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Analysis of bloom conditions in fall 2013 in the Strait of Hormuz using satellite observations and model simulations

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ABSTRACT

In this study an algal bloom event in fall 2013 in the Strait of Hormuz was thoroughly investigated using satellite remote sensing and hydrodynamic modeling. The motivation of this study is to deduce ambient conditions prior to and during the bloom outbreak and understand its trigger. Bloom tracking was achieved by sequential MODIS imagery and numerical simulations. Satellite observations showed that the bloom was initiated in late October 2013 and dissipated in early June 2014. Trajectories of bloom patches were simulated using a Lagrangian transport model. Model-based predictions of bloom patches' trajectories were in good agreement with satellite observations with a probability of detection (POD) reaching 0.85. Analysis of ancillary data, including sea surface temperature, ocean circulation, and wind, indicated that the bloom was likely caused by upwelling conditions in the Strait of Hormuz. Combined with numerical models, satellite observations provide an essential tool for investigating bloom conditions.

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1. Introduction

Algal bloom outbreaks are due to the proliferation of phytoplankton in the water. They may yield depletion of oxygen which can lead to death of fish and marine mammals. If the dominant bloom species is toxin-producing, not only the marine environment could be adversely impacted, but it may do harm to human health and incur significant economic losses (Anderson, 1989, 2009; Hallegraeff, 1993). Increased occurrences of algal blooms have been reported in different waters across the world (Ahn and Shanmugam, 2006; Cannizzaro et al., 2008; Cullen et al., 1997; Shanmugam et al., 2013; Zhao and Ghedira, 2014; Zhao et al., 2015b). In the middle-east, the Arabian Gulf (hereafter referred to as the Gulf) is not an exception as an increasing number of algal bloom outbreaks have been reported in recent years (Al Shehhi et al., 2014; Gomes et al., 2008; Zhao et al., 2016). The disastrous impact of a major algal bloom outbreak that occurred in late 2008 in the Gulf and lasted almost a year was described in details by Richlen et al. (2010). This adverse impact becomes more critical with the high dependence of the Gulf countries on seawater desalination for domestic and industrial water supply. Some harmful algal blooms (HABs) can produce neurotoxins or taste and odor compounds that can persist in treated water. Continuous monitoring of such threats is essential for response readiness and to take the appropriate mitigation action ahead of time. However, the planning of responses to such outbreaks requires a prompt detection and assessment of the extent of bloom and the prediction of its trajectory. These critical elements represent the primary purposes of this study and will be addressed thoroughly in this paper.

On-site monitoring-based methods with ship and buoy are efficient to monitor algal blooms. However, these methods are limited by sparse sampling in space and time. Synoptic satellite observations enhanced our capability to detect and monitor algal blooms over large spatiotemporal scales, which overcome drawbacks of traditional field-based methods for bloom detection. Advantages of remote sensing for bloom detection and monitoring have been highlighted in numerous studies (Hu et al., 2005; Tomlinson et al., 2004; Zhao et al., 2013b). Several approaches have been developed to detect algal blooms from ocean color remote sensing. For example, Stumpf et al. (2003) proposed a chlorophyll-*a* anomaly approach that flags areas with an increase in chlorophyll-*a* concentration of 1 mg m^{-3} from the mean value of 2 antecedent months ending two weeks before the current day. This technique is being used operationally by National Oceanic and Atmospheric Administration (NOAA) as an indicator of bloom occurrence on the west Florida shelf. Significant efforts have been made to detect, track, and characterize algal blooms in the Gulf region using satellite ocean color measurements. Moradi and Kabiri (2011) covered the 2008 bloom event in the Strait of Hormuz using Moderate Resolution Imaging Spectroradiometer (MODIS) fluorescence data, and indicated the importance of MODIS fluorescence data for bloom monitoring in the Gulf region. Zhao and Ghedira (2014) used multi-sensor data to track the movement of bloom patches in 2008 in the Gulf. Combined with numerical circulation models, their results demonstrated the importance of

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integrating multiple platforms to establish an early warning and forecasting system for detection and monitoring of algal blooms.

Particle-tracking models have been widely used to simulate initiation and trajectories of algal blooms (Cerejo and Dias, 2007; Lanerolle et al., 2006). Compared with an Eulerian method, a Lagrangian particle-tracking method has the advantage of producing a more sub-grid scale motion and better approximates of particle movement (Havens et al., 2010). Lee et al. (2011) used a Lagrangian particle-tracking model to study the spatial distribution of massive floating algae in 2008 in the Yellow Sea China and demonstrated the role of physical factors in transporting algae. Giddings et al. (2014) used a numerical simulation to investigate transport pathways of HABs on the Pacific Northwest coast. Son et al. (2015) combined GOCI satellite data and numerical simulations to trace floating green algae blooms and identify the source of blooms in the Yellow Sea and the East China Sea. To the best of our knowledge, the capability of Lagrangian models for bloom tracking has never been examined in the Gulf.

The Gulf is a semi-enclosed marginal sea with an average depth of ~35 m (Fig. 1). It is connected to the Sea of Oman through the Strait of Hormuz and bordered by Kuwait, Iraq, Saudi Arabia, Bahrain, Qatar, United Arab Emirates (UAE), Iran, and Oman. It is located in the arid Middle East region where evaporation is high while precipitation is low. The salinity of the Gulf water can exceed 43 particular salinity unit (psu) resulting from the arid climate and limited exchange with the open ocean as well as the increasing rate of hyper-saline brine discharge from desalination plants (Mezhoud et al., 2016; Swift and Bower, 2003; Yao and Johns, 2010). In addition, the temperature of the Gulf water varies from <20 °C in winter to over 32 °C in summer (Shirvani et al., 2015). The ocean circulation in the Gulf exhibits a pattern of cyclonic nature (Al Azhar et al., 2016; Thoppil and Hogan, 2010). Wind is an important factor that regulates the stratification of the water column. Persistent northwesterly winds associated with Shamal events blow over the Gulf region and the atmospheric monsoon regime over the northern Indian Ocean strongly influences the surface

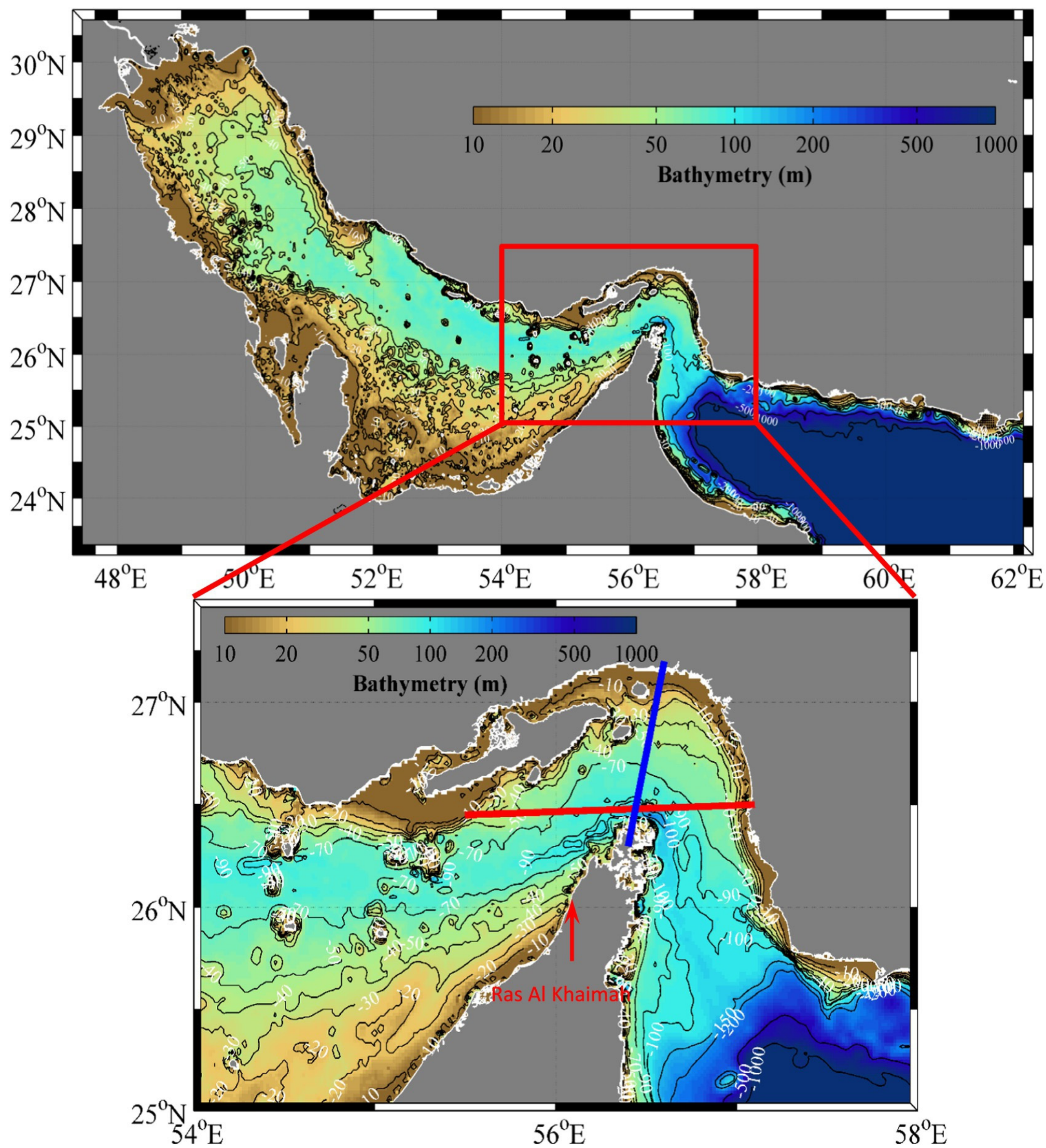

Fig. 1. The upper panel shows a map of the Arabian Gulf with the study area outlined with a red box. The study area is enlarged in the lower panel. The colors show the bathymetry obtained from NOAA at a spatial resolution of ~2 km. Isobaths of 10, 20, 30, 40, 50, 70, 90, 100, 200, 500, 1000 m are annotated. The blue and red lines denote the tracks whose temperature profiles simulated with a Regional Oceanic Modeling System (ROMS) model are shown in Figs. 6c and d, respectively. Ras Al Khaimah (RAK) is also annotated where the UAE Ministry of Environment and Water reported the presence of an algal bloom in fall 2013. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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