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Evaluation of model simulated and MODIS-Aqua retrieved sea surface chlorophyll in the eastern Arabian Sea

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A B S T R A C T

In this study we assess the accuracy of sea surface Chlorophyll-*a* (Chl*a*) retrieved from satellite (MODIS-Aqua), using standard OC3M algorithm, and from a Regional Ocean Modelling System (ROMS) bio-physical model against *in situ* data, measured in surface waters of the eastern Arabian Sea, from April 2009 to December 2012. MODIS-Aqua OC3M Chl*a* concentrations showed a high correlation with the *in situ* data with slope close to unity and low root mean square error. In comparison, the ROMS model underestimated Chl*a*, though the correlation was significant indicating that the model is capable of reproducing the trend in *in situ* Chl*a*. Time Series trends in Chl*a* were examined against wind driven Upwelling Indices (UI^W) from April 2009 to December 2012 in north-eastern (Gujarat) and south-eastern (Kochi) coastal waters of the Arabian Sea. The annual peak in Chl*a* along the Kochi coast during the summer monsoon was adequately captured by the model. It is well known that the peak in surface Chl*a* along the Kochi and Gujarat coasts during the summer monsoon is the result of coastal upwelling, which the ROMS model was able to reproduce accurately. The maximum surface Chl*a* along the Gujarat coast during the winter monsoon is due to convective mixing, which was also significantly captured by ROMS biophysical model. There was a lag of approximately one week between the maximum surface Chl*a* and the peak in the Upwelling Index.

1. Introduction

Ocean color remote sensing data are increasingly being used to address globally relevant questions such as decadal trends in primary production (Tilstone et al., 2014) and shifts in the distribution of phytoplankton functional groups in the coastal zone with respect to changes in water quality. Ocean color data from satellite sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Medium Resolution Imaging Spectrometer (MERIS) are being increasingly used to assess Chl*a* and total suspended particulate matter (TSM) concentrations to monitor cyanobacterial blooms (Kutser et al., 2006) and water quality (Hellweger et al., 2004; Erkkila and Kalliola, 2004). As proof of concept, one of the first studies using remote sensing to detect increases in surface Chl*a* was from radiometric data measured from aircraft which showed a shift in the shape of reflectance spectra (Clarke et al., 1970). Following this, the Coastal Zone Color Scanner (CZCS) was used in tandem with *in situ* data to assess spatial and seasonal variations in absolute concentrations of Chl*a* in the Black Sea (Kopelevich et al., 2002). Similar studies were then conducted using *in situ* and Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) data to assess the spatial patterns and time evolution of Chl*a* at times of the year when ship-bourne data are particularly limited (Ribeiro et al., 2005). Over the last three decades, novel algorithms have been developed to derive other ocean color products such as particulate organic carbon concentrations (Gardner et al., 2006).

The use of sun synchronous polar orbiting satellite sensors has undoubtedly enhanced the global coverage of Chl*a*. The sampling frequency however, which is typically once per day, is too low to resolve tidal and sub-diurnal processes, especially in coastal waters. Though this has been significantly improved through the use of Geo-stationary satellite data (Nezlin et al., 2007; Choi et al., 2012), this is only available over limited spatial areas and is not available for the coastal waters of the Arabian Sea and Bay of Bengal. In

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addition, the presence of clouds also creates spatial and temporal gaps in ocean color satellite data. High TSM concentrations in coastal waters can lead to an over-estimation in satellite Chl*a* (Tilstone et al., 2011) and similarly high bottom reflectance can produce errors in satellite Chl*a* (Mobley, 1994). Some of these gaps can be filled by *in situ* Chl*a*, but these are not taken at sufficient frequency to resolve large scale dynamics.

To overcome these limitations, several bio-physical models have been constructed and validated to provide Chl*a* data at the resolution required to resolve tidal and subdiurnal processes (Lacroix et al., 2007; Allen et al., 2001; Chai et al., 2002; Brigolin et al., 2009). In addition, a number of ecosystem models have also been deployed to address these issues (e.g. Fiechter et al., 2009; Fiechter and Moore, 2009; Zeebe and Wolf-Gladrow, 2001; Aksnes and Lie, 1990; Swaney et al., 2008). In the Indian Ocean, ecosystem modelling activities have mainly focused on the Arabian Sea. A study by McCreary et al. (1996) for example, was the first to simulate an annual cycle in the Arabian Sea ecosystem, which successfully captured several prominent, annually recurring phytoplankton blooms and bloom features associated with pronounced mixed-layer detrainment following the monsoons. Shortly afterwards, Ryabchenko et al. (1997) deployed an ecosystem model in the region which produced similar results. In the northeast Arabian Sea however, neither of the models captured the bloom observed by CZCS during the southwest monsoon, which was attributed to excessive grazing in the models. In more recent biogeochemical modelling studies, the magnitude and persistence of phytoplankton blooms during the seasonal monsoons has been reproduced successfully (Wiggert et al., 2000; Kawamiya, 2001; McCreary et al., 2001; Wiggert et al., 2002; Hood et al., 2003). Wiggert et al. (2005) published a comprehensive review of how these modelling studies have advanced our understanding of the biogeochemical variability in the Arabian Sea. A climatological solution to run a fully coupled physical-biogeochemical model was then developed to study basin wide biogeochemical dynamics in the Arabian Sea (Wiggert et al., 2006). Lévy et al. (2007) then employed an ocean general circulation model over the North Indian Ocean to assess the dynamics of near-surface Chl*a* concentrations and the physical mechanisms that drive patterns in blooms.

The eastern Arabian Sea (EAS), located along the western continental margin of the Indian subcontinent, which is driven by atmospheric forcing, is an ideal laboratory to study the ecosystem dynamics. The seasonally reversing monsoons, Southwest (summer) and Northeast (winter), trigger high biological productivity over the region, but the underlying mechanisms between these two periods are different. The northern Arabian Sea exhibits a number of physical and biogeochemical responses to monsoonal atmospheric forcing. In the northern Arabian Sea, atmospheric conditions during the North-East (winter) Monsoon lead to deep convective mixing. This deepens the upper mixed layer, entrains nutrients from the depth and subsequently triggers phytoplankton blooms and high primary productivity (Madhupratap et al., 1996). By contrast, alongshore wind stress parallel to the coast drives upwelling during the summer monsoon in February to March, when the Chl*a* concentration increases due to the entrainment of subsurface nutrients to the surface which similarly promotes high productivity (Gupta et al., 2016).

In this study we statistically validate model simulated Chl*a* against *in situ* data collected from several coastal locations of India and also compare this with MODIS-Aqua Chl*a*. We then use model simulated and satellite Chl*a* to assess the temporal evolutionary dynamics of phytoplankton blooms with respect to wind driven upwelling indices.

1.1. Study area

The study areas are the coastal waters of the north-eastern Arabian Sea and including Gujarat, Goa, Northern Karnataka and Kerala. In these regions during winter, eddies and associated blooms of *Noctiluca* sp. are a frequent occurrence. As highlighted above, during the summer monsoon, upwelling is driven by southwest winds from June to September, which stimulates high productivity along the north-eastern Arabian Sea coast and shelf. During the winter monsoon, cool, dry continental air is carried over the region by the prevailing northeast trade winds which intensify evaporation leading to surface cooling and higher primary productivity (Prasannakumar and Prasad, 1996). This, combined with reduced incoming solar radiation and high ambient salinity, drives convective mixing in the northern Arabian Sea which results in the upwards transport of nutrients from the base of the mixed layer and the upper thermocline.

The coastal waters of Kerala are largely influenced by freshwater discharge and the seasonal reversing of the monsoon which reverses the surface circulation and the fresh water discharge. Wind-induced upwelling, along with a northward undercurrent and southward surface flow, are responsible for the vertical mixing that occurs during the transition between the summer and winter monsoons. During the summer monsoon the effects of upwelling are enhanced by the southerly current that travels along the coast. Riverine optically active material discharges along coast which can lead to an over-estimate in satellite Chl*a* concentrations in the region. Strong fresh water discharge from the estuaries after the monsoon, however results in low primary production in the region (Srinivas and Kumar 2006; Jayalakshmi et al., 2008).

Goa, Mandovi and Zuari estuaries are some of the most complex environments in the Arabian Sea. They are influenced by both river runoff and tides during the summer monsoon, but during the post-monsoon (October to November), the runoff decreases rapidly and by November it becomes negligible. Subsequently, the flow propagated by the tide (semi-diurnal with a range 0.2–2 m) at the mouth of the estuary becomes the principal hydrodynamic feature. Along the Goan coast the change from dry (non-monsoon in March to May) to wet (monsoon in June to September) seasons leads to the formation of a homogeneous, salt-wedge followed by a partially mixed estuaries (Qasim, 2003).

The coastal waters of Northern Karnataka are significantly affected by the seasonal oceanic currents (Chauhan et al., 2011), wind forcing (Verlecar et al., 2006) and upwelling (Jayaram et al., 2010; Madhupratap et al., 2001). In this region the Nethravathi River flushes a large quantity of fresh water into the region and consequently sewage from Mangalore city acts as a nutrient supply to the coast. The large fresh water flux during the southwest monsoon reduces salinity (Chauhan et al., 2011).

Bio-geochemically, the north-eastern Arabian Sea basin is unique. Each year during the Indian summer monsoon, the spring bloom is transported across the basin by the wind-driven upwelling (Tilstone et al., 2013). The majority of the north-western Indian economic zone is characterized by a wide continental shelf that is affected by mixing during the winter monsoon and upwelling during the summer monsoon. During these periods, cloud cover can reduce photosynthetically active radiation for short periods over the region. This region has one of the most economically important fisheries in India which is sustained by the high productivity induced by wind driven mixing during post-monsoon (Prasannakumar et al., 2001). The major rivers in the region empty into the Gulf of Khambhat (Cambey) and load high sediment into a shallow bay (Nayak and Shetye, 2003; Kunte, 2008) which again can create errors in satellite ocean color estimates of Chl*a*. The temporal variation in Chl*a* in these areas has been described in a