TITLE

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Seasonal Phytoplankton Blooms in the Gulf of Aden revealed by Remote Sensing

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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.

Keywords: ocean colour remote sensing, chlorophyll, phenology, Gulf of Aden, upwelling, monsoon

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 km² [*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 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 metres. 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.

2. DATA AND METHODOLOGY

2.1 Ocean-colour data from satellites

Version 1 of the ESA OC-CCI product [*Sathyendranath et al.*, 2016], comprising error-characterised, merged SeaWiFS, MODIS and MERIS data, was used in this study. Level 3 mapped data were acquired at 4 km and daily resolutions from http://www.esa-oceancolour-cci.org. The seasonal 8-day composites and climatologies of Chl-a data were constructed for the period 1997 to 2012. For further analyses, quarterly seasonal periods were chosen after careful analysis of time series of 8-day composite images (spring: April-June; summer: July-September; autumn: October-December; winter: January-March). It is worth mentioning that this study also refers to the southwest (summer) and northeast (winter) periods of the Arabian monsoon (which may span across two of our defined quarterly seasons) when we discuss the reversal in wind direction over the Gulf of Aden.

2.2 Sea-surface temperature data from satellites

MODIS monthly Night-time Sea-Surface Temperature (NSST) level 3 data products (4 km resolution) were acquired from the Goddard Earth Sciences Data and Information Services Centre at http://disc.sci.gsfc.nasa.gov/ for the period 2003-2013. Seasonal SST climatology maps were then generated for this period. Changes in SST may provide an indirect indication for the presence of upwelling/downwelling areas and eddies, which may influence nutrient availability (e.g. *Goes et al*., 2000), thus making SST a valuable physical variable to consider when investigating the generation and development of phytoplankton blooms. We constructed seasonal climatologies of SST for the spring, summer, autumn and winter seasons (as described in section 2.1).

2.3 Wind-stress curl data from satellites

Wind can have a key influence on the spatial and temporal variability of phytoplankton blooms. For this study, we reconstructed seasonal climatologies of wind-stress curl for two of the months in winter (January-February) and summer (July-August) from the 1/4 degree Scatterometer Climatology of Ocean Winds (SCOW, *Risien and Chelton*, 2008), which is based on the 1999-2009 QuikSCAT scatterometer data. Due to its relatively high resolution, the SCOW dataset can resolve dynamically important features in the surface wind-stress field.

2.4 Geostrophic current data from satellites

Satellite altimetry can be used to study the propagation pathways of warm and cold-core oceanic eddies. In this study, we used altimeter sea-level anomaly and associated geostrophic velocity data produced by Ssalto/Ducas and distributed by Aviso with support from the Centre National D'Etudes Spatiales (CNES). The geostrophic velocities are computed from gridded sea surface heights with respect to a twenty-year mean, based on multi-mission satellite altimeter observations. We used a minimum curvature surface fitting method [*Franke*, 1982] to interpolate the weekly, 1/3° products on to a 1/4° equi-rectangular grid. The full methodological approach, and its application in the nearby Red Sea, can be found in *Raitsos et al.* [2015].

2.5 Temperature and nutrient profiles

The vertical structure of the water column, and temporal variations in nutrient and temperature, can modify phytoplankton growth. To depict the seasonal temperature and nutrient distributions, one-degree, monthly, climatological, *in situ* data on temperature and nutrients were retrieved from the objectively-analysed World Ocean Atlas 2009 [WOA09, *Garcia et al.*, 2010; *Locarnini et al.*, 2010]. The WOA09 data are based on various types of *in situ* observations, including Conductivity-Temperature-Depth (CTD) profiles, Expandable Bathythermographs (XBT) and moored and drifting buoys. The monthly climatologies derived from the WOA09 data provide profiles of temperature and nutrients at standard depths for the Gulf of Aden, approximately along the zonal axis of the gulf.

2.6 Phytoplankton phenology maps

Phenology can be defined as the study of the timing of periodic biological events [*Schwartz*, 2003]. The phenological indices (initiation, peak, termination and duration, *Platt and Sathyendranath*, 2008) of phytoplankton blooms have been estimated using the OC-CCI Chl-a climatology time-series for the period 1997-2012. Methods to estimate phenological indicators are susceptible to the presence of gaps in the ocean colour time-series [*Racault et al.*, 2014b]. In the region of study, an 8-day temporal resolution has been shown to be the most suitable, balancing the finest temporal resolution feasible with fewest missing data. *Steinmetz et al*. [2011] reported a significantly higher number of observations in the Arabian Sea when using the atmospheric correction algorithm POLYMER for processing MERIS data and *Racault et al*. [2015] have shown a significant increase in OC-CCI data coverage in summer months in the Red Sea. To further reduce missing data from the Chl-a time-series prior to estimating the timing of ecological events, a linearisation scheme was applied, on each 8-day composite, sequentially in the order: longitude and latitude. Gaps were filled with the average value of the bordering grid points along the indicated axis [*Racault et al*., 2012; *Racault et al*., 2014b]. The averaging window had a width of three points and the surrounding points were weighted equally. The cumulative sum of anomalies method based on a threshold criterion previously applied in the Red Sea to estimate phenological indices of the phytoplankton growth period [*Racault et al*., 2015] has been adapted to estimate the indices in the Gulf of Aden, as outlined below.

First, the timings of peak Chl-a concentration were examined during two time-intervals: winter (January-March) and summer (July-September), corresponding to possible growth periods in the Gulf of Aden. These time-intervals were selected after visual examination of the time-series in the different regions of the Gulf of Aden. The maximum Chl-a concentrations estimated in the two periods were compared and the season in which the higher of the two peaks occurred was recorded as the “main” phytoplankton growth period in the year. The threshold of 20% of the maximum climatological Chl-a concentration [*Platt et al*., 2009] was then estimated using the higher of the two peak Chl-a values from the two periods. Then, we computed the cumulative sum of anomalies [*Lozowski et al*., 1989] using the Chl-a climatology. The cumulative sum method has been shown to reduce the potential effect of “noise” or short pulses in the Chl-a data without filtering the signal [*Greve et al*., 2005; *Brody et al*., 2013]. The cumulative sum of anomalies method used in the present study further allows us to identify persistent periods of Chl-a increase above the threshold, characterizing the phytoplankton growth period [*Racault et al*., 2015]. The timings of initiation and termination were identified as the times when Chl-a concentrations rose above and later fell below the threshold respectively. The duration was estimated as the number of

8-day periods between the timings of initiation and termination. For convenience, the number of 8-day periods will be referred to as 'weeks' throughout the manuscript.

2.7 *Validation of ocean-colour data*

To confirm the reliability of satellite data in the Gulf of Aden (and thus the interpretation of our results), OC-CCI Chl-a data were validated by *in situ* measurements obtained within and just outside of the Gulf of Aden. *In situ* Chl-a data were acquired from two sources: (i) High Performance Liquid Chromatography (HPLC) data (8 measurements) from the GeP&CO program in August-September 2002 (http://lodyc.jussieu.fr/gepco; see *Dandonneau et al*., 2004) (ii) *in situ* data (42 measurements) from a lidar fluorosensor operated onboard the RV *Italica,* collected as part of the MIPOT oceanographic campaign during November 2001 [*Barbini et al*., 2004]. Daily satellite Chl-a data from OC-CCI were matched in time (over a 3-day temporal window) and space (latitude and longitude, closest 4 km pixel) with *in situ* Chl-a data. The coefficient of variation (median coefficient of variation for remote-sensing reflectance bands between 412 and 555 nm) for a box of nine pixels surrounding each match-up was computed. To ensure homogeneity of the match-up site, only match-ups with a coefficient of variation < 0.15, and > 5 of the 9 pixels were included (Bailey & Werdell 2006; Brewin et al. 2015c). The daily OC-CCI Chl-a data were averaged over the 3-day period centred on the day of *in situ* data collection. A total of 36 OC-CCI match-ups were obtained; 30 for MIPOT and 6 for GeP&CO.

To compare the performance of the satellite Chl-a data with the *in situ* data in the Gulf of Aden, two univariate statistical tests were used: the Pearson correlation coefficient (r), and the root mean square error (ψ). The equations used for each of these statistical tests are provided in Section 4.1 of *Brewin et al.* [2015a]. All statistical tests were performed in $\log_{10}$ space, considering Chl-a is approximately log-normally distributed [*Campbell et al*., 1995].

Given the limited coincident *in situ* observations of a_{dg} and Chl-a, it is difficult to determine the extent to which our temporal analysis of Chl-a may be influenced by a_{dg}. In order to test this, we used monthly OC-CCI data of $a_{dg}(443)$ between January 1998 and December 2010, absorption by phytoplankton ($a_{ph}(443)$), estimated from the algebraic Quasi-Analytical Algorithm (QAA) of *Lee et al.* [2002], and monthly OC-CCI Chl-a data. The QAA is designed to retrieve estimates of a_{dg} and a_{ph} independently, such that the influence of a_{dg} and a_{ph} on the reflectance spectrum can be separated. For the absorption data, the wavelength of 443 nm was chosen as $a_{ph}(443)$ typically has the highest signal at 443 nm and correlates very well with Chl-a at this wavelength [*Bricaud et al.*, 2004], and a_{dg} also has a high signal at this wavelength (decreases exponentially with increasing wavelength).

3. RESULTS AND DISCUSSION

3.1 Phytoplankton phenology

Phenological maps of the Gulf of Aden were produced to examine the timings of the phytoplankton growth periods (Fig. 2). Excluding a small region along the southern coastline and lower central gulf (indicated by violet area), the main phytoplankton growth period across the gulf starts towards the end of spring (June, weeks 20 to 25, Fig. 2a). This coincides with the onset of the southwest monsoon season after the annual reversal in wind direction across the entire Gulf of Aden [*Clemens et al.*, 1991]. Phytoplankton biomass at the western gulf, northern coastline and eastern gulf peaks during summer (August, weeks 24 to 30), indicating a distinct summer bloom (Fig. 2b). The phytoplankton bloom terminates abruptly at the end of summer (September, weeks 32 to 34) just prior to the transitional period (October) between the southwest and northeast monsoon [*Prasad and Ikeda*, 2001]. The duration of the summer phytoplankton growth (from initiation to termination) is about ~2.5 to 4 months (i.e. 8 to 15 weeks, Fig. 2d).

In the lower central gulf and along the southeast coast, phytoplankton growth starts at the end of summer (September, weeks 32 to 33, Fig. 2a). The discrepancy in bloom timing between regions continues, as a peak in phytoplankton biomass is evident in the central gulf and southern coastline during autumn (November, weeks 39 to 41, Fig. 2b). The phytoplankton growth continues throughout the remainder of autumn and winter before terminating at the commencement of spring (late March/April, weeks 9 to 13, Fig. 2c). Thus, in this region, Chl-a concentrations may remain higher than the threshold criterion for several months (Fig. 2d), and the duration of phytoplankton growth may span from autumn to spring; an estimate of approximately 6 months (i.e. 25 weeks) can be made for a large portion of the region (Fig. 2d).

To investigate the underlying causes of the two contrasting patterns in the seasonal blooming (i.e. in summer and late autumn), the 8-day mean climatology of Chl-a for the last 15 years was further analysed for the two regions. Two specific areas, which will be referred to as Area A (western gulf) and Area B (lower central gulf), were selected to represent the two distinct blooming regions described above (e.g. Fig. 2b and 2c). These areas were chosen based on the phenological characteristics highlighted in the gulf and are indicated by red boxes in Figure 2c. No area was selected for the eastern gulf, as preliminary analysis showed that it exhibits a similar seasonal cycle to that of the region chosen for Area A (western gulf). The Chl-a data from these two areas were plotted as time-series, providing a representation of the seasonality of phytoplankton biomass (Fig. 3).

In Area A (Fig. 3a), the lowest concentrations of Chl-a are detected during spring (weeks 12 to 23). This corresponds to the transition between the northeast and southwest monsoon when winds are weak [*Al Saafani*, 2008; *Al Saafani and Shenoi*, 2007], probably resulting in reduced mixing, stronger stratification of the water column, and minimal upward transfer of nutrients into the euphotic zone. Following this, the highest Chl-a concentrations occur in summer (weeks 26 to 30). As previously observed in Fig. 2b, a rapid increase in phytoplankton biomass occurs at the end of spring following the establishment of the southwest monsoon (Fig. 3a). Chl-a concentrations are highest during early August when a climatological mean of approximately 3.3 mg/m^3 is observed, which then decreases rapidly in September (Fig. 3a). The standard error of Chl-a concentrations at the peak of the summer bloom (August) indicates that concentrations may reach ~5 mg/m^3 in some years (Fig. 3a). These high concentrations are consistent with previous studies using *in situ* measurements taken in the western gulf, south of the Bab-el-Mandeb strait, during the peak of the southwest monsoon [*Wiebinga et al.*, 1997, month not specified]. From week 35 in autumn until week 5 in mid-winter, concentrations of Chl-a decrease and fluctuate between 0.6 and 0.8 mg/m^3 (Fig. 3a), signifying the end of the phytoplankton growth period.

Chl-a concentrations in Area B reach, on average, lowest levels during spring (April-June) with a minimum concentration of 0.15 mg/m^3 occurring between weeks 16 to 20 (Fig. 3b). Low Chl-a concentrations are observed throughout the summer period, with the exception of a very short-term increase at the beginning of July that diminishes abruptly (weeks 22 to 24, Fig. 3b). There is a gradual increase in Chl-a until the end of October (~ week 36), before its peak in late November, when a climatological mean of 1.1 mg/m^3 can be observed (Fig. 3b). Following the autumnal peak, Chl-a concentrations show a small decrease at the end of December, but they remain elevated and stabilise at approximately 0.75 mg/m^3 throughout winter (January-March).

3.2 Seasonal climatology of Chl-a and SST

To elucidate the spatiotemporal distribution of Chl-a and SST in the Gulf of Aden, seasonal climatologies were produced, covering the four main seasons (Fig. 4); spring: April-June; summer: July-September; autumn: October-December; and winter: January-March.

Satellite observations reveal distinct spatial features in the seasonal succession of phytoplankton biomass in the gulf, consistent with the phenological characteristics reported in Figures 2 and 3. The entire gulf experiences lowest Chl-a concentrations during spring (April-June, Fig. 4a). Based on multiple sources of hydrographic data, *Al Saafani* [2008] reported the presence of two anticyclonic eddies within the gulf during May, possibly explaining the wide-scale oligotrophy present across the gulf during spring (due to downwelling). SST is relatively uniform across the gulf throughout spring and remains warm, with temperatures between 27.4˚C and 28.1˚C (Fig. 4e).

In summer, Chl-a concentrations increase markedly across the western gulf and northern coastline, corresponding closely to the large region (Area A) defined in Figure 2c. During this season, Area A is characterised by substantially lower SST in contrast to Area B (Fig. 4f). The presence of colder SST in Area A coincides with an increase in Chl-a. These observations are also consistent with those of *Wiebinga et al*. [1997], who detected colder temperatures and *in situ* concentrations of Chl-a as high as 5 mg/m^3 in the western Gulf of Aden during summer (months not specified). *Baars et al*. [1995] also reported a phytoplankton bloom in August within the same area. Nevertheless, both of the aforementioned studies state that despite the appearance of phytoplankton blooms in the western gulf, the gulf is generally oligotrophic during summer. In fact, *Wiebinga et al*. [1997] described the whole gulf as being most productive during the northeast monsoon. Thus, prior to this study, the main months during which phytoplankton biomass is highest were unknown.

A region of low Chl-a and increased SST can be observed within Area B during summer, possibly indicating the presence of an anticyclonic eddy (Fig. 4b, f). *Prasad and Ikeda* [2001] identified the 'Gulf of Aden Eddy' (GAE), which forms within the vicinity of the gulf during mid-spring (May) and could be associated with the arrival of Rossby waves from the interior of the Arabian Sea due to possible forcing from the southern Arabian Sea high. *Bower and Furey* [2012] concluded that two additional eddies are generated during the onset of the southwest monsoon. They suggest that these eddies are formed as a result of positive wind-stress curl and a shoaling thermocline at the entrance of the Gulf of Aden, which divides the GAE (detected by *Prasad and Ikeda*, 2001) into two smaller anticyclonic eddies; the 'Summer Eddy' and 'Lee Eddy'. *Bower and Furey* [2012] proposed that the 'Summer Eddy' moves westwards into the Gulf of Aden (strengthening as it moves), and is sustained by Ekman convergence associated with patches of negative wind-stress curl caused by wind jets through the elevated terrain of the area. The anticyclonic eddy identifiable in Figures 4b and f is perhaps the 'Summer Eddy' reported by *Bower and Furey* [2012]. Wind jets associated with mountainous topography along the northern Somali coastline could also be responsible for the formation of mesoscale eddies in the centre of the gulf, particularly during August, when the monsoonal winds are at their strongest [*Fratantoni et al.*, 2006].

Higher concentrations of Chl-a are present along the northern coastline of the Gulf of Aden during summer (Fig. 4b). In accordance with the monsoon regimes, *Johns et al.* [1999] proposed that upwelling occurs along the northern coastline during summer due to the formation of a wind-driven coastal current, contributing to the generation of phytoplankton blooms along the Yemeni coastline. *Aiki et al.* [2006] also demonstrated that positive wind-stress curl induces large-scale coastal Ekman upwelling over the gulf during the summer. *Al Saafani* [2008] suggested that conditions are favourable for upwelling along the northern coastline of the gulf during summer as a result of Ekman drift.

In autumn, there is a reduction in phytoplankton biomass throughout the Gulf of Aden, with the exception of higher concentrations of Chl-a across the southern coastline (Fig. 4c). During the northeast monsoon, winds across the Gulf of Aden blow from the northeast [*Al Saafani and Shenoi*, 2007]. It is highly possible that the seasonal reversal in wind direction at the beginning of the northeast monsoon induces an upwelling event along the southern coastline of the gulf during autumn, which is analogous to the upwelling observed along the northern coastline during summer. This view is supported by the presence of a prominent band of low SST along the southern coastline during autumn (Fig. 4g). *Al Saafani* [2008] demonstrated that upwelling generated by Ekman pumping occurs due to the establishment of a prominent westward current along the southern coastline of the gulf at the commencement of the northeast monsoon. Upwelling along the southern coastline of the gulf has also been reported and schematised by *Johns et al*. [1999]. These coastal upwelling events could be controlled by monsoonal winds, which generate prominent eastward (summer) and westward (autumn) coastal currents that are subject to Ekman drift [*Johns et al*., 1999; *Al Saafani*, 2008]. During autumn, it is likely that upwelling is established over the southern gulf and occupies much of the area we define as Area B. Consequently, the November peak that can be observed in Area B (Fig. 2b, Fig. 3b) is most likely representative of annual coastal upwelling that stimulates a large phytoplankton bloom.

In winter, the higher concentrations of Chl-a observed along the southern coastline of the gulf during autumn are no longer apparent (Fig. 4d). Overall, the whole gulf exhibits relatively similar levels of higher Chl-a, although an area of slightly reduced Chl-a values is present in the eastern gulf between 49ºE and 50ºE. *Bower et al*. [2002] reported the presence of an anticyclonic eddy between 48ºE and 49ºE based on *in situ* data collected between February and March 2001, possibly providing an explanation for the diminished levels of Chl-a in this area. The presence of an anticyclonic eddy within this area between January and

March has also been reported by *Al Saafani* [2008], using altimetry-derived sea-surface-height anomalies.

3.3 Thermocline depth, nutrients and wind-stress curl

To investigate further the influence of physical forcing on summer phytoplankton biomass in Areas A and B, vertical cross-sections of temperature and nutrients, approximately along the zonal axis of the gulf, were plotted for two months representative of the quarterly winter and summer seasons respectively (Fig. 5a). During winter (January-February in this figure) the thermocline and nutriclines of nitrate and phosphate are relatively deep, with a distinct surface layer of warmer water extending down to approximately 125 m. During summer (July-August in this figure), the thermoclines and nutriclines have shoaled to approximately 75 m. *Aiki et al*. [2006] investigated the depth of the thermocline in the Gulf of Aden and also observed that the shallowest thermocline depth occurs during summer followed by a significant deepening of the thermocline in late winter. According to these authors, the shoaling of the thermocline in the western Gulf of Aden is caused mainly by the strong summer monsoonal winds. *Bower and Furey* [2012] noted that the depth of the 20˚C isotherm (situated in the middle of the main thermocline) is roughly 50 m shallower during mid-summer (August) in comparison with that in late winter (March). The deepening of the thermocline during winter can be attributed to the presence of colder winds, which cool surface waters in the western gulf, resulting in the sinking of more dense water.

The depth of the thermocline varies with longitude during summer (Fig. 5a). Between 44ºE and 46ºE, a prominent 'bulge' (shallow thermocline) can be observed (Fig. 5a). The feature is located within Area A, the western gulf, and most likely signifies an upwelling event. The shoaling is also seen in the vertical cross-sections of nitrate and phosphate, which exhibit elevated concentrations at a lower depth in the western gulf during summer (July-August, Fig. 5a). The depth of the thermocline decreases between 46ºE and 49ºE during summer, indicating the effect of the anticyclonic eddy within the centre of the gulf (i.e. Area B, Fig. 4b and f). This is commensurate with the climatology for geostrophic currents presented in Figure 5c, where vectors show a clockwise circulation (indicative of anticylonic eddies in the northern hemisphere), and a region of apparently high sea-level anomaly in the central gulf during July and August, indicating the presence of a deeper surface mixed layer and lower Chl-a concentrations [*Everett et al*., 2012]. Similar features are also evident in the sections of nitrate and (in particular) phosphate (Fig. 5a). Previous studies in the Mediterranean Sea have shown that anticyclonic eddies are characterised by the presence of a deeper nutricline and a limited input of nutrients to surface waters [*Salihoğlu et al*., 1990, *Yılmaz et al*., 1994]. It is possible that the anticyclonic system observed in Area B during summer induces downwelling of surface waters [e.g. *Fong et al*., 2008], reducing the concentration of nutrients in the euphotic zone, decreasing the productivity of the area [*Triantafyllou et al*., 2014], ultimately resulting in low Chl-a concentrations.

Climatologies of wind-stress curl and geostrophic currents (indicative of upwelling/downwelling) across the Gulf of Aden for both winter and summer seasons are shown in Figs. 5b and 5c. Wind-stress curl appears to be relatively low across the gulf during the northeast monsoon [Fig. 5b, *Al Saafani and Shenoi*, 2007]. Interestingly, an anticyclonic eddy is apparent in the gulf, approximately between 48E° and 51°E (Fig. 5c). This appears to agree with Figure 4d, where concentrations of Chl-a in this same region are reduced in comparison with the rest of the gulf.

During summer, strong winds generate positive wind-stress curl in the far western gulf adjacent to the Bab-El-Mandeb strait (Fig. 5b), inducing upwelling and resulting in the shoaling of the nutricline/thermocline [*Triantafyllou et al*., 2014, Fig. 5a]. Thus, prolonged positive wind-stress curl during summer can break down the shallow thermocline, allowing the transport of colder, nutrient-rich waters to the surface, providing favourable conditions for phytoplankton growth and stimulating a large bloom in August (Fig.2b; Fig.3a; Fig. 4b). Supporting these observations, *Johns et al.* [1999] showed that seasonal upwelling occurs in the western Gulf of Aden at the onset of the southwest monsoon.

Al Saafani et al. [2007] showed that Ekman pumping is an important mechanism for generating mesoscale eddies within the Gulf of Aden during the southwest monsoon. Localised Ekman pumping generated by the strong monsoonal winds could contribute to the development of an eddy within Area A. Utilising 3D regional models (ROMS), nested within a data-assimilating global model (HYCOM) to investigate the interaction of Red Sea Outflow Water with eddies in the gulf, *Ilıcak et al.* [2011] demonstrated the presence of a large cyclonic eddy in the gulf during April 2007. By August, the cyclonic eddy had moved towards the southwest and increased in strength, occupying the area in the far western gulf where cooler water can be observed during summer (Fig. 4f). This cyclonic eddy may provide an alternative explanation for the strong upwelling (and peak in Chl-a) that can be observed in Area A during summer (Fig. 2b; Fig. 3a); the formation and intensification of cyclonic eddies are known to induce a flux of nutrients from deeper waters to the surface layer [*McGillicuddy and Robinson*, 1997].

It is worth noting that other factors can influence phytoplankton bloom dynamics. Light availability across oceanic regions is known to have an important role in controlling bloom initiation. For example, *Sverdrup* [1953] described the roles of both light availability and vertical mixing in the generation of the North Atlantic spring bloom; enhanced light availability during spring and the shoaling of the mixed layer allows phytoplankton productivity to exceed community loss processes and rapid phytoplankton growth can occur (whereas deeper mixed layers and reduced light availability during winter prevents net community production). However, for tropical marine ecosystems such as the Gulf of Aden, light availability is relatively consistent annually and the presence of a permanent thermocline can act as a barrier to the upward transport of nutrients (thus, nutrient concentration is the primary factor limiting phytoplankton growth in the surface ocean). The role of zooplankton in modulating Gulf of Aden phytoplankton dynamics is yet to be studied. However, as seen in other oceanic blooming regions such as the North Atlantic Ocean and the Arabian Sea, it is possible that the reduction in Chl-a concentrations at the end of September in the western gulf may be attributed to increased grazing pressure following a rise in zooplankton abundance [*Banse*, 1992; *Goericke et al*., 2002]. After the southwest monsoon, the re-development of the thermocline following a reduction of local wind stress may also contribute to diminished levels of Chl-a.

3.4 Satellite validation and impact of absorption by non-algal particles and dissolved matter

The geographical distribution of the match-ups between the satellite and *in situ* data (see section 2.7 of the methodology), and the results from the comparison, is shown in Figure 6a. In general, statistical comparisons show good agreement between the satellite and *in situ* data, with a statistically significant correlation (r = 0.84, p <0.001), and a low root mean square error ($\psi = 0.16$, Fig. 6b). In fact, the root mean square ($\psi = 0.16$) is about half that reported in other studies using global datasets [*Gregg and Casey*, 2004; *Werdell and Bailey*, 2005; *Bailey and Werdell*, 2006; *Brewin et al*., 2015c], and comparable with a recent study in the Atlantic Ocean [*Brewin et al*., 2016]. Statistical tests also compare favourably with regions that are within close proximity to the Gulf of Aden, such as the Red Sea [*Brewin et al*., 2013; 2015b]. For instance, *Brewin et al*. [2015b] report a correlation coefficient (r) of 0.84 and a ψ of 0.29 in the Red Sea using OC-CCI and the OC4 algorithm (see their Fig. 5). The validation results presented here (Fig. 6) provide confidence in the use of OC-CCI Chl-a data in the Gulf of Aden.

Remotely-sensed estimates of Chl-a in optically complex waters can be complicated by the presence of coloured dissolved organic matter (CDOM), which may affect the absorption of shorter (blue) visible light wavelengths, leading to an overestimation of Chl-a concentration [*Matsuoka et al.*, 2007]. The OC-CCI Chl-a data is computed using the OC4 blue-green band-ratio algorithm [*O'Reilly et al.*, 2000]. Whilst validation in the Gulf of Aden showed good performance (Fig. 6b), the empirical nature of the OC4 algorithm means that it implicitly assumes absorption by dissolved substances and non-algal particles (a_{dg}) co-varies in a predictable manner with Chl-a [*Dierssen*, 2010]. Figure 7a shows the determination coefficient (r^2), derived from correlating monthly data (1998-2010, 156 months) of $\log_{10}$-transformed $a_{ph}(443)$ and $\log_{10}$ transformed $a_{dg}(443)$ on a pixel-by-pixel basis over the Gulf of Aden. Over the majority of the gulf, the two variables are positively correlated (r^2 is between 0.6 and 1.0, $p < 0.05$), indicating that $a_{ph}(443)$ and $a_{dg}(443)$ co-vary in the Gulf of Aden and their temporal patterns are correlated, suggesting seasonal cycles in OC-CCI Chl-a should be relatively insensitive to the influence of non-algal particles and CDOM. In order to further confirm the validity of the OC-CCI Chl-a data, the determination coefficient (r^2), derived from correlating monthly data (1998-2010, 156 months) of OC-CCI $\log_{10}$-transformed $a_{ph}(443)$ and $\log_{10}$-transformed Chl-a, was also computed on a pixel-by-pixel basis over the Gulf of Aden (Figure 7b). Seasonal cycles of Chl-a in the Gulf of Aden, derived using the OC4 algorithm, are highly correlated with $a_{ph}(443)$ derived from QAA ($r^2 >$ 0.8, Figure 7b), suggesting consistent seasonal cycles (i.e. phenology) between the two variables ($a_{ph}(443)$ and Chl-a).

4. CONCLUSIONS

Prior to this study, knowledge on the large-scale phytoplankton dynamics within the Gulf of Aden was limited. Due to the paucity of biological data from *in situ* sampling, the gulf had been characterised as a winter-blooming region. The 15 years of high-resolution remotely-sensed Chl-a data produced by the ESA OC-CCI project has revealed that different regions of the Gulf of Aden exhibit distinct phytoplankton growth periods. The northern coastline (south Yemen) and the far western part of the gulf (Area A) are characterised by a prominent summer bloom, which is initiated in late spring (June) and peaks during mid-summer (August) when the southwesterlies prevail. Conversely, waters in the lower central gulf (Area B) and southern coastal region demonstrate maximum Chl-a concentrations during autumn (late November), indicating that the major phytoplankton growth period in these regions occurs during the northeast monsoon when the northeasterlies prevail.

Seasonal climatology maps of Chl-a, SST, wind-stress curl, sea-level anomaly, geostrophic currents and vertical profiles of nutrients showed that the spatial distribution of phytoplankton biomass within the gulf is related to changes in the physical environment, which are driven by the monsoon reversal. An increase in Chl-a concentrations occurs when wind-stress curl intensifies in the western gulf during summer, causing a shallowing of the thermocline and nutriclines, colder SSTs, and an increase in nutrient concentrations in the surface waters of the region. Conversely, the central gulf is dominated by an anticyclonic eddy during summer, resulting in reduced Chl-a concentrations and elevated SST as a consequence of downwelling. High Chl-a concentrations occur along the southern coastline (autumn) and northern coastline (summer). This is associated with colder SSTs, indicating the presence of large monsoonal-driven zones of coastal upwelling and enhanced nutrient availability.

Using ocean colour remote sensing observations (OC-CCI), our study presents, for the first time, a complete seasonal cycle of phytoplankton in the Gulf of Aden. The timing and magnitude of phytoplankton blooms have been shown to be among the determining factors for the survival of fish larvae [*Platt et al.*, 2003, *Lo-Yat et al.*, 2011]. Thus, further understanding of inter-annual variations in food availability along the coastline of the gulf (during the summer and autumn seasons) will be highly relevant to support the management of fisheries resources provided by tropical coral reef ecosystems, and could be a potential avenue for future research.

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LIST OF FIGURE CAPTIONS

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

Figure 2. Phenological stages of the main phytoplankton growth period in the Gulf of Aden (based on OC-CCI 15 year-climatology of 8-day composites); **a)** timing of initiation, **b)** timing of peak, **c)** timing of termination and **d)** duration of the growth period. For panels **a, b,** and **c,** the colour scale illustrates the timing within a year in 8-day time steps (i.e. a year is expressed as 46 eight-day time steps, with 1 representing the first eight days of January) and in corresponding months (i.e. 12 months per year), whereas for panel **d**, the colour scale indicates the number of 8-day periods (or 'weeks', see 'W' on the left-hand side of the colour scale) between the initiation and termination. The red boxes depicted in panel **c** indicate areas selected for the time-series analysis (Area A in the western part of the gulf and Area B in the eastern/lower central part of the gulf).

Figure 3. Seasonal cycle of Chl-a from climatology of OC-CCI Chl-a (1997-2012) in the Gulf of Aden; **a)** Area A, and **b)** Area B (the locations of the areas are indicated by the red boxes in Fig. 2c). Blue-Grey shading indicates +/-1 Standard Error of OC-CCI climatology Chl-a concentrations.

Figure 4. (**a to d)** Seasonal mean of Chl-a concentration (OC-CCI 1997-2012, mg/m^3), (**e to h)** Seasonal mean of Night-time Sea Surface Temperature (MODIS-aqua 2003-2013, ºC).

Figure 5. a) Vertical cross sections for temperature (top panel), nitrate (middle panel) and phosphate (bottom panel) in the Gulf of Aden. The black solid line indicates the location of the thermocline (represented by the 20°C isotherm). Grey shaded areas represent absence of data. **b)** Seasonal mean of wind stress curl (10^{-7} N m^{-3}) for winter (Jan-Feb, left panel) and summer (Jul-Aug, right panel). Black arrows indicate wind pressure (0.1 N m^{-2}) on the sea surface. **c)** Seasonal climatology of geostrophic sea-level anomalies (cm) currents for winter (Jan-Feb, left panel) and summer (Jul-Aug,

right panel). Black arrows indicate geostrophic velocities anomaly depicting the warm- (anti-cyclonic) and cold-core (cyclonic) eddies in the gulf.

Figure 6: **a)** *In situ* Chl-a gathered from two sources in the Gulf of Aden, from the GeP&CO program [*Dandonneau et al.*, 2004] and from the MIPOT oceanographic campaign [*Barbini et al.*, 2004], with satellite match-ups shown as green circles. Yellow box defines the Gulf of Aden region used for the validation analysis. **b)** Statistical comparison between *in situ* and OC-CCI Chl-a for the match-ups, with the correlation coefficient (r), root mean square error (ψ) and number of retrievals (N). The yellow circles represent the satellite match-ups obtained within the Gulf of Aden (see corresponding yellow box in Figure 6a). The solid black line represents the 1:1 line.

Figure 7: **a)** The determination coefficient (r^2), derived from correlating monthly OC-CCI data (1998-2010, 156 months) of $\log_{10}$-transformed $a_{\mathrm{ph}}(443)$ and $\log_{10}$-transformed $a_{\mathrm{dg}}(443)$ on a pixel-by-pixel basis over the Gulf of Aden. OC-CCI data for $a_{\mathrm{ph}}(443)$ and $a_{\mathrm{dg}}(443)$ were derived using the QAA of Lee et al. (2002), and are available through the OC-CCI project. **b)** Determination coefficient (r^2), derived from correlating monthly OC-CCI data (1998-2010, 156 months) of $\log_{10}$-transformed $a_{\mathrm{ph}}(443)$ and $\log_{10}$-transformed OC-CCI Chl-a on a pixel-by-pixel basis over the Gulf of Aden.