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Monitoring red tide with satellite imagery and numerical models: A case study in the Arabian Gulf ☆

Jun Zhao *, Hosni Ghedira

Institute Center for Water and Environment (iWATER), Masdar Institute of Science and Technology, Masdar City, PO Box 54224, Abu Dhabi, United Arab Emirates

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ABSTRACT

A red tide event that occurred in August 2008 in the Arabian Gulf was monitored and assessed using satellite observations and numerical models. Satellite observations revealed the bloom extent and evolution from August 2008 to August 2009. Flow patterns of the bloom patch were confirmed by results from a HYCOM model. HYCOM data and satellite-derived sea surface temperature data further suggested that the bloom could have been initiated offshore and advected onshore by bottom Ekman layer. Analysis indicated that nutrient sources supporting the bloom included upwelling, *Trichodesmium*, and dust deposition while other potential sources of nutrient supply should also be considered. In order to monitor and detect red tide effectively and provide insights into its initiation and maintenance mechanisms, the integration of multiple platforms is required. The case study presented here demonstrated the benefit of combing satellite observations and numerical models for studying red tide outbreaks and dynamics.

1. Introduction

The Arabian Gulf is of paramount economic importance in the world. The tremendous oil resources and their maritime transportations in the area have constantly drawn compelling attention.

The Arabian Gulf is a shallow, semi-enclosed marginal sea, which is connected to the Gulf of Oman through the Strait of Hormuz in the east (Fig. 1). Its mean depth is ~35 m, its length is ~990 km, and its maximal width is 370 km. The Arabian Gulf has asymmetric bathymetrical features along the main axis with a deeper zone off the Iranian coast and broad shallow shelf along the southern and western coasts from Kuwait to the United Arab Emirates (UAE). Additionally, the surrounding arid climate, in which evaporation surpasses the combination of precipitation and river runoff, results in hypersaline water mass production (Nezlin et al., 2010). These extreme conditions lead to an inverse estuarine circulation of cyclonic nature (Reynolds, 1993). The basin-scale circulation consists of two components. One current flows northwesterly from the Strait of Hormuz along the southern Iranian coast. The other one is a southeastern-flowing current in the southern Arabian Gulf (Reynolds, 1993). It flows out of the Arabian Gulf and spreads into the Gulf of Oman and the Arabian Sea at 200–300 m depth through the Strait of Hormuz (Prasad et al., 2001). The major rivers that empty into the Arabian Gulf are located in the north and northwest with an average discharge rate of 36–1000 $km^3\ year^{-1}$ (Reynolds, 1993). The maximum river discharge was recorded in late spring-early summer (Nezlin et al., 2010). The precipitation over the Arabian Gulf area is very low at a rate of 0.07–0.1 $m\ year^{-1}$ (Marcella and Eltahir, 2008). Evaporation exceeds combined rainfall and freshwater discharge, which results in high salinity up to 44.3‰ (Jacob and Al-Muzaini, 1990). In addition to the high salinity, the Arabian Gulf is one of the warmest water bodies on earth with water temperature reaching 32 °C during the summer (ROPME, 1999). Other special characteristic of the Arabian Gulf region is its high aerosol concentration. Dust storms occur frequently in the gulf area, mainly in May–July, when dust deposition can amount to over 30 $g\ m^{-2}$ (Subba Rao and Al-Yamani, 1999).

Red tide, also known as harmful algal bloom, is caused by proliferation of a toxic or nuisance algae species and has been a preeminent topic of world-wide research communities for several decades (Cullen et al., 1997; Kahru et al., 2000; Stumpf et al., 2003; Ahn and Shanmugam, 2006; Gower et al., 2008; Zhao et al., 2008; Cannizzaro et al., 2008; Hu et al., 2011; Wang et al., 2011). Increasing frequency in red tide outbreaks has been reported around the world. It is of great concern due to not only their adverse effects on human health and marine organisms, but also their impacts on the economy of the affected areas. The recurrence of red tide depends on the species. Some species recur in the same area every year while others are episodic. The duration may differ from days to months.

The Arabian Gulf has been subject to red tide regularly with outbreaks recorded almost every year (Subba Rao and Al-Uamani,

* Corresponding author. Tel.: +971 28109125.
E-mail address: jzhao@masdar.ac.ae (J. Zhao).

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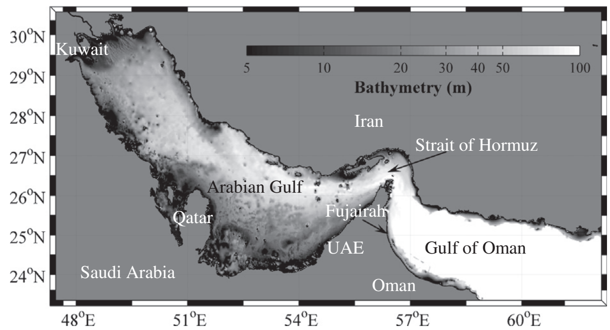

Fig. 1. Map of the study area. Overlaid are the bathymetry data with a spatial resolution of ∼2 km from NOAA.

1998; Heil et al., 2001; Glibert et al., 2002; Moradi and Kabiri, 2012). A catastrophic red tide event happened in 2008 in the Arabian Gulf. Richlen et al. (2010) reported that the 2008 bloom was first observed on the east coast of the UAE in late August 2008 and dominated by *Cochlodinium polykriloides*. Although 38 types of taxa have been identified in the Arabian Gulf, *Cochlodinium polykriloides* was found for the first time in the region. Sale et al. (2011) demonstrated that the bloom patch dissipated in August 2009. According to Berktay (2011), the 2008 red tide event has affected more than 1200 km of coastline and has destroyed thousands of tons of fish and marine mammals. This disastrous event also did harm to local aquaculture (Richlen et al., 2010), coral reef community (Bauman et al., 2010), and fishery (Berktay, 2011). Additionally, red tide outbreaks could force the shutdown of desalination plants, which pose a major threat to the potable water supply (Berktay, 2011). Indeed, all Arabian Gulf countries rely on desalinated seawater for most of their potable water supply where 61% (17.1 M m^3 day^{-1}) of the global seawater desalination capacity is located along the Arabian Gulf coastlines (Lattemann et al., 2010).

For the reasons stated above, effective and timely observation of red tide is urgently required. Compared with conventional *in situ* ship surveys and buoy stations, which are time and cost consuming, satellite measurements have shown to be more effective in such applications thanks to their high spatial and temporal coverage over large scales. Furthermore, satellite measurements can cover regions unreachable for humans. For example, the 13-year of daily global imagery collected by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) at 1-km resolution was made available to the scientific community by NASA. To our knowledge, only two papers about the 2008 red tide event in the Arabian Gulf using satellite imagery have been published. Moradi and Kabiri (2012) used Moderate Resolution Imaging Spectroradiometer (MODIS) fluorescence data to detect the 2008 red tide with more focus on the Strait of Hormuz and the eastern region of the Arabian Gulf. Hamzei et al. (2012) have also investigated the 2008 red tide event using MODIS images and suggested that upwelling and sewage were the key nutrient sources that trigged the bloom in the Arabian Gulf and the Gulf of Oman. However, the 2008 red tide throughout the whole period has not been fully examined. Furthermore, the real causes of this bloom event is still unknown although Richlen et al. (2010) proposed that the 2008 bloom initiation may be related to monsoon-driven convective mixing. Meanwhile, the possible causes that might have led to the formation and lasting of the 12-month event have not been thoroughly studied yet.

Numerical model simulations offer an important and unique opportunity to improve our understanding of the mechanisms that regulate bloom initiation and evolution (He et al., 2008; Wang et al., 2011). Numerical models have been widely used for studies of algal bloom in other regions around the world (Olascoaga et al., 2008; McGillicuddy et al., 2011). But to the best of our knowledge, there are no published papers on the use of numerical models to study algal blooms in the Arabian Gulf.

The main objectives of this paper are:

1. analyzing the formation and evolution of the 2008 red tide event in the Arabian Gulf using multisource satellite images and numerical models;
2. interpreting the initiation and sustaining mechanisms for the unusual long-lasting red tide event.

2. Data and method

In coastal waters, the accuracy of retrieving chlorophyll-a concentration based on the operational algorithms (O'Reilly et al., 1998) was significantly compromised due to the effects of other optically active components, i.e. suspended sediments and CDOM, which do not co-vary with chlorophyll-a (Mobley et al., 2004). Therefore, chlorophyll-a concentration alone is not sufficient to demonstrate bloom outbreaks. The feasibility of using ERGB images to differentiate bloom waters from other waters has been shown in previous studies (Hu et al., 2003, 2004; Zhao et al., 2013). In this work, satellite-derived chlorophyll-a concentration and ERGB images were used together as indicators of the 2008 bloom in the Arabian Gulf.

MODIS Aqua and Terra, SeaWiFS, and MERIS (Medium Resolution Imaging Spectrometer) data from August 2008 to September 2009 covering the study area (Fig. 1) were downloaded from NASA ocean color data archive. Only images with clear sky conditions were retained for further analysis. In total, 22 images were retained: 12 MODIS, 6 SeaWiFS and 4 MERIS. These images were processed using the most recent calibration and algorithms embedded in the SeaDAS package (version 6.4). Normalized water-leaving radiance (nL_w) at three wavelengths (i.e., 547 nm, 488 nm, and 443 nm for MODIS; 555 nm, 490 nm, and 443 nm for SeaWiFS; and 560 nm, 490 nm, and 443 nm for MERIS) was generated. Enhanced RGB (ERGB) images were composited using nL_w at the three wavelengths with 547 nm, 555 nm, and 560 nm as the red channel for discrete sensors. These ERGB images are very useful in differentiating different water types. Previous studies have suggested that brownish/reddish color is attributed to high concentrations of phytoplankton; the bright color is caused by sediment-rich waters and/or shallow bottom reflection; and the darkish color results from high concentration of phytoplankton and/or colored dissolved organic matter (CDOM) (Hu et al., 2003, 2004; Shanmugam et al., 2008; Simon and Shanmugam, 2012; Shanmugam, 2012; Zhao et al., 2013). Chlorophyll-a concentrations based on the default algorithms were also derived. Remote sensing reflectance (R_{rs}) at 443, 469, 488, 531, 547, 555, 645, 667, and 678 nm, and sea surface temperature (SST) from MODIS were produced. All satellite images were then resampled to 1-km resolution for further analysis.

MODIS/Aqua derived 8-day composite SST images for 2008 and monthly mean aerosol optical thickness (AOT) at 869 nm images from 2002 to present with spatial resolution of 4 km were also acquired from NASA ocean color data achieve. The monthly climatology and anomaly of AOT were then calculated. The monthly anomaly was defined as the difference between the monthly mean and the corresponding monthly climatology.

HYbrid Coordinate Ocean Model (HYCOM) is a primitive equation ocean general circulation model (Bleck, 2002; Chassignet et al., 2009) that describes the effects of tide, wind, earth's rotation, and other factors on the ocean water flow. HYCOM derived surface current and sea surface height (SSH) were obtained from the HYCOM data server (www.hycom.org/dataserver) for chosen dates as shown in Fig. 3. HYCOM-derived ocean circulation data were