



Comparison of Seasonal Cycles of Phytoplankton Chlorophyll, Aerosols, Winds and Sea-Surface Temperature off Somalia

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In climate research, an important task is to characterize the relationships between Essential Climate Variables (ECVs). Here, satellite-derived data sets have been used to examine the seasonal cycle of phytoplankton (chlorophyll concentration) in the waters off Somalia, and its relationship to aerosols, winds and Sea Surface Temperature (SST). Chlorophyll-a (Chl-a) concentration, Aerosol Optical Thickness (AOT), Ångström Exponent (AE), Dust Optical Thickness (DOT), SST and sea-surface wind data for a 16-year period were assembled from various sources. The data were used to explore whether there is evidence to show that dust aerosols enhance Chl-a concentration in the study area. The Cross Correlation Function (CCF) showed highest positive correlation ($r^2 = 0.3$) in the western Arabian Sea when AOT led Chl-a by 1–2 time steps (here, 1 time step is 8 days). A $2 \times 2^\circ$ box off Somalia was selected for further investigations. The correlations of alongshore wind speed, Ekman Mass Transport (EMT) and SST with Chl-a were higher than that of AOT, for a lag of 8 days. When all four variables were considered together in a multiple linear regression, the increase in r^2 associated with the AOT is only about 0.02, a consequence of covariance among AOT, SST, EMT and alongshore wind speed. The AOT data show presence of dust aerosols most frequently during the summer monsoon season (June–September). When the analyses were repeated for the dust aerosol events, the correlations were generally lower, but still significant. Again, the inclusion of DOT in the multiple linear regression increased the correlation coefficient by only 2%, indicating minor enhancement in Chl-a concentration. Interestingly, during summer monsoon season, there is a higher probability of finding more instances of positive changes in Chl-a after one time step, regardless of whether there is dust aerosol or not. On the other hand, during the winter monsoon season (November–December) and rest of the year, the probability of Chl-a enhancement is higher when dust aerosol is present than when it is absent. The phase relationship in the 8-day climatologies of Chl-a and AOT (derived from NASA's SeaWiFS and MODIS-A ocean colour processing chain) showed that AOT

led Chl-a for most of the summer monsoon season, except when Chl-a was very high, during which time, Chl-a led AOT. The phase shift in the Chl-a and AOT climatological relationship at the Chl-a peak was not observed when AOT from Aerosol Climate Change Initiative (Aerosol-CCI) was used.

Keywords: essential climate variables, aerosol optical thickness, Ångström exponent, chlorophyll-a, ocean colour climate change initiative, climate change, remote sensing, dust aerosols

1. INTRODUCTION

Phytoplankton, Sea-Surface Temperature (SST), sea-surface winds and aerosols are all Essential Climate Variables (ECVs) identified by the Global Climate Observation System (GCOS, 2011) as being worthy of sustained global observations at high spatial resolution and over long time scales, to aid studies of Earth's climate and climate change. As we strive to understand how the Earth system might respond holistically to climate change, it is important to explore not only the behavior of individual ECVs, but also their inter-relationships and the feedbacks between them. In the western Arabian Sea, the relationships between phytoplankton, winds and SST are better understood than that between phytoplankton and aerosols.

Yet, there are known functional links between marine aerosols and phytoplankton. For example, dust aerosols, transported by winds over the ocean, can be an important source of micronutrients such as iron, essential for phytoplankton growth (Duce and Tindale, 1991; Martin et al., 1991, 1994; Prospero et al., 2002; Cropp et al., 2005; Jickells et al., 2005; Mahowald et al., 2005; Meskhidze et al., 2005; Gallisai et al., 2014), with the proviso that not all the iron contained in dust particles is usable by phytoplankton. Winds over the ocean are also responsible for the formation of aerosols through generation of sea salt sprays (O'Dowd et al., 1997; Smirnov et al., 2003; Satheesh et al., 2006; Mulcahy et al., 2008; Glantz et al., 2009; Huang et al., 2010; Meskhidze and Nenes, 2010) and the same winds also mix the surface layer of the ocean, dictating the entrainment of nutrients from the deeper waters into the surface layer and controlling the average light available for phytoplankton growth in the layer. In addition to sea salt sprays, biological particles (for example, fragments of phytoplankton) contained in sea spray can also aid aerosol formation (Leck and Bigg, 2005; Facchini et al., 2008; Hawkins and Russell, 2010; Quinn and Bates, 2011). Feedback mechanisms (both positive and negative) have been proposed between dimethyl sulphide in the atmosphere of phytoplanktonic origin and the Earth's radiation budget, *via* aerosols (Charlson et al., 1987; Lovelock, 2006).

Positive (Martin et al., 1994; Jickells et al., 2005; Patra et al., 2007; Banerjee and Prasanna Kumar, 2014) and negative (Mallet et al., 2009; Paytan et al., 2009; Jordi et al., 2012) correlations between marine aerosols and phytoplankton concentration have been reported for different parts of the world ocean. Some studies have also identified regions where no relationship exists between the two (Cropp et al., 2005; Gallisai et al., 2014). Possible explanations for the positive correlations include the fertilizing role of iron contained in dust aerosols, or phytoplankton themselves, acting as a source of marine aerosols. Negative

correlations might arise from high winds causing production of wind-spray aerosols, while at the same time forming deep mixed layers that may be able to support only low concentrations of phytoplankton, because of low average light levels available in the layer.

Satellite-based measurements provide a valuable tool for studies of aerosols and phytoplankton. Aerosol Optical Thickness (AOT), amenable to remote sensing, is an often-used measure of aerosol concentration. The Ångström Exponent (AE), which defines the wavelength dependence of AOT, is indicative of the type of aerosols present, and is also available through remote sensing. Dust Optical Thickness (DOT) can be inferred from AOT and the AE. Satellite data have been used to track dust aerosols for thousands of kilometers away from their source (Myhre et al., 2005). Likewise, ocean colour measured from space provides information on the concentration of chlorophyll-a (Chl-a), which is a major photosynthetic pigment contained in phytoplankton. Furthermore, estimates of winds (speed and direction) and SST, essential for understanding phytoplankton dynamics, are also available through remote sensing. An advantage of remote sensing is that it provides data at large scales and over many years, allowing studies of time-series at multiple locations in a systematic manner. But some caution should be exercised when using ocean colour derived Chl-a concentration, AOT and AE. Sometimes they are all produced from the same processing chain, and one might argue that, in the extreme case, any relationships observed between the three are purely artifacts of the processing algorithm. Furthermore, the effects of clouds on satellite retrievals are significant and sometimes lead to biases by overestimation or underestimation of aerosol data, particularly for dust aerosols (Levy et al., 2007; Torres et al., 2007; Baddock et al., 2009; Kahn et al., 2010). However, some authors have used cloud-screening techniques to reduce such errors (Kaufman et al., 2005). Therefore, the processing chain issues should be verified to arrive at conclusive results.

In this paper, we examine the relationships of Chl-a with winds, SST, AOT and dust aerosols in the western Arabian Sea, at a selected site off Somalia. The region is characterized by a high dynamic range in Chl-a values that vary seasonally, in response to the reversing wind patterns and associated upwelling (Prasanna Kumar et al., 2001; Schott and McCreary, 2001; Schott et al., 2002; Shankar et al., 2002; Wiggert et al., 2005; Lévy et al., 2007; Wiggert and Murtugudde, 2007; Prakash et al., 2012). Diverse physical forcings of both oceanic and atmospheric origins drive biological production off Somalia region. During summer monsoon season, the Somalia coastal region is characterized by strong upwelling with high primary productivity due to the swift Somali current caused by strong

south-westerlies along the coast (Smith and Codispoti, 1980; Schott, 1983; Hitchcock and Olson, 1992; Brock et al., 1994; Schott et al., 2002; deCastro et al., 2016). The anti-cyclonic eddies associated with the Somali current during the same season further enhance production by transporting and mixing upwelled water (Fischer et al., 1996; McCreary et al., 1996; Schott et al., 1997; Koning et al., 2001; Schott et al., 2002; Santos et al., 2015). The consequent nutrient enrichment in the mixed layer of the ocean leads to high phytoplankton production during summer monsoon season (Banse, 1987; Owens et al., 1993). Because of its proximity to the Arabian Peninsula, the region also receives seasonally-varying dust deposition (Pease et al., 1998; Li and Ramanathan, 2002; Prospero et al., 2002; Léon and Legrand, 2003; Zhu et al., 2007; Prasanna Kumar et al., 2010). Thus, the same winds that transport dust aerosols to the western Arabian Sea during the summer monsoon season also induce upwelling, favoring phytoplankton blooms. Hence the relationship between Chl-a and aerosols in this region would be incomplete, unless we examined the effect of winds on phytoplankton dynamics as well. Here, we use 16 years of satellite data (1998–2013) to make a systematic study of the relationship of Chl-a with AOT, winds and SST in the waters off Somalia.

2. MATERIALS AND METHODS

2.1. Data

Level-3 8-day composite Aerosol Optical Thickness (AOT) at 865 nm and Ångström Exponent (AE) from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) during January 1998–December 2010 and Moderate Resolution Imaging Spectro-radiometer (MODIS) Aqua during January 2011–December 2013 downloaded from National Aeronautics and Space Administration's (NASA's) ocean colour website (<https://oceancolor.gsfc.nasa.gov>) were used in this work. The AOT and AE data from NASA are referred to here as NASA-AOT and NASA-AE respectively. The daily AOT at 550 nm and AE data from European Space Agency's (ESA's) Aerosol Climate Change Initiative (Aerosol-CCI) programme (de Leeuw et al., 2015; Popp et al., 2016, see also <http://www.esa-aerosol-cci.org>) were also used in this study, as an independent source of aerosol data, unconnected with ocean colour atmospheric correction routines. The AOT and AE data from the Aerosol-CCI website are referred to here as CCI-AOT and CCI-AE respectively. The data are available at 1° spatial resolution for the period from January 1998–December 2010.

The relationship between the AOT (τ) at any given wavelength λ_0 and that at any other wavelength λ depends on the AE (α) through the equation:

$$\left(\frac{\tau_{\lambda}}{\tau_{\lambda_0}}\right) = \left(\frac{\lambda}{\lambda_0}\right)^{-\alpha} \quad (1)$$

In principle, if the optical thickness at one wavelength and the AE are known, the optical thickness can be computed at any other wavelength using Equation (1).

Chlorophyll-a (Chl-a) concentration, for the period January 1998–December 2013, was obtained from ESA's

Ocean Colour-Climate Change Initiative (OC-CCI) website (Sathyendranath et al., 2016, see also <https://www.oceancolour.org>). One of the major reasons for the choice of the Chl-a data was the improved coverage provided by the OC-CCI data in the Arabian Sea, especially during the summer monsoon season. The 8-day composite AOT data from SeaWiFS are available at only 9 km resolution, so we used MODIS Aqua data at the same resolution (9 km) even though they are available at 4 km resolution. The Chl-a concentration from OC-CCI (version-2), which is available at 4 km resolution, was also re-gridded to 9 km resolution. Since the CCI-AOT data are available at 1° spatial resolution, the Chl-a concentration from OC-CCI was also re-gridded to 1° resolution to analyse the correlation between them. The daily value of AOT at 865 nm was calculated from daily CCI-AOT at 550 nm and CCI-AE using Equation (1). The data were merged to generate 8-day composites and extracted for the region off Somalia. The daily 1° gridded Sea Surface Temperature (SST) data were obtained for the period January 1998–December 2013 from Woods Hole Oceanographic Institute's (WHOI's) objectively-analyzed air-sea heat fluxes available at Asia-Pacific Data-Research Centre (APDRC) website (<http://apdrc.soest.hawaii.edu>). The SST anomaly has been calculated using these data after merging into 8-day composites. In addition, the daily NCEP/NCAR reanalysis U-wind (zonal velocity) and V-wind (meridional velocity) data with $2.5 \times 2.5^\circ$ spatial resolution at 10 m above the sea surface were obtained for the same period from their official website (<https://www.esrl.noaa.gov/psd>). The data have been merged to generate 8-day composites and used to derive the south westerly wind component along the Somalia coast. All the above mentioned information is summarized in Table 1.

2.2. Methods

The methods used in this study are shown schematically in Figure 1, and described below.

2.2.1. Correlation between Chl-a and AOT in the Arabian Sea

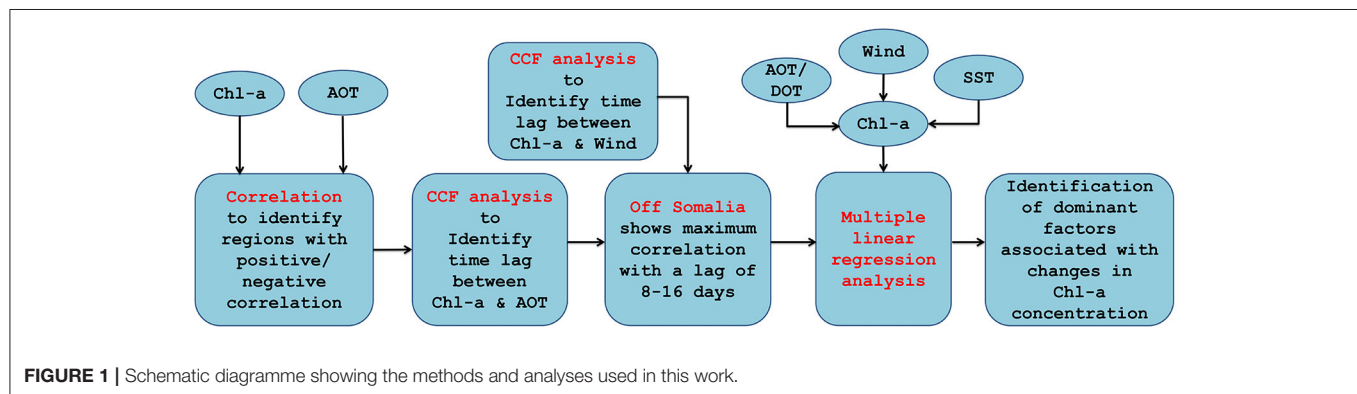
Correlation between Chl-a and AOT concentration for the 1998–2013 period over the Arabian Sea was studied using the 8-day composites. The results showed areas of both positive and negative correlation. The western Arabian Sea showed strong positive correlation. A $2 \times 2^\circ$ box ($54\text{--}56^\circ$ E longitude and $10\text{--}12^\circ$ N latitude) off Somalia coast, with high positive correlation, was chosen for further analyses.

2.2.2. CCF Analysis and Lagged Correlation

We studied the lags in the correlation between Chl-a and AOT using Cross Correlation Function (CCF). CCF analysis produces cross correlations in which the observations of one time series are correlated with the observations of another time series at different lags and leads, to identify the variables which are leading or lagging indicators of other variables. The basic premise is that, if the relationships between the variables were merely a processing artifact, the correlations would peak at zero lag. In instances where phytoplankton might be contributing biological material for aerosol formation, the correlation would

TABLE 1 | Summary of data sets analyzed in the study.

Variable	Sensor/provider	Units	Spatial resolution	Temporal extent	Source
Chlorophyll-a (Chl-a)	Ocean Colour Climate Change Initiative (OC-CCI)	mg m^{-3}	4 km	1998–2013	https://www.oceancolour.org
Aerosol Optical Thickness (AOT)	Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectro-radiometer Aqua (MODIS-Aqua)	Dimensionless	9 km	1998–2013	https://oceancolor.gsfc.nasa.gov
Ångström Exponent (α)	Aerosol Climate Change Initiative (Aerosol-CCI)	Dimensionless	1°	1998–2010	http://www.esa-aerosol-cci.org
	SeaWiFS and MODIS Aqua	Dimensionless	9 km	1998–2013	https://oceancolor.gsfc.nasa.gov
	Aerosol-CCI	Dimensionless	1°	1998–2010	http://www.esa-aerosol-cci.org
Sea Surface Temperature (SST)	Woods Hole Oceanographic Institute (WHOI)	°C	1°	1998–2013	http://apdrc.soest.hawaii.edu
U & V wind components	NCEP NCAR	ms^{-1}	2.5°	1998–2013	https://www.esrl.noaa.gov/

**FIGURE 1** | Schematic diagramme showing the methods and analyses used in this work.

be maximum when AOT lagged behind Chl-a concentration. On the other hand, if the oceans were fertilized by aerosols, then Chl-a would lag behind AOT.

The CCF analysis was also carried out between Chl-a concentration and alongshore component of wind speed. If wind-induced upwelling were a causative factor for the increment in Chl-a concentration in the Somalia coast, then we anticipate that the correlation between them would peak when Chl-a lagged behind wind (because of the finite time it takes for phytoplankton to bloom in response to the nutrients brought to the surface by upwelling). Though the alongshore wind speed over the Somalia coast is a fairly good indicator of upwelling strength, we have calculated the Ekman Mass Transport (EMT) as an upwelling index for the analysis. Since a surface signature of upwelling is a decrease of SST in the upwelling zone, we have also taken SST as another proxy for upwelling.

2.2.3. Ekman Mass Transport

For the Somalia region, the alongshore component of the wind stress is favorable for upwelling during summer monsoon season. A positive value for the EMT represents upwelling along the coast of Somalia. The alongshore wind stress for Somalia coast was calculated by the bulk aerodynamic formula from Koracin et al. (2004) as shown in Equation (2):

$$\tau_y = \rho_a \times C_d \times w \times v. \quad (2)$$

where τ_y is the alongshore wind stress; ρ_a is the density of air, which was taken to be 1.2 kg/m^3 ; w is the magnitude of the wind speed; v is the alongshore component of wind speed in m/s; and C_d is the nonlinear drag coefficient based on Large and Pond (1981) and Trenberth et al. (1990) for low wind speeds. So, the EMT along the Somalia coast can be calculated using Equation (3):

$$M_{ev} = \frac{\tau_y}{f}. \quad (3)$$

where, M_{ev} is mass transport by the alongshore wind, f is the Coriolis parameter ($2 \times \Omega \times \sin\phi$), Ω is the angular frequency of the Earth and ϕ is the latitude.

Multiple linear regression analysis with Chl-a as dependent variable and NASA-AOT (or DOT), alongshore wind speed, EMT and SST as independent variables was carried out. We used 8-day composites with lags of 1–2 time steps for this analysis (these lags correspond to the maximum correlation between Chl-a and NASA-AOT data). The analysis was repeated by replacing NASA-AOT with CCI-AOT (or DOT) with a lag of 3 time steps, corresponding to the maximum correlation between Chl-a and CCI-AOT. We have also calculated the 8-day climatologies of all these variables, and plotted against time of year, to study their phase relationships.

2.2.4. Derivation of Dust Optical Thickness (DOT)

The desert dust transported by winds over the ocean contains micronutrients such as iron, which can regulate phytoplankton

activity (Martin et al., 1994; Lenes et al., 2001; Muhs et al., 2007; Donaghay et al., 2015). Since the seasonal monsoon winds bring large quantities of iron-containing dust aerosols to the study area (Li and Ramanathan, 2002; Banerjee and Prasanna Kumar, 2014), we investigated the effect of dust aerosols on Chl-a concentrations. The AE, which is often used as a qualitative indicator of aerosol particle size, and AOT, which indicates the aerosol load, can be used to differentiate dust aerosol from other types of aerosol. Generally, a higher value of AE ($\alpha > 1$) is indicative of fine, submicron aerosols, whereas lower values ($\alpha < 1$) are representative of coarse, super-micron particles (Kaufman, 1993; Gobbi et al., 2007; Yoon et al., 2012). The AOT values are lower for fine aerosols and higher for coarse aerosols. In the literature, different criteria have been proposed to identify dust aerosols at different locations: for example, $\alpha < 0.6$ (Dubovik et al., 2002; Brindley et al., 2015), $\alpha < 0.8$ (Eck et al., 2005; Che et al., 2013), $\alpha < 1$ (Eck et al., 1999; Schuster et al., 2006; Papayannis et al., 2007; Yoon et al., 2012; Valenzuela et al., 2014; Zu et al., 2014; Pakszys et al., 2015) and $\alpha < 1.4$ (Gobbi et al., 2007; Pereira et al., 2011; Shinozuka et al., 2011); similarly, AOT > 0.11 (Toledano et al., 2007; Balarabe et al., 2016), AOT > 0.2 (Salinas et al., 2009; Pakszys et al., 2015) and AOT > 0.25 (Guleria et al., 2012) have been recommended to identify dust aerosols. After considering all these studies, we have adopted the ranges of AOT and AE for off Somalia as follows: AE less than 1, and AOT at 440 nm (τ_{440}) greater than 0.2 (i.e., $\alpha < 1$ and $\tau_{440} > 0.2$) are designated as DOT or dust aerosols. The NASA-AOT at 865 nm (τ_{865}) and NASA-AE were used to calculate NASA-AOT at 440 nm (τ_{440}), using Equation (1). Similarly, CCI-AOT at 550 nm (τ_{550}) and CCI-AE were used to calculate CCI-AOT at 440 nm (τ_{440}), using Equation (1).

3. RESULTS

3.1. Relationship between Chl-a and AOT in the Arabian Sea

The correlation between Chl-a and NASA-AOT using 8-day time series from 1998 to 2013 data for the Arabian Sea is mapped in **Figure 2**. The results are based on data for all the seasons rather than for specific seasons as in Patra et al. (2007) or in Banerjee and Prasanna Kumar (2014). The western Arabian Sea exhibits high positive correlations, whereas the south eastern Arabian Sea shows low to moderate positive correlations. There are also regions (south central) where no statistically-significant correlation is evident and extensive regions (north-central and north-eastern) of significant negative correlations. The region off Somalia shows high positive correlation between Chl-a and NASA-AOT and it is located along the path of winds carrying dust aerosols emanating from South Asia, South-West Asia, North Africa (Sahara) and the eastern Horn of Africa (Pease et al., 1998; Ginoux et al., 2001; Goudie and Middleton, 2001; Prospero et al., 2002; Léon and Legrand, 2003). Although there are several studies (Banzon et al., 2004; Kayetha et al., 2007; Patra et al., 2007; Singh et al., 2008; Nezhlin et al., 2010; Banerjee and Prasanna Kumar, 2014) that have examined the relationship between Chl-a and AOT in various parts of the Arabian Sea, the

region off Somalia has not yet been explored in detail, and it is the region selected for our investigation.

3.2. Climatologies of Chl-a, Aerosols, Winds and SST off Somalia

The 16-year 8-day climatological seasonal cycles of Chl-a concentration, NASA-AOT, CCI-AOT, SST and along-shore wind speed are shown in **Figure 3A**, for the selected study area off Somalia. SST data are reported as anomalies from 8-day average. When the aerosols are identified as dust aerosols, they are indicated in the plot using black and purple filled circles. Out of 46 observations involved in both AOT data sets, for the 8-day climatology, 24 observations were dust aerosols for CCI-AOT data whereas 14 were identified as dust aerosols for NASA-AOT data. It was found that the CCI-AOT data showed the presence of dust aerosols not only during the summer monsoon season, but also during the winter monsoon season. The corresponding climatological wind vectors are shown in **Figure 3B**. During the first 100 days of the year, winds are north easterly, the wind speed decreasing with time. These conditions are unfavorable for upwelling off Somalia. During this period, SST increases steadily by some 3°C. At the same time, the Chl-a concentrations decrease, and AOT also remains low. After this, the winds reverse direction and intensify, resulting in upwelling (indicated by decreasing SST) that favors phytoplankton growth. We note that the initial response of phytoplankton to the intense south westerly winds is a decrease in concentration, perhaps a consequence of the phytoplankton being mixed into deeper layers. After this, the Chl-a increases, with a lag of a couple of time steps behind the increasing wind speed. Both AOT and Chl-a reach their respective maxima during the summer monsoon season.

In **Figure 3A**, the NASA-AOT and Chl-a reach their respective maxima during the summer monsoon season. Although the seasonality of CCI-AOT is more or less similar to that of NASA-AOT, the occurrence of peak values is different. The maximum value for CCI-AOT occurred during early summer monsoon season (Day of Year, DoY 170) while the Chl-a is still increasing, whereas the NASA-AOT peak occurred at DoY 224 during the waning phase of summer monsoon season and after the Chl-a peaks at DoY 216. An interesting feature in the figure is that, towards the peak of the summer monsoon (around DoY 180), when Chl-a concentration reaches $\approx 0.8 \text{ mg m}^{-3}$, there is a brief period when Chl-a continues to increase and leads NASA-AOT by up to 3 time steps until DoY ≈ 220 . However, this feature was not found in CCI-AOT data. Just before the Chl-a peak is reached, the wind speed starts to drop, followed by Chl-a and NASA-AOT, until all variables reach minima toward DoY 300, at which point the wind direction again reverses. SST starts to increase when the south-westerly winds drop, reaching a secondary peak at around DoY 310.

The seasonal patterns are consistent with the known geography of the area. However, there is a tantalizing suggestion in **Figure 3** that when the winds speed are at their highest, and Chl-a levels are high, the NASA-AOT concentrations may be enhanced by maritime aerosols, in addition to the dust aerosols,

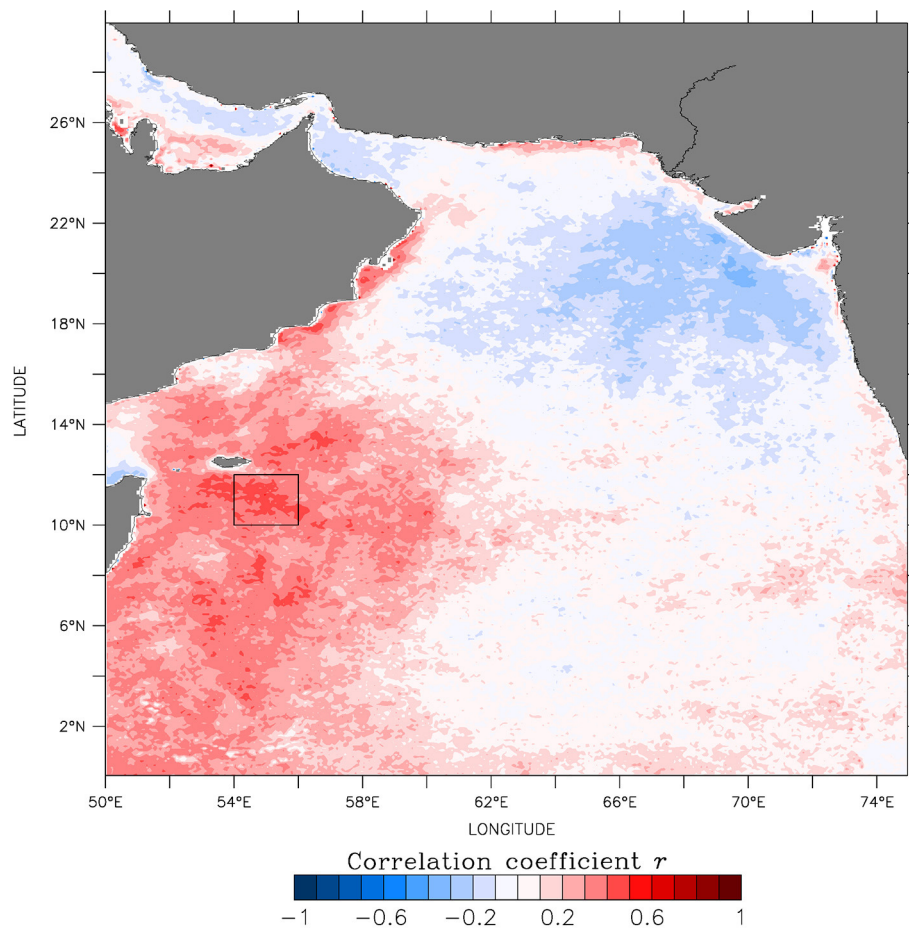


FIGURE 2 | Correlation map between 8-day composited Chl-a and NASA-AOT during 1998–2013 for the Arabian Sea. Pale to dark red shading and pale to dark blue shading represent positive and negative correlation respectively. The black square box off Somalia shows the study area selected for further analyses.

and that some of these aerosols may have a biological origin, as indicated by Chl-a leading NASA-AOT during this period. However, this observation is not supported by CCI-AOT, and in the absence of additional information, it would be premature to conclude that such is the case. But it would be a point worthy of further investigation.

3.3. The Relationship between Chl-a, AOT and DOT off Somalia

Since **Figure 3** indicates that there is a lag in the relationships between Chl-a and the other variables studied here, further analysis has been made for the $2 \times 2^\circ$ box using Cross Correlation Function (CCF) between Chl-a and AOT. The result (**Figure 4A**) shows that the highest significant positive correlation ($r = 0.55$) between Chl-a and NASA-AOT in the study region occurred for Chl-a lagging NASA-AOT by 1 to 2 time steps (1 time step is 8 days). The CCF analysis was also carried out between CCI-AOT and Chl-a and shows a significant positive correlation. Further, the maximum correlation ($r = 0.54$) occurred when Chl-a lagged behind CCI-AOT by 3 time steps (**Figure 4B**). So the analysis using CCI-AOT data confirmed the results obtained

using NASA-AOT on the existence of a significant correlation between Chl-a and AOT in the region off Somalia, the magnitude of the correlation and also the sign of the lag.

The relationship between Chl-a and AOT (or DOT) with lag of 8 days is explored further in **Figure 5** using NASA-AOT (or DOT). Scatter plot between Chl-a and AOT is shown in **Figure 5A**, with the fitted curve and the r value of 0.55 for the fit, consistent with the CCF. However, we recognize that the relationship of maritime and dust aerosols with Chl-a would be functionally different (for example, we do not anticipate that maritime aerosols could fertilize the oceans, whereas it would be plausible with dust aerosols). Dust aerosols are present more frequently during the summer monsoon season because of the favorable wind from adjacent land masses, compared with other seasons. Out of 736 observations over 16 years, around 203 observations were identified as dust aerosols. **Figure 5B** shows the relationship between Chl-a and DOT. We see that there is a general tendency for Chl-a to increase with DOT.

We checked further whether the presence of dust aerosols enhances the Chl-a concentration in the subsequent time steps by calculating the difference in Chl-a ($\Delta\text{Chl-a}$) in 1 time step after

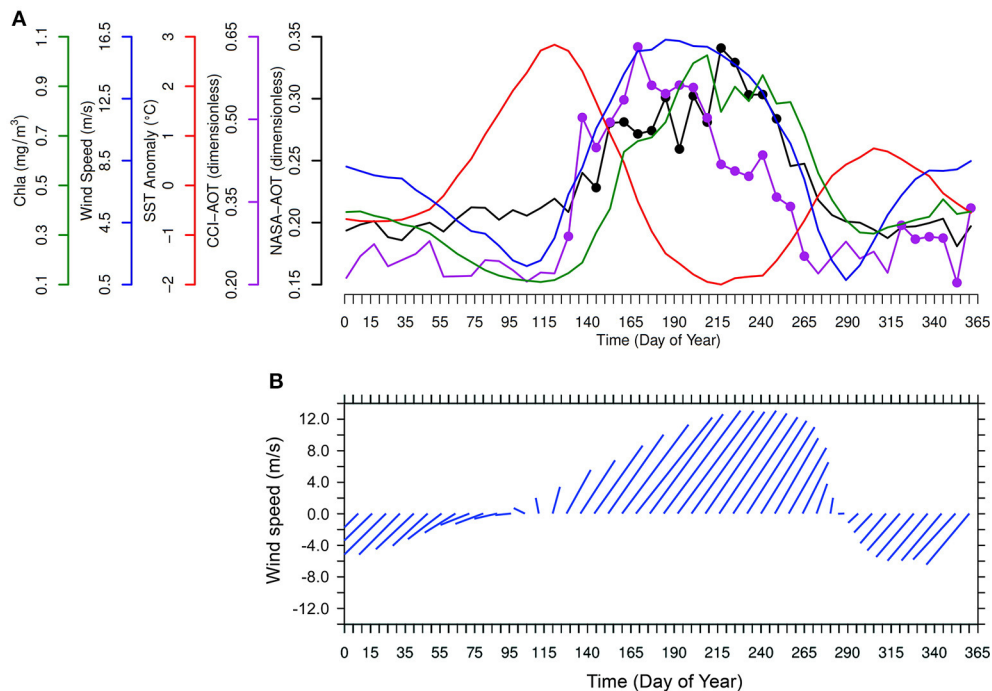


FIGURE 3 | Time series of 8-day climatology, **(A)** for Chl-a, NASA-AOT, CCI-AOT, SST anomaly and Wind speed and **(B)** for the wind vectors. The black and purple coloured dots in the NASA-AOT and CCI-AOT graph denote the presence of dust aerosols.

a dust event, and plotting it against NASA-AOT (**Figure 5C**). The presence of more positive $\Delta\text{Chl-a}$ following high aerosol events would be indicative of a positive effect of aerosols on phytoplankton concentration. The data (**Figure 5C**) show no obvious relationship between aerosols and $\Delta\text{Chl-a}$ either for all aerosols taken together or for dust aerosol events (circles in red colour) by themselves. However, for all the DOT events considered by themselves, the frequency of $\Delta\text{Chl-a}$ is slightly skewed toward positive numbers, with some 114 values being positive out of 203 events (see histogram of $\Delta\text{Chl-a}$, **Figure 5D**). So the probability that Chl-a enhancement is associated with the presence of dust aerosols throughout the year is 56% (114 out of 203), compared with 238 out of 532 in the absence of dust aerosols (45%). The higher number of positive $\Delta\text{Chl-a}$ observations is significant ($p < 0.05$) according to a binomial test. For the non-dust events, there is a higher number of negative values (294) compared with positive values (238) of $\Delta\text{Chl-a}$. These results are summarized in **Table 2**.

We supplemented these calculations after splitting the data according to monsoon (summer monsoon) and non-monsoon seasons, recognizing the differences in oceanographic and meteorological conditions during these two parts of the year (**Table 2**). Out of 224 observations during the summer monsoon season, 140 are dust aerosol events and 84 are non-dust events. Within these 140 dust events, the number of positive $\Delta\text{Chl-a}$ values is 82 (59%), compared with 58 (41%) negative values. However, for non-dust events during this season, we also find more positive $\Delta\text{Chl-a}$ values (58 events, or 69%) than negative

ones (26 events, or 31%). For the non-monsoon season, out of 511 total observations, 448 are non-dust aerosol events and 63 are dust events. Within these non-dust observations, there is higher number of negative values (268, or 60%) when compared with positive values (180 or 40%). But during dust events, the number of positive observations is slightly higher, with 32 (51%) positive values compared with 31 (49%) negative ones. We conclude from all of the above that the probability of Chl-a enhancement during the summer monsoon season does not depend much on the presence or absence of dust aerosols. In other words, during the summer monsoon season, there is a higher probability of finding positive $\Delta\text{Chl-a}$ values, regardless of whether there is a dust event or not. On the other hand, during the rest of the year, the probability of chlorophyll enhancement is a little higher during dust events than during non-dust events.

The analysis was also repeated for CCI-AOT data to verify the above results and is presented in **Table 3**. For this dataset, the probability of Chl-a enhancement is again more in the presence of dust aerosols when the whole year is considered, at 53% (134 out of 251), compared with 142 out of 344 in the absence of dust aerosols (41%). Out of 208 observations during the summer monsoon season, 154 are dust aerosol events and 54 are non-dust events. Within these 154 dust events, the number of positive $\Delta\text{Chl-a}$ values is 83 (54%), compared with 71 (46%) negative values. However, for non-dust events during this season, we also find more positive $\Delta\text{Chl-a}$ values (31, or 57%) than negative ones (23, or 43%). The results from winter monsoon season indicate

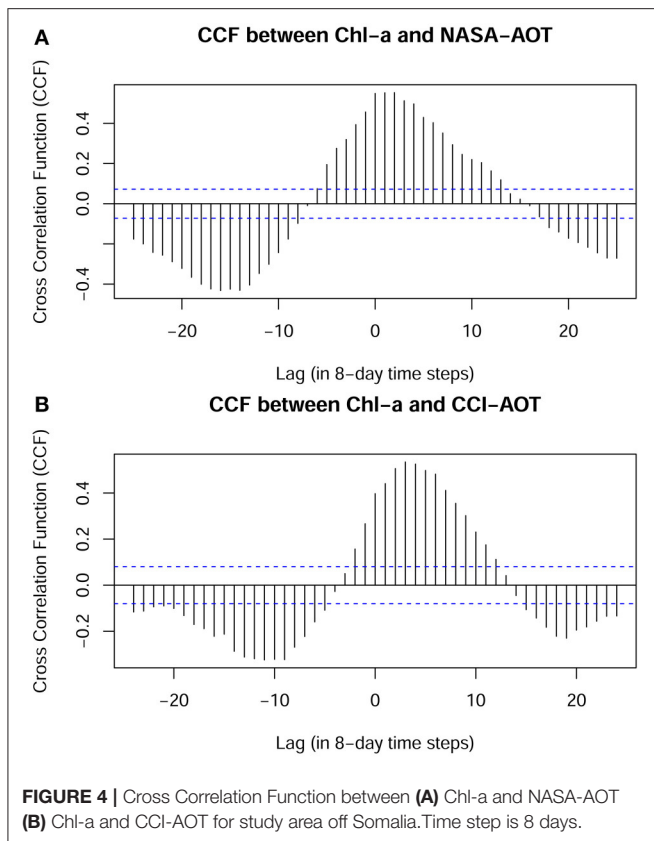


FIGURE 4 | Cross Correlation Function between **(A)** Chl-a and NASA-AOT **(B)** Chl-a and CCI-AOT for study area off Somalia. Time step is 8 days.

that, though the dust aerosol events are fewer in number (49) compared with non-dust (93) within 142 observations, there were more positive $\Delta\text{Chl-a}$ values (28, or 57%) than negative values (21, or 43%) when dust aerosols were present in the region. But, during the absence of dust aerosols, there is a higher number of negative values (48, or 52%) compared with positive values (45 or 48%).

Thus both NASA-AOT and CCI-AOT lead to the conclusion that the probability of Chl-a enhancement during the summer monsoon season does not depend on the presence or absence of dust aerosols. In other words, during the summer monsoon season, there is a higher probability of finding positive $\Delta\text{Chl-a}$ values, regardless of whether there is a dust event or not. On the other hand, during the winter monsoon season and rest of the year, the probability that dust events may be associated with chlorophyll enhancement is higher than that during non-dust periods.

3.4. Relationship of Chl-a with Winds, SST, AOT, and DOT

To elucidate further the relationship between Chl-a and environmental conditions, we next examined the CCF between Chl-a and alongshore wind speed, since it is known that the alongshore winds determine upwelling, and hence influence phytoplankton dynamics in the area (Goes et al., 2005; Gregg et al., 2005; Wiggert et al., 2005; Prasanna Kumar et al., 2010); (see also **Figure 3**). The result (**Figure 6**) shows, similar to the

CCF between Chl-a and NASA-AOT, that the correlation peaks with a lag of 1-2 time steps, with wind speed leading Chl-a, but with a higher correlation coefficient ($r = 0.69$, $p < 0.05$).

Since the correlation coefficients of Chl-a with both aerosols and wind speed peak with a lag of 1-2 time steps, we chose a lag of 1 time step, for a linear step-wise multiple regression study with Chl-a as dependent variable, and NASA-AOT (or DOT), Ekman Mass Transport (EMT), alongshore wind speed and SST as independent variables. The upwelling indices, the wind speed and EMT both show more or less similar correlation with Chl-a. So, we excluded the EMT from the multiple linear regression analysis (but the results from the multiple linear regression including EMT are presented as Table S1). When the correlations with each of the independent variables are considered individually, the highest r^2 values were found for alongshore wind speed ($r^2 = 0.47$) for the ensemble of year-round data, with the corresponding r^2 dropping to 0.17 when dust aerosol events are considered separately (140 dust events during the summer monsoon, and 63 outside of it, totalling 203), followed by SST ($r^2 = 0.33$ and $r^2 = 0.20$ for the same two cases respectively), and then by NASA-AOT ($r^2 = 0.30$ and $r^2 = 0.08$ for the corresponding cases). From the results of pair-wise regression analysis, we see that the addition of NASA-AOT (or DOT) as an independent variable, in addition to wind speed, increases r^2 values by a modest 0.02. With all three variables taken together as independent variables, the explained variance (r^2) is 0.52 for all data, and 0.25 for DOT events (**Table 4**). The results for a lag of 2 time steps (not shown) are similar to those for lag of 1 time step, but with lower correlation coefficients.

The multiple regression analysis was also repeated for CCI-AOT data with Chl-a as dependent variable and CCI-AOT (or DOT), alongshore wind speed and SST as independent variables (**Table 5**). Since the correlation coefficients of Chl-a with CCI-AOT peak with a lag of 3 time steps, we chose a lag of 3 time steps for this analysis. When the correlations with each of the independent variables are considered individually, the highest r^2 values were again found for alongshore wind speed ($r^2 = 0.49$) for year-round data and $r^2 = 0.38$ for dust aerosol events (154 dust events during the summer monsoon, and 97 outside of it, totalling 251) considered separately, followed by SST ($r^2 = 0.32$ and $r^2 = 0.15$ for the same two cases respectively), and then by CCI-AOT ($r^2 = 0.29$ and $r^2 = 0.09$ for the corresponding cases). From the results of pair-wise regression analysis, the addition of CCI-AOT (or DOT) on wind speed as independent variables did not make any improvement in the r^2 value of 0.49. However, a small increase in r^2 value by 0.06 or 0.08 was found when adding CCI-AOT (or DOT) respectively to SST.

4. DISCUSSION

4.1. The Satellite Data Used

Much of the interpretation of results for the region off Somalia depends on the quality of the satellite data used for the analysis, especially during the summer monsoon season, since this is a highly dynamic season, with high winds, high AOT and high Chl-a concentrations. The OC-CCI Chl-a dataset (Sathyendranath et al., 2016) was selected because of the significantly-improved

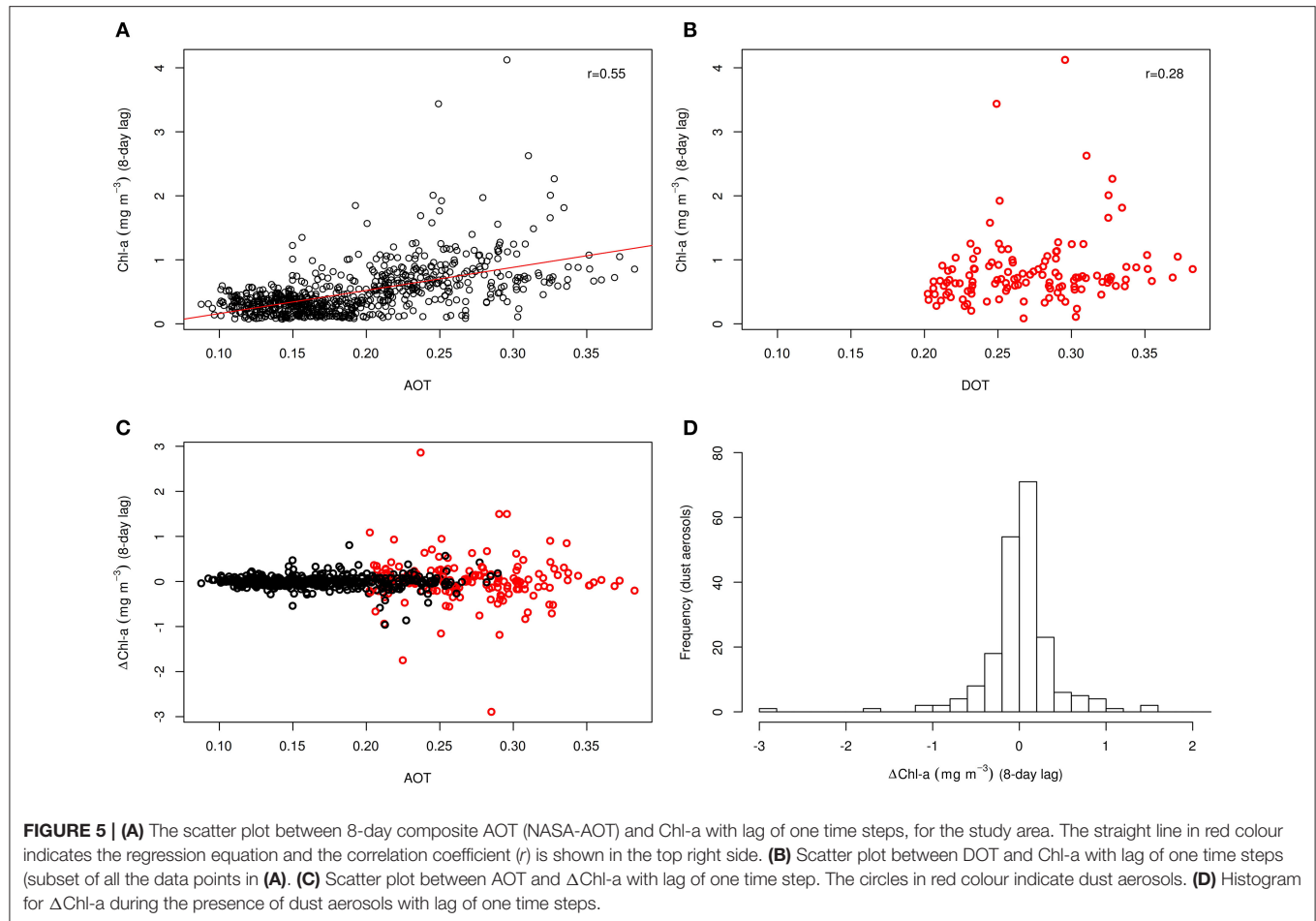


TABLE 2 | The number of observations with enhancements in Chl-a (+ve Δ Chl-a) or reductions in Chl-a (–ve Δ Chl-a), for all data, and for the summer monsoon, for the non-monsoon and sorted according to whether the aerosols were identified as dust or not (here, dust aerosols were derived from NASA-AOT data).

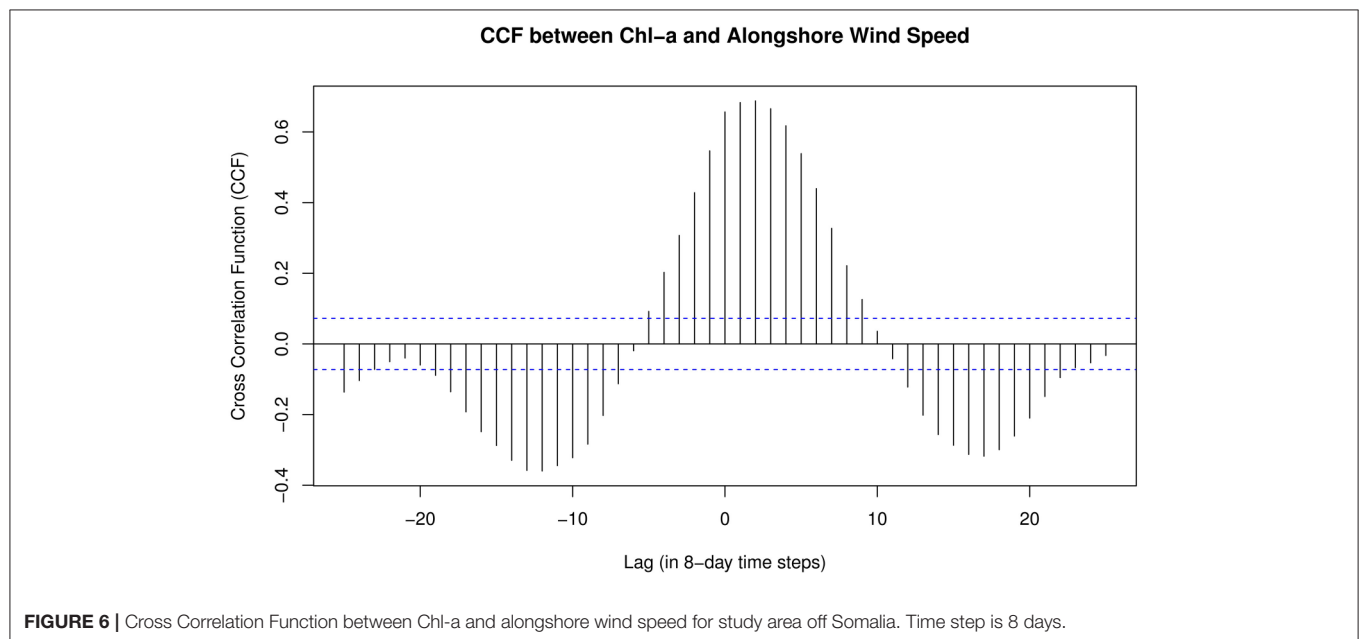
Dust + non-dust, All seasons		Dust, All seasons		Non-dust, All seasons		Dust + non-dust, Summer monsoon season		Dust, Summer monsoon season		Non-dust, Summer monsoon season		Dust + non-dust, Non-monsoon season		Dust, Non-monsoon season		Non-dust, Non-monsoon season	
TOTAL NUMBER OF OBSERVATIONS																	
735		203		532		224		140		84		511		63		448	
NUMBER OF POSITIVE AND NEGATIVE ΔChl-a VALUES																	
+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve
352	383	114	89	238	294	140	84	82	58	58	26	212	299	32	31	180	268
PERCENTAGE OF POSITIVE AND NEGATIVE ΔChl-a VALUES																	
48	52	56	44	45	55	62	38	59	41	69	31	41	59	51	49	40	60

seasonal coverage that the data provide in the study area, compared with other datasets, especially during the summer monsoon season. But it is important to reassure ourselves that the data are of sufficient quality for the analysis presented. Though the OC-CCI data have been validated using a global dataset as part of the project, and also for the neighboring Red Sea

(Brewin et al., 2015) and the Gulf of Aden (Gittings et al., 2016), we do not have *in situ* data from off Somalia region for local validation. However, the data are reassuring in some respects: the first one is that, if the relationship between Chl-a and AOT were an artifact of the processing, then one would anticipate that the relationship would peak at zero lag. In fact, we see

TABLE 3 | The number of observations with enhancements in Chl-a (+ve $\Delta\text{Chl-a}$) or reductions in Chl-a (–ve $\Delta\text{Chl-a}$), for all data, and for the summer monsoon, for the winter monsoon and sorted according to whether the aerosols were identified as dust or not (here, dust aerosols were derived from CCI-AOT data).

Dust + non-dust, All seasons		Dust, All seasons		Non-dust, All seasons		Dust + non-dust, Summer monsoon season		Dust, Summer monsoon season		Non-dust, Summer monsoon season		Dust + non-dust, Winter monsoon season		Dust, Winter monsoon season		Non-dust, Winter monsoon season	
TOTAL NUMBER OF OBSERVATIONS																	
595		251		344		208		154		54		142		49		93	
NUMBER OF POSITIVE AND NEGATIVE ΔChl-a VALUES																	
+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve	+ve	−ve
276	319	134	117	142	202	114	94	83	71	31	23	73	69	28	21	45	48
PERCENTAGE OF POSITIVE AND NEGATIVE ΔChl-a VALUES																	
46	54	53	47	41	59	55	45	54	46	57	43	51	49	57	43	48	52



that, typically, the maximum correlation occurred with a lag, suggesting a functional relationship between the two variables, rather than an artifact. The second is that the seasonal patterns in Chl-a are consistent with the known oceanography of the area, and appear as a consequence of the seasonal changes in the oceanographic conditions, as indicated by the winds and SST. The AOT and AE data from both NASA and CCI also show seasonal changes with high AOT values and low AE during summer monsoon season and vice versa for the rest of the year.

We have used aerosol data from the NASA ocean colour web site, partly to reassure ourselves that the aerosol and Chl-a products that are outputs of the same processing chain do not show inter-dependencies associated with the assumptions that underlie the processing. In the OC-CCI processing version-2 used here, SeaWiFS and MODIS-Aqua data were processed using NASA's SeaDAS software, consistent with the processing chain that generated the aerosol products at the NASA ocean colour

website. That the analysis presented here has indicated that the patterns in Chl-a and in the aerosol properties are consistent with the known oceanography of the study area, and that the correlations vary with region (Figure 2) as oceanographic and meteorological conditions change, lends some confidence to the quality of the data, in the absence of direct validation data. To further substantiate the application of satellite data to studies of relationship between aerosol and phytoplankton, Aerosol-CCI data sets were also subjected to identical analysis and the data confirmed our findings.

4.2. Aerosols and Phytoplankton in the Western Arabian Sea off Somalia

There have been a few previous studies that dealt with the influence of aerosols on phytoplankton dynamics in the Arabian Sea. A recent study (Banerjee and Prasanna Kumar, 2014) has shown that episodic dust storms could generate phytoplankton

TABLE 4 | Results of multiple linear regression analysis with Chl-a as the dependent variable and NASA-AOT or DOT, alongshore wind speed and SST as independent variables for 1 time step lag.

NASA-AOT	DOT	Wind	SST	N	r^2	Adj. r^2	r
+	–	+	+	735	0.52	0.52	0.72
+	–	–	–	735	0.30	0.30	0.55
–	–	+	–	735	0.47	0.47	0.69
–	–	–	+	735	0.33	0.33	0.57
+	–	+	–	735	0.49	0.49	0.70
+	–	–	+	735	0.46	0.46	0.68
–	–	+	+	735	0.50	0.49	0.71
–	+	+	+	203	0.25	0.24	0.50
–	+	–	–	203	0.08	0.07	0.28
–	–	+	–	203	0.17	0.17	0.41
–	–	–	+	203	0.20	0.19	0.45
–	+	+	–	203	0.19	0.18	0.44
–	+	–	+	203	0.22	0.21	0.47
–	–	+	+	203	0.24	0.24	0.49

Number of observations (N), r^2 , adjusted r^2 and r are shown, for each of the analyses and they are statistically significant ($p < 0.05$). The first set of calculations with 735 observations is for the whole year. The second set, with 203 observations, is for the dust aerosol events. Plus signs indicate variables that were used, and minus signs indicate variables that were excluded in each analysis.

blooms in the central Arabian Sea during the winter monsoon. Nezhlin et al. (2010) reported a correlation between Chl-a and aerosols when studying inter-annual variations in the Persian Gulf area. Prasanna Kumar et al. (2010) reported an increasing trend in phytoplankton in the central Arabian Sea during winter months of 1997–2007, and attributed it to increasing supply of iron by dust aerosols. Singh et al. (2008) studied a series of dust storms in the northern Arabian Sea during a 3-year period, and reported chlorophyll enhancement within 1–4 days of dust events, but also pointed out other mechanisms that might be responsible for the relationship observed.

Our results for the western Arabian Sea off Somalia indicate only a possible minor role for dust aerosols enhancing Chl-a concentration during the summer monsoon, supplementing the major role of alongshore winds inducing upwelling favorable for phytoplankton growth. The upwelling component of winds off Somalia during summer monsoon season appears to be far stronger than the classic eastern coastal upwelling zones in the world ocean (Bakun et al., 1998). In the data used here, the wind speed was greater than 15 m/s during summer monsoon season over the Somalia coast. Recently, deCastro et al. (2016) studied the evolution of Somali coastal upwelling under future warming scenarios using models. When the intensity of Somali coastal upwelling during summer monsoon season was projected for the twenty first century, the trends showed that changes in coastal upwelling were mainly related to the wind-induced Ekman transport. Further, our findings are consistent with those of Gallisai et al. (2014) for the Mediterranean: they concluded that the main driver of phytoplankton dynamics is the supply of nutrients from the deep water to the surface layers through

TABLE 5 | Results of multiple linear regression analysis with Chl-a as the dependent variable and CCI-AOT or DOT, alongshore wind speed and SST as independent variables for 3 time step lag.

CCI-AOT	DOT	Wind	SST	N	r^2	Adj. r^2	r
+	–	+	+	595	0.49	0.49	0.70
+	–	–	–	595	0.29	0.29	0.54
–	–	+	–	595	0.49	0.49	0.70
–	–	–	+	595	0.32	0.32	0.57
+	–	+	–	595	0.49	0.49	0.70
+	–	–	+	595	0.38	0.38	0.62
–	–	+	+	595	0.49	0.49	0.70
–	+	+	+	251	0.39	0.38	0.62
–	+	–	–	251	0.09	0.09	0.30
–	–	+	–	251	0.38	0.38	0.62
–	–	–	+	251	0.15	0.15	0.39
–	+	+	–	251	0.38	0.38	0.62
–	+	–	+	251	0.23	0.22	0.48
–	–	+	+	251	0.38	0.38	0.62

Number of observations (N), r^2 , adjusted r^2 and r are shown, for each of the analyses and they are statistically significant ($p < 0.05$). The first set of calculations with 595 observations is for the whole year. The second set, with 251 observations, is for the dust aerosol events. Plus signs indicate variables that were used, and minus signs indicate variables that were excluded in each analysis.

vertical mixing. However, the results of the multiple regression presented here do not necessarily imply that the effect of aerosols on Chl-a is only 2%, but only that, because AOT covaries with the other variables, especially wind speed, it is difficult to disentangle their individual effects on Chl-a concentration. Perhaps more interesting is the possibility that the effect of dust events on Chl-a enhancement might be a little stronger during the winter monsoon season and rest of the year than during the summer monsoon season (Tables 2, 3), consistent with the results of Prasanna Kumar et al. (2010) for the central Arabian Sea during winter monsoon season. The direction of the winds during the winter monsoon would suggest an origin in the Asian subcontinent for these dust aerosols, rather than the Arabian peninsula.

We used the cross correlation function to study the phase relationship between aerosol (AOT) and phytoplankton (Chl-a) dynamics. The correlation between the two variables peaked at a lag of 1–2 time steps, with AOT leading. However, since a similar lag was found in the CCF between Chl-a and alongshore winds, it is difficult to attribute a causal relationship to the aerosols by themselves. The phase relationship also throws light on whether or not the biological particles might be enhancing the production of aerosols in the study area. If such events were commonplace, then one would expect that Chl-a enhancement might occur prior to increase in aerosol concentration. The CCF results do not support this in general, but the climatologies of the studied variables (Figure 3A) do show that there is a reversal in the phase relationship for a brief period, with Chl-a leading NASA-AOT when Chl-a concentration approaches its peak during the summer monsoon season. However, this result

is not confirmed by CCI-AOT data. Thus, conclusive evidence for biological enhancement of aerosols remains elusive. The intriguing result with the NASA-AOT certainly merits further investigation.

5. CONCLUDING REMARKS

Essential Climate Variables, or ECVs, are our sentinels for observation of climate change. However, to understand climate change, it is not sufficient to study individual ECVs in isolation. Instead, it is also important to study how they interact with each other, and to understand how these interactions might change in the future. Of the marine ECVs, Chl-a concentration is the only biological ECV that is currently amenable to routine observations by remote sensing.

In this paper, we have examined one piece of the puzzle, by studying how the variability of Chl-a in the western Arabian Sea is related to those in three other ECVs: aerosols, winds and SST, focussing more on aerosol-Chl-a interactions, using 16 years of satellite data. What emerges is a complex pattern of relationships, in an area where many ECVs co-vary with each other. While it is difficult to elucidate causal relationships from simple correlations, the phase relationships between the variables can throw some light on the underlying causes.

A question that had to be addressed first, when using satellite data for the analysis, was whether there were artifacts in the patterns in Chl-a, introduced by the atmospheric correction process, which depends to some extent on aerosol optical properties. The correlation between Chl-a and NASA-AOT (a by-product of ocean colour processing) peaking with a lag provided reassurance on this point, since the peak should have been observed at zero lag had processing artifacts been the cause of the correlation. This point was reinforced by repeating the analysis with data from Aerosol-CCI products, which are derived independently of the ocean colour processing chain.

Though the NASA aerosol properties and the CCI aerosol properties are generally consistent with each other, there is a significant phase shift in the time when they peak during the summer monsoon season. The underlying causes for this difference deserve to be investigated further, but fall outside

the scope of this paper. In the Somali region, under upwelling regimes, the Chl-a concentration is strongly correlated with wind. Analysis of Ekman Mass Transport supports the hypothesis that wind-induced upwelling is the underlying cause of the high correlation between wind and Chl-a. According to the linear multiple regression analysis, aerosols have a modest effect on Chl-a, at best, with a lag of one to two time steps during this period. An unexpected outcome from this study is related to the importance of dust aerosols in stimulating Chl-a enhancement during the winter monsoon season, suggesting that the abundance of dust aerosols might enhance Chl-a in the absence of wind-induced upwelling.

AUTHOR CONTRIBUTIONS

MS carried out all the data analyses and produced the figures. MS and SS wrote the manuscript. SS conceived the scientific plan, with help from TP. TP provided scientific advice, and led the project. GG contributed to the planning and discussions, and along with AB, provided supervision.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2017.00386/full#supplementary-material>

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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