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Review

Understanding how physical-biological coupling influences harmful algal blooms, low oxygen and fish kills in the Sea of Oman and the Western Arabian Sea

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ABSTRACT

In the last decade, green *Noctiluca scintillans* with its symbiont and other dinoflagellates such as *Cochlodinium polykrikoides*, *Prorocentrum micans* and *Scrippsiella trochoidea* have become the dominant HABs, partially replacing the previously dominant diatoms and red *Noctiluca scintillans*, especially during the northeast monsoon. Fish kills in the Sea of Oman are linked to a slow seasonal decline in oxygen concentration from January to November, probably due to the decomposition of a series of algal blooms and the deep, low oxygen waters periodically impinging the Omani shelf. In the western Arabian Sea, cyclonic eddies upwell low oxygen, nutrient-rich water and the subsequent algal bloom decays and lowers the oxygen further and leads to fish kills. Warming of the surface waters by 1.2 °C over the last 5 decades has increased stratification and resulted in a shoaling of the oxycline. This has increased the probability and frequency of upwelling low oxygen water and subsequent fish kills.

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1. Introduction

Algal blooms can occur quickly when physical and chemical conditions are near optimum and cell numbers can explode from 1000 cells L^{-1} to $>10^6$ cells L^{-1} in just 4 days when cells double ~3 times per day at high water temperatures. Bloom can be observed in surface waters and defined on the basis of a chlorophyll concentration of about 10 Chl μg L^{-1} or over about 1 million cells L^{-1} (depending on the size of the cells). The term harmful algal blooms (HABs) were introduced several decades ago in order to include algal blooms of a wide variety of algal species and their potential impacts. Previously, the focus was on the term red tides to describe these blooms because of the reddish color of the surface waters that make these blooms highly visible. However, there are also blooms of other species that color the water brown or green and these blooms have been termed brown and green tides. Currently, the use of the term HAB is preferred to the use of red tide since it includes all of these variations in algal blooms that are potentially harmful (Harrison et al., 2010). Some HABs may contain toxic compounds and become harmful when their toxin is transferred via herbivore grazers (e.g. bivalves, copepods, etc.) to higher organisms including humans. In some cases, HABs may elicit harm even at low cell

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concentrations of 1000 cells L^{-1} when the setae of some *Chaetoceros* sp. irritate the gills of fish (Harrison et al., 1993). Other HABs are harmful indirectly when these dense blooms run out of nutrients, die, sink and are decomposed by bacteria which draw oxygen down to hypoxic levels (<2 mg L^{-1}) and result in fish kills (Sellner et al., 2003).

In Omani coastal waters, some HABs such as *Cochlodinium polykrikoides,* and *Gonyaulax polygramma* may be associated with fish kills (Al-Gheilani et al., 2012; Piontkovski et al., 2012b). Other HABs such as *Noctiluca scintillans* are only occasionally indirectly associated with fish kills due to lower oxygen concentrations which occur when the bloom declines. Physical processes are strongly associated with HAB occurrences and fish kills and therefore it is necessary to understand the complex physical spatial and temporal dynamics along the Omani coast and the importance of physical-biological coupling that may trigger an algal bloom.

2. Physical processes and their spatial and temporal dynamics

The complex physical dynamics have been documented in a series of papers that have analyzed historical data from various international expeditions, satellite images, ARGO drifting floats, etc. (Claereboudt et al., 2001; Piontkovski et al., 2011, 2012a, 2012b, 2012c, 2013a; Piontkovski and Nezlin, 2012; Piontkovski and Al-Jufaili, 2013). The coastline of Oman is over 3500 km long and links with the western Arabian Sea in the southern part of Oman and the Sea of Oman along the northern coast (Fig. 1). During the winter northeast monsoon (NEM) in the Sea of Oman, the inflow of Indian Ocean/Arabian Sea water occurs along the southern coast of Iran with upwelling in February and March (Piontkovski et al., 2012a). The Arabian (Persian) Gulf lies to the west of the Sea of Oman and it is a shallow (~35 m depth) high salinity (~40) area and particularly during summer, its high density water outflows through the Strait of Hormuz and flows at depth along the south coast of the Sea of Oman. Therefore, the Sea of Oman can be visualized as a two-layer system with Indian Ocean water in the top layer and higher salinity low oxygen (<1.5 mg O_2 L^{-1}) water from the Arabian Gulf below the pycnocline at ~50 m (Piontkovski et al., 2012a).

The Oman Coastal Current (east Arabian Current) is an extension of the Somali Current and is driven by the SWM (southwest monsoon) in summer and flows north along the Omani coast (Fig. 1). The confluence of this current and the outflowing Sea of Oman current forms a frontal zone near the most eastward land projection of Oman, named Ras Al Hadd (Fig. 1). This frontal zone partially separates the western Arabian Sea from the Sea of Oman and therefore these two areas may be treated somewhat as different ecosystems (Piontkovski and Chiffings, 2014). This frontal zone generates well developed cyclonic and anti-cyclonic eddies in summer and fall and fewer eddies in winter. Based on SeaWIFS, and TOPEX/Poseidon data, these mesoscale eddies are ~200 km in diameter with sea surface anomalies of up to 25 cm (Piontkovski and Nezlin, 2012). Cyclonic eddies bring large amounts of nutrients up to the surface and hence stimulate phytoplankton growth in the western Arabian Sea which leads to large temporal variations in chlorophyll. In contrast, anti-cyclonic eddies downwell and are associated with low nutrients and chlorophyll in the Sea of Oman (Piontkovski et al., 2012c). Previously, it was thought that eddies were only associated with the SWM, but they have been shown to be associated with both the SWM and the NEM (Fig. 2) (Piontkovski and Nezlin, 2012). Satellite tracking of eddies revealed an average life time of several months. During the NEM, the Oman Coastal Current reverses direction with a southeast flow and some downwelling occurs along the eastern coast of Oman. During the NEM, these eddies are thought to transport and disperse blooms from the Sea of Oman offshore into the western Arabian Sea (Gomes et al., 2008).

Overall, in order to understand the interplay between the basin scale water mass transport by main geostrophic currents and eddies, monthly

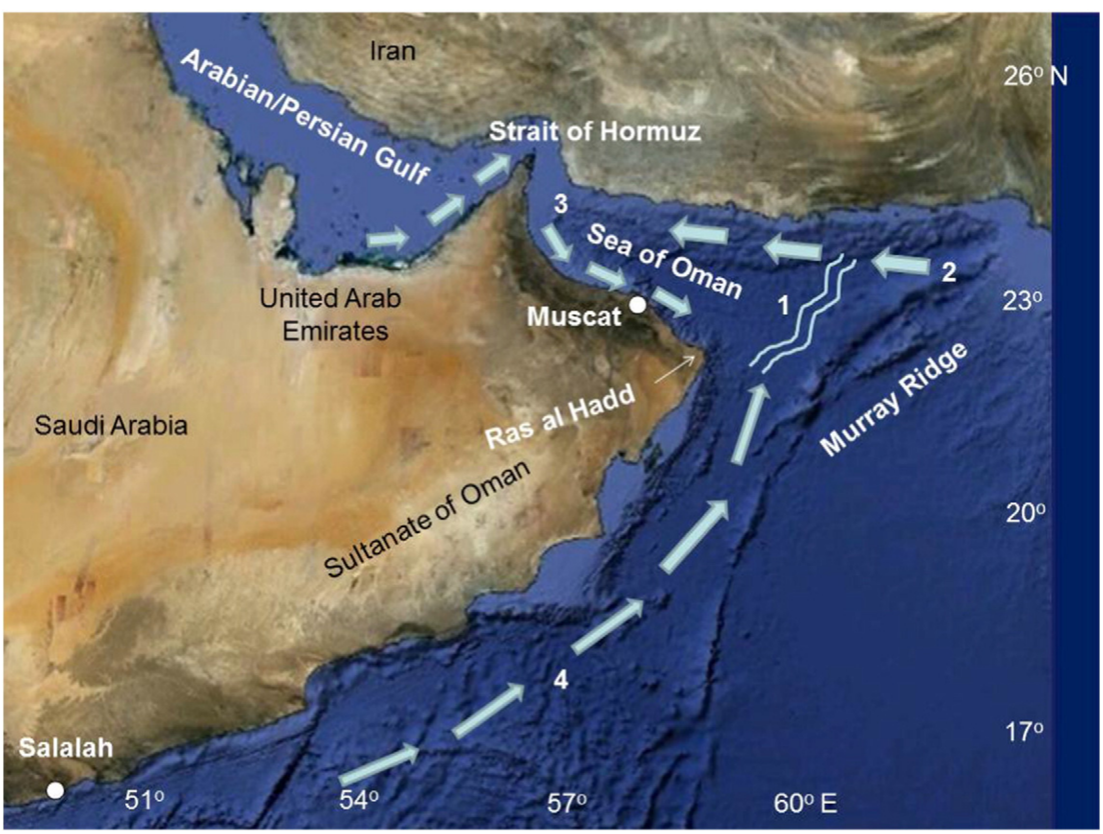

Fig. 1. The system of currents and water mass transport along the Omani coast. Background image: three-dimensional bathymetric map (www.earth.google.com). Two parallel lines: (1) demarcate the location of the Ras Al Hadd frontal zone formed by the confluence of currents (3 and 4). Arrows (2–4) indicate direction of the main currents in summer through the fall period. (2): inflow of the Indian Ocean Water mass, (3): outflow of the (Arabian Gulf) Persian Gulf Water mass, and (4): Oman Coastal Current (East Arabian Current).