persian Gulf and its southern banks. Again the latter is divided into two parts, one goes towards Bahrain and Kuwait coasts and the other one selects a path which heads towards the coasts of UAE entering the Gulf of Oman through the southern part of the Strait of Hormuz.
CONCLUSIONS

Here we have presented the emerging, developing, spreading and vanishing of the alga bloom of 2008-2009 in the Persian Gulf region. Physical growth limits of this type of alga were defined by Kim et al, 2001, 2004; Lee et al 200 as: temperature: 21 to 25 °C, Salinity: 15 to 50 psu. However, here, after the change of the environmental condition, we witnessed the growth of the algae even when temperature was 29 °C in Persian Gulf and Gulf of Oman.

High rates of organic matters in coastal waters of Bandar Abbas and Qeshm industrial zones in the northern side of the Strait of Hormuz, and failure of filtering the urban and industrial sewage wastes in this area seem to have led to high algal density during the whole mentioned 9-month period. The algal patch with high density seemed to have swayed periodically towards other areas which was more visible in northern and southern parts of Gulf of Oman.

Our image analyses results with the data obtained on temperature variations indicate that the seawater temperature drops below 27 °C and sewage wastes appear to have fueled this red tide event. The satellite images show the high density of chlorophyll in water in the areas where suffered from this red tide. There were more algal densities of the red tide across the crowded industrial cities along the Strait of Hormuz such as Bandar Abbas and Qeshm; and the inflow water into the Persian Gulf appears to have been effective in stretching the red tide to the more western regions of the Persian Gulf.

The most observable density and growth of the red tide observed by satellites was located across the northern Strait of Hormuz which has been survived there for more than 9 consecutive months.

Growth and extension of the red tide has followed the current and flow pattern of the Persian Gulf and Sea of Oman, while the oceanic mesoscale eddies have played an important role in the Gulf of Oman to transfer algal patches from southern parts to the central and northern regions. Lack of nutrients was another limit that led to the stoppage of algal growth and bloom mostly in the Oman Sea.

Temperature condition (weather), nutrients and biological constraints of algae appear to explain the long term persistence and disappearance of the red tide in the region. Detailed in situ measurements and also numerical modeling are required for such studies which require the cooperation of neighboring countries on this region.

ACKNOWLEDGMENTS

We would like to thank all the technical and scientific staff of Persian Gulf and Oman Sea Ecological Institute. The satellite data is from the ocean color website.

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