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# Seasonal phytoplankton blooms in the Gulf of Aden revealed by remote sensing

John A. Gittings [a,*], Dionysios E. Raitsos [a,b], Marie-Fanny Racault [a,b], Robert J.W. Brewin [a,b], Yaswant Pradhan [c], Shubha Sathyendranath [a,b], Trevor Platt [a]

[a] Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, United Kingdom
[b] National Centre for Earth Observation, Plymouth Marine Laboratory, Prospect Place, The Hoe, PL1 3DH, Plymouth, United Kingdom
[c] Met Office, FitzRoy Road, Exeter, Devon EX1 3PB, United Kingdom

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ABSTRACT

The Gulf of Aden, situated in the northwest Arabian Sea and linked to the Red Sea, is a relatively unexplored ecosystem. Understanding of large-scale biological dynamics is limited by the lack of adequate datasets. In this study, we analyse 15 years of remotely-sensed chlorophyll-a data (Chl-*a*, an index of phytoplankton biomass) acquired from the Ocean Colour Climate Change Initiative (OC-CCI) of the European Space Agency (ESA). The improved spatial coverage of OC-CCI data in the Gulf of Aden allows, for the first time, an investigation into the full seasonal succession of phytoplankton biomass. Analysis of indices of phytoplankton phenology (bloom timing) reveals distinct phytoplankton growth periods in different parts of the gulf: a large peak during August (mid-summer) in the western part of the gulf, and a smaller peak during November (mid-autumn) in the lower central gulf and along the southern coastline. The summer bloom develops rapidly at the beginning of July, and its peak is approximately three times higher than that of the autumnal bloom. Remotely-sensed sea-surface temperature (SST), wind-stress curl, vertical nutrient profiles and geostrophic currents inferred from the sea-level anomaly, were analysed to examine the underlying physical mechanisms that control phytoplankton growth. During summer, the prevailing southwesterlies cause upwelling along the northern coastline of the gulf (Yemen), leading to an increase in nutrient availability and enhancing phytoplankton growth along the coastline and in the western part of the gulf. In contrast, in the central region of the gulf, lowest concentrations of Chl-*a* are observed during summer, due to strong downwelling caused by a mesoscale anticyclonic eddy. During autumn, the prevailing northeasterlies enable upwelling along the southern coastline (Somalia) causing local nutrient enrichment in the euphotic zone, leading to higher levels of phytoplankton biomass along the coastline and in the lower central gulf. The monsoon wind reversal is shown to play a key role in controlling phytoplankton growth in different regions of the Gulf of Aden.



## 1. Introduction

The Gulf of Aden is a narrow, elongated, oceanic basin bordering the coastlines of southern Yemen and northern Somalia (Fig. 1). The gulf is ~900 km in length, with an average depth of approximately 1800 m, and has a total area of ~220,000 km$^2$ (Al Saafani and Shenoi, 2007). On its western side, the strait of Bab-El-Mandeb permits water exchange between the Gulf of Aden and the Red Sea, whereas the eastern end of the gulf opens to the northwest Arabian Sea.

The Gulf of Aden is characterised by high levels of marine biodiversity and species richness (Gladstone et al., 1999) - a consequence of the tropical coral reef ecosystems located within coastal areas around the gulf. Through commercial and artisanal fisheries, the gulf provides an essential resource to its neighbouring countries and is an important provider of food to coastal populations (Gladstone et al., 1999). The Gulf of Aden is also an important commercial shipping route for international trade, particularly petroleum. A substantial 12% of the world's oil supply is transported through the Gulf of Aden by ~50,000 vessels each year (Kraska and Wilson, 2009). For this reason, the physical oceanography of the area has been carefully studied and the main physical processes that occur in the gulf are well understood (Al Saafani, 2008). Water exchange between the Red Sea and the Gulf of Aden is influenced by the seasonal reversal of wind patterns (*via* the Indian monsoon), which alters the flow regime across Bab-El-Mandeb (Murray and Johns, 1997; Smeed, 1997), playing an important role in the stratification and circulation of the gulf (Johns and Sofianos, 2012). Using remotely-sensed SST imagery and datasets from Air-deployed Expendable Bathythermograph (AXBT) surveys, Johns et al. (1999) demonstrated that the general

* Corresponding author at: King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.
*E-mail address:* john.gittings@kaust.edu.sa (J.A. Gittings).

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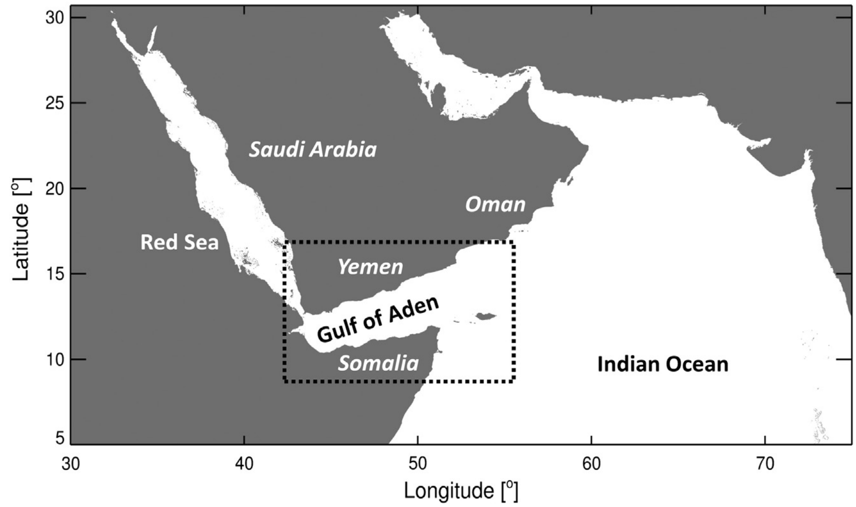


**Fig. 1.** Location of the Gulf of Aden and the surrounding land/water masses.

surface circulation within the Gulf of Aden is characterised by mesoscale eddies (mostly anticyclonic). These are commensurate with the width of the gulf and may have a substantial impact on its biology.

Knowledge on large-scale and long-term biological processes in the gulf is limited, primarily due to the lack of adequate data. Data paucity is aggravated by political instability in neighbouring countries and threats of piracy (Bower and Furey, 2012). As a result, existing literature describing biological dynamics in the region is inconclusive. In particular, it is not clear when phytoplankton biomass across the Gulf of Aden is highest. Using *in situ* measurements, Baars et al. (1995) concluded that the majority of the Gulf of Aden is more oligotrophic during the spring and summer seasons, although they also observed a phytoplankton bloom in the western gulf (south of Bab-El-Mandeb) during August (southwest monsoon, June–September). Based on *in situ* observations, Wiebinga et al. (1997) found that there were low nutrient and chlorophyll-*a* (Chl-*a*) concentrations in surface waters, across most of the Gulf of Aden (samples taken in central and eastern gulf), during the southwest monsoon. An exception to this was a cold water mass observed in the western part of the gulf during the peak of the southwest monsoon (month not defined) in which the recorded *in situ* concentrations of Chl-*a* were as high as 5 mg/m$^3$. However, Baars et al. (1995) and Wiebinga et al. (1997) came to the overall conclusion that the gulf was most productive during the northeast monsoon (November–February) whilst the former study also reported relatively large levels of mesozooplankton biomass associated with the northeast monsoon, including diapausing populations of the copepod *Calanoides carinatus* which were found across the entire gulf between depths of 300–1500 m. Both of the studies described above have proposed that phytoplankton communities in the Gulf of Aden are dominated mainly by picophytoplankton (primarily *Prochlorococcus* and two strains of *Synechococcus* according to Baars et al., 1995). This is consistent with the results of a study carried out by Gradinger et al. (1992), who found that picoplankton were the dominant size fraction in the Gulf of Aden during February/March 1987.

The abundance, phenology (bloom timing) and size-structure of phytoplankton in the oceans have a vital influence on the structure of marine food webs. Phytoplankton provides an essential food source for some marine mammals and numerous species of commercially important fish, whereas fluctuations in the spatiotemporal distribution of phytoplankton have been shown to influence the biodiversity trends of various marine organisms (Nybakken, 1997). Phytoplankton also have a key role in maintaining the biodiversity of coral reef ecosystems; Lo-Yat et al. (2011) demonstrated a strong relationship between Chl-*a* concentration and fish larval supply on a tropical coral reef ecosystem. Despite the importance of phytoplankton in the function of marine ecosystems, the seasonal succession of phytoplankton biomass in the Gulf of Aden has not yet been well established, mainly because of the lack of adequate *in situ* data.

An alternative approach to *in situ* data collection is visible spectral radiometry (ocean colour remote sensing) from which we can estimate phytoplankton biomass indexed as concentrations of Chl-*a*. An overview of the ocean colour remote sensing missions can be found in the review by McClain (2009). Remote sensing measurements of ocean colour have provided scientists with valuable information essential to characterise the seasonality of phytoplankton biomass in the surface of the ocean (*e.g.* Dandonneau et al., 2004; Raitsos et al., 2013). Satellite remote sensing allows synoptic observations of Chl-*a* concentration which provides the basis to determine ecological indicators characterising the state of the marine ecosystem at regional and global scales (Platt and Sathyendranath, 2008; Racault et al., 2014a).

Satellite-derived observations of ocean colour can be limited by cloud cover, sun-glint and high concentrations of atmospheric aerosols. In these conditions, atmospheric-correction algorithms may not work, resulting in missing data in the ocean colour time-series. This is especially true for the Gulf of Aden, as the region is subject to persistent cloud cover during the southwest monsoon period, particularly throughout July (Fratantoni et al., 2006). Consequently, detecting the seasonal cycle of phytoplankton biomass in the gulf has been challenging using observations from single-satellite ocean colour missions. However, new approaches have been recently developed to provide a significantly higher number of observations using multiple missions. One such approach is that employed by the Ocean Colour Climate Change Initiative (OC-CCI, Sathyendranath et al., 2016) of the European Space Agency (ESA). In this project, data from multiple satellite instruments (SeaWiFS, MODIS, and MERIS) have been merged, after band shifting and bias correction, to achieve consistency across sensors, and then error-characterised based on validation using global *in situ* data. For processing MERIS data, OC-CCI made use of an atmospheric correction algorithm (POLYMER, Steinmetz et al., 2011) capable of retrieving ocean data under some adverse conditions (high sun-glint, thin clouds and high aerosol optical depths). For MODIS and SeaWiFS, the SeaDAS atmospheric correction algorithm was used (see Fu et al., 1998). The result is a time-series of ocean colour data, which provides significantly improved coverage compared with what had been possible previously (Racault et al., 2015, their Fig. 2; Sathyendranath et al., 2016). In particular, for the Gulf of Aden, OC-CCI products have allowed us to observe the complete phytoplankton seasonality for the first time. The purpose of this study is to use the OC-CCI data to describe the spatiotemporal distribution of phytoplankton biomass in the Gulf of Aden, and to investigate its relationship with the regional physical and environmental drivers.