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Response of surface chlorophyll to aerosol dust input in the Central Arabian Sea

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The decadal trends in satellite-derived surface chlorophyll in conjunction with Aerosol Optical Depth (AOD) are explored in a unique area in the central Arabian Sea, known to mimic High Nutrient and Low Chlorophyll (HNLC) like conditions during late summer monsoon. The analysis indicates two recurring seasonal blooms, possibly associated with distinct biogeochemical processes in the studied region. Furthermore, the mineral dust deposition in July every year coincides with one such increase in surface chlorophyll followed by a lag period until winter monsoon. This rapid increase in the phytoplankton biomass just after the aeolian input is possibly due to an enhancement in soluble iron within the mixed layer, as suggested by AOD dust data. Most likely, this rapid increase in biomass may induce further depletion of soluble iron leading to HNLC-like conditions during the late Summer Monsoon, as reported earlier. This hypothesis is consistent with the satellite observation, which shows a decrease in surface chlorophyll during subsequent months until the convective mixing between December – January (winter monsoon). The study reveals that the presence of the HNLC region in the central Arabian Sea during the summer monsoon is not perennial like the Southern Ocean. Instead, it is a transient phenomenon primarily controlled by aerosol deposition and rapid uptake of soluble iron, which facilitate the diatom blooms as suggested by the recent output from the NASA Ocean Biogeochemical Model (NOBM).

[**Keywords**: Aerosol, Arabian Sea, Chlorophyll, Summer monsoon]

Introduction

The Arabian Sea undergoes seasonally reversing surface circulation[1-3] with strong upwelling along the east coasts of North Africa and Arabia and the southwest coast of India during the summer monsoon and convective mixing during winter[4]. These two physical processes enhance biological production in the Arabian Sea[5,6]. Primary production in the Arabian Sea is chiefly controlled by the availability of macronutrients, especially nitrate[7,8]. The iron (Fe) concentrations were never reported limiting[9]. However, Moffett *et al.*[10] observed iron concentrations close to the detection limit in conjunction with high nutrients in the central Arabian Sea during the late southwest monsoon (August), which led to the proposed High Nutrient and Low Chlorophyll (HNLC) hypothesis[11]. Mineral dust is an essential source of iron in the open ocean leading to elevated mixed layer concentrations once dissolved[12]. Iron is a vital micronutrient for phytoplankton because of its presence in different enzymes influencing redox transformations, including nitrogen fixation by organisms such as *Trichodesmium*[13]. If such pockets of HNLC regions exist in the Arabian Sea, a feature similar to the Southern Ocean[14,15], it will add a new dimension to the ongoing research in this region.

The decadal trends in surface chlorophyll in tandem with the aerosol input and mineral dust were studied in the region between 63° E – 65° E and 14° N – 16° N, which showed below-detectable iron during the late summer monsoon[10,11]. Aerosol data from the U.S. Joint Global Ocean Flux Study (US JGOFS) revealed significant deposition occurring twice in this region[16]. The period of high accumulation is mainly in July (early summer monsoon), followed by a marginal increase during winter monsoon (December – January)[16,17]. The above-studied region is located ~ 400 km offshore therefore, it is expected that any trend in the satellite data observed is presumably driven by natural processes, as signatures of anthropogenic perturbation will be low.

This article deals with the decadal changes in surface chlorophyll and its relation with dust input from a unique region in the central Arabian Sea. Further, an attempt is made to understand the processes involved in the formation of such HNLC areas in this region. The output data of the NASA Ocean Biogeochemical Model (NOBM) is employed to validate if the model simulations are consistent with the proposed hypothesis.

Materials and Methods

An assimilated product of surface chlorophyll from the SeaWiFS (Sea-Viewing Wide Field-of-View Sensor) and Moderate Resolution Imaging Spectroradiometer (MODIS) for the central Arabian Sea from 1998 to 2012 was analyzed to understand the temporal trends within a grid from 63° E to 65° E and 14° N to 16° N (Fig. 1). Monthly aerosol optical depth at 510 nm (SWDB_L3M05: SeaWiFS Deep Blue Aerosol Optical Depth and Angstrom Exponent Monthly Level 3 Data Gridded at 0.5 Degrees V004) from SeaWiFS (till 2010) was processed using the online tool Giovanni-4 (Geospatial Interactive Online Visualization And Analysis Infrastructure, Version 4) at https://giovanni.gsfc.nasa.gov/giovanni/, to interpret the seasonal trends in dust deposition over the study location from 1998 to 2010.

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) retrievals of the altitude profiles of aerosol extinction coefficient (α)

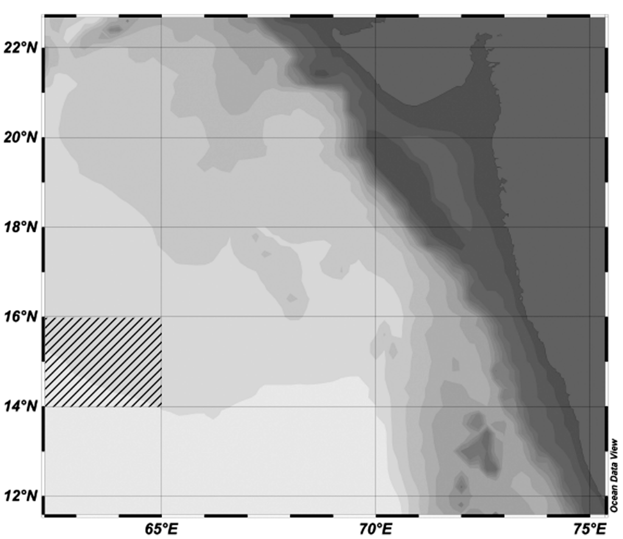

Fig. 1 — Shaded grid highlights the studied area for analysis of the temporal trends in surface chlorophyll and phytoplankton groups, AOD, SST, MLD and modelled derived soluble iron

and Volume Depolarization Ratio (VDR) along the sub-satellite track since June 2006[ref. 18], provides an opportunity to quantitatively investigate the vertical distribution of aerosols over this region, and assess the role of different mechanisms in the genesis of the observed abnormalities in aerosol loading. VDR is an indicator of the non-sphericity of aerosols and can be applied to clearly distinguish the highly non-spherical mineral dust from other aerosol types. Hence, α and VDR from CALIPSO have been implemented to infer dust aerosol loading in the atmosphere[17,19]. Level 3 dust Aerosol Optical Depth (AOD; AOD_{DUST}) from CALIPSO is used to examine inter-annual variations and trends of dust loading over the study region.

Further, the dataset derived from the most recent model run of the NOBM was studied, to decipher its consistency with the satellite observations. The model provides daily to monthly assimilated concentrations of four phytoplankton functional groups, iron and nitrate concentrations and mixed-layer depth. NOBM is a comprehensive, interactive ocean biogeochemical model coupled with the circulation and radiative model of the global oceans[20]. It spans the domain n from 84° to 72° latitude in increments of 1.25° longitude by 2/3° latitude, including only open ocean areas where bottom depth > 200 m. NOBM contains four phytoplankton groups, four nutrient groups, a single herbivore group, three detrital pools and the major ocean carbon components: Dissolved Organic and Inorganic Carbon (DOC and DIC) as detailed here (https://gmao.gsfc.nasa.gov/products/documents/NOBM_Readme-20120606.pdf).

The NOBM has been extensively validated[20], involving a comparison of 9 of the 14 model state variables against *in-situ* and/or satellite data sets, excluding three detrital components and DOC, which we have not discussed here. The model contains four explicit phytoplankton taxonomic groups: diatoms, cyanobacteria, chlorophytes and coccolithophores. As with nutrients and total chlorophyll, the phytoplankton groups in the model have been substantiated against *in-situ* data[21]. The model output has been verified for understanding the global trends in ocean phytoplankton and corrected for its inherent bias, making it useful for such studies[21].

Ocean surface mixed layer depth was derived using the online visualization tool provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/) to discern the changes in the Mixed Layer Depth (MLD) between early and peak winter monsoon periods. Monthly composite images of chlorophyll and Sea Surface Temperature (SST) were prepared using the MODIS (http://daac.gsfc.nasa.gov/giovanni) online visualization tool to comprehend the interannual changes which are developed and maintained by the NASA GES DISC.

Results

Average surface data with range and variability encompassing the geographic location between 63° E – 65° E and 14° N – 16° N from 1998 to 2012 is presented in Table 1. Monthly variations in AOD_{DUST} over the Arabian Sea (13° – 17° N and 60° – 65° E) from June 2006 to December 2016 are illustrated in Figure 2, and the variability of total aerosol loading (columnar) at 510 nm at a 0.5-degree interval from 1998 to 2010 is depicted in Figure 3a.

The region receives a high influx of mineral dust in July each year, followed by a lag period and a marginal increase during late December (Fig. 2). Total aerosol loading exhibited four sizable episodic events during 2000, 2003, 2007 and 2009, with AOD > 0.8 at the sampling locations (Fig. 3a).

Table 1 — The interannual average and the ranges of different surface oceanographic parameters from 1998 to 2012 from satellite data and NOBM model output

Parameter	Average	Range	SD
SST (°C)	26.73	24.95 – 29.92	± 1.27
MLD (m)	42	11 – 97	± 23
NOBM Iron (nmol)	1.52	1.04 – 2.08	± 0.21
Chl-*a* (mg m^{-3})	0.184	0.050 – 0.680	± 0.077
Diatoms (mg m^{-3})	0.031	0.000 – 0.209	±0.050

The modest dust loading observed between 2010 – 2012 is presumably due to ENSO activity (https://ggweather.com/enso/oni.htm). Banerjee & Kumar[22] propounded that in the years following the La Niña event, enhanced dust transport by the low-level southwesterly winds and higher-level westerly winds was the main factor contributing to the elevated dust levels over the Arabian Peninsula, which is in line with the spike observed in 2013.

Further, this data was superimposed on remotely sensed chlorophyll extending up to 2012 to understand the interrelationships. Interestingly, most of the seasonal increase in AOD in July is trailed by a peak in surface chlorophyll during early August, which declines subsequently until a similar surge in December. The increase in chlorophyll during the early summer monsoon (August) is within 0.3 – 0.4 mg m^{-3} (Fig. 3a). A similar enhancement is observed during December (winter monsoon) in tandem with the deepening of the mixed layer. Some of the highest chlorophyll values observed within the time series data corresponding to the early southwest monsoon (*i.e.* 0.68 mg m^{-3}) were seen in 2009 and contributed mostly by diatoms, according to the NOBM model (Fig. 3b). According to the model data, the diatoms nearly contributed half of the total chlorophyll as noticed from satellites and followed the chlorophyll trend.

The monthly SST and MLD variability for the location, from January 1998 to November 2012, is plotted to understand the MLD and nutrient entrainment from the deep-water during southwest

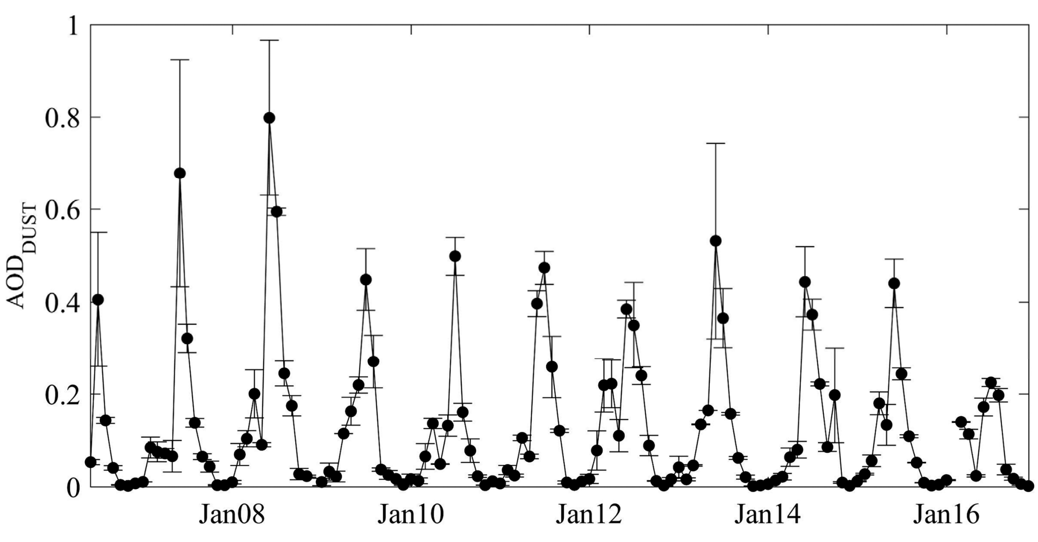

Fig. 2 — Monthly mean values of dust AOD (AOD_{DUST}) over the Arabian Sea (13° – 17° N and 60° – 65° E) during the period from Jun 2006 – Dec 2016. The figure exhibits a decadal trend in dust aerosols over the study region

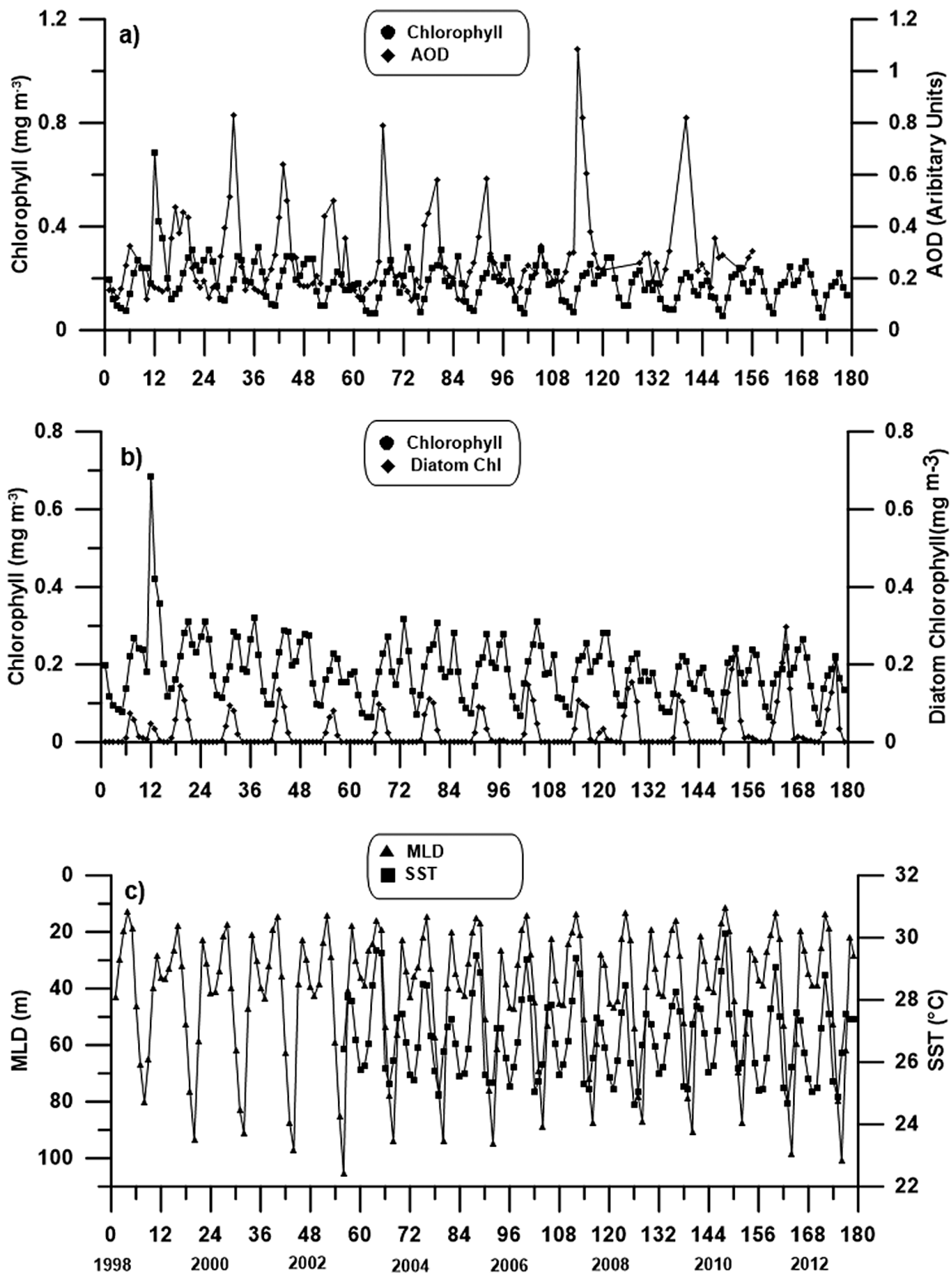

Fig. 3 — Exhibits the temporal trends in a) AOD and chlorophyll; b) Chlorophyll and NOBM modelled diatoms; and c) SST and MLD

and winter monsoon, based on assimilated data from NOBM (Fig. 3c). It is evident that the deepest MLD was associated with the summer monsoon with a range of 70 – 100 m trailed by a shallower MLD during the winter monsoon (Fig. 3c). The lowering of SST contributed to the deep mixing as observed in the data sets (Fig. 3c). Both SST and MLD show a monthly and interannual trend.

Discussion

Although the prevalence of the HNLC region in the central Arabian Sea is proposed recently, the underlying processes remain poorly investigated[10,11,21]. The decadal analysis of AOD_{DUST} highlights significant deposition in the studied region during the early summer monsoon (Fig. 2). This observation is consistent with the past study[17]. The present study reveals a significant amount of surface chlorophyll each year, coinciding with the early summer monsoon (August) in tandem with dust episodes. However, it is followed by a lag period until winter monsoon, which indicates something limiting. Since the MLD is supposed to be deep enough during summer monsoon, a continuous recharge of nutrients from the deeper layer is expected (Fig. 3c). Moffet *et al.*[10] reported the maxima in Fe (II) located at 200 – 250 m at this region. Our analysis suggests this is far beyond the mixing depth observed during the summer monsoon therefore, recharge of soluble iron from deeper depth is presumably negligible if not upwelled.

Moreover, it is plausible that the increase in surface chlorophyll during August after the dust episode leads to rapid biological uptake of dissolved Fe (DFe). It is proposed that with a rapid biological uptake in combination with negligible recharge from the deeper layers and less mineral dust in the atmosphere during September, the studied region becomes iron deficient (Fig. 2). However, a marginal increase in surface chlorophyll is seen during winter monsoon. It is consistent with the earlier hypothesis where low productivity in the region is attributed to the low dissolved iron in the water column[10,11]. The available data sets of the dissolved Fe (DFe) from the Arabian Sea are presented in Table 2. Although a study Measures & Vink[9] reports significant DFe in July however, the latest data sets from the GEOTRACES-India initiative published in 2022 show low DFe in the central Arabian Sea during September – October[22]. This difference may be linked with biological uptake, as corroborated by the annual increase in surface chlorophyll in August, but to delineate more data sets are required. Lately, a significant difference in the soluble iron content in the mineral dust is observed, with the Arabian Sea receiving coarse dust from the desert region compared to the Bay of Bengal. The transport of alluvial dust in the Bay of Bengal from the Indo-Gangetic plain is found to have more soluble iron compared to the adjacent basin[23]. However, at present, a detailed discussion on their influence on ocean productivity is beyond the scope of the present manuscript.

Dust is an essential source of iron on the ocean surface, which can often vary temporally and spatially. Several studies have displayed that the nutrients and micronutrients from the atmosphere can impact biogeochemical cycles and biological productivity in coastal and open ocean surfacewaters[22-24]. Here, the NOBM phytoplankton data set is explored to deduce the long-term trend in community dynamics in the studied region. The model has been extensively validated with the available in situ data and hence, employed to test the proposed hypothesis. The increase in surface chlorophyll is consistent with the surge in the diatom populations, which hints that dust input possibly catalyzes the growth of larger phytoplankton in this region. The relation between total AOD columnar and model iron with surface chlorophyll was investigated, which is illustrated in Figure 4. Apparently, the relationship between AOD and surface chlorophyll is poor with a large scatter. Similar relationships between other macronutrients and chlorophyll from the Arabian Sea have also been reported to be poor[25,26]. The model iron and surface chlorophyll show significant positive linear relations advocating the enhancement of surface chlorophyll in the presence of iron. However, modelled observation should be carefully evaluated for such a conclusion. In addition, the current study implies that the presence of the HNLC region in the central Arabian Sea is not a perennial but a transient phenomenon mainly regulated

Table 2 — Reports of historical and newly published data sets of surface dissolved iron concentrations from the Arabian Sea

S. No	Study area	Location	Time period	DFe (nM)	References
1	Western Arabian Sea	22° – 12° N, 57 – 62° E	Sept – Oct	0.49 ± 0.26	Chinni & Singh[27]
2	Eastern Arabian Sea	17° – 15° N, 69 – 75°E	Sept – Oct	1.04 ± 0.46	Chinni & Singh[27]
3	Central Arabian Sea	22° – 17° N, 65° E	Sept – Oct	0.48 ± 0.12	Chinni & Singh[27]
4	Central Arabian Sea	17° – 5° N, 65° E	April – May	0.22 ± 0.10	Chinni & Singh[27]
5	Central Arabian Sea	18° – 10° N, 68° E	Dec – Jan	Range: 0.15 – 0.30	Nishioka *et al.*[28]
6	Arabian Sea	24° – 10° N, 56 – 65° E	Mar – April	0.98 ± 0.34	Measures & Vink[9]
7	Arabian Sea	24° – 10° N, 56 – 65° E	Jul – Aug	1.31 ± 0.51	Measures & Vink[9]
8	Arabian Sea	24° – 10° N, 56 – 65° E	Oct – Nov	1.05 ± 0.40	Measures & Vink[9]
9	Arabian Sea	22°30’ N – 7°30’ N, 65° E	Dec – Jan	Range: 0.15 – 0.47	Takeda *et al.*[29]
10	Western Equatorial Indian Ocean	5° N – 5° S, 57 – 59° E	Sep – Oct	0.34 ± 0.14	Chinni & Singh[27]

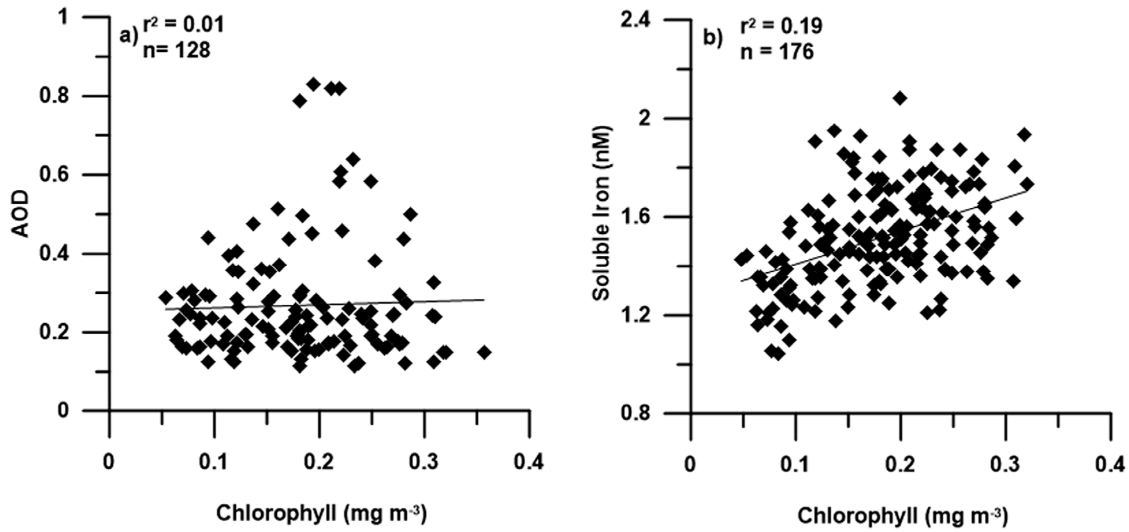

Fig. 4 — Shows the relationships observed between columnar a) AOD; and b) NOBM-derived soluble iron with satellite chlorophyll

by dust deposition and diatom uptake, followed by negligible recharge of soluble iron from deeper depths as the subsurface Fe (II) maxima resides below the mixed layer.

Conclusion

The present study examines the decadal trends in AOD and satellite-derived surface chlorophyll from the central Arabian Sea. It is noticed that annual dust deposition in July leads to a significant rise in surface chlorophyll in the studied region. It is presumably related to mineral dust deposition and bioavailability of soluble iron, which triggers rapid uptake by larger phytoplankton as suggested by NOBM. However, as the subsurface Fe (II) maxima reside at greater depths than the mixed layer, entrainment of bioavailable iron does not occur until any possible dust event, thereby limiting phytoplankton growth leading to HNLC-like characteristics for a transient period during late summer monsoon.

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Conflict of Interest

The authors declare no competing or conflict of interest.

Ethical Statement

This is to certify that the reported work in the paper entitled “Response of surface chlorophyll to aerosol dust input in the Central Arabian Sea” submitted for publication is an original one and has not been submitted for publication elsewhere. I/we further certify that proper citations to the previously reported work have been given and no data/table/figure has been quoted verbatim from other publications without giving due acknowledgement and without the permission of the author(s). The consent of all the authors of this paper has been obtained for submitting the paper to the “Indian Journal of Geo-Marine Sciences”.

Author Contributions

Conceptualization: RR, SP & AL. Data curation: RR & PSS. Formal analysis: RR, SP, AL & PSS. Project administration: SBC. Manuscript writing: RR. Manuscript reviewing & editing: RR & AL.

References

1 Banse K, Hydrography of the Arabian Sea shelf of India and Pakistan and effects on demersal fishes, *Deep-Sea Res Oceanogr Abstr*, 15 (1) (1968) 45-79.

2 Schott F A & Julian P M Jr, The monsoon circulation of the Indian Ocean, *Prog Oceanogr*, 51 (1) (2001) 1-123.

3 Shankar D, Vinayachandran P N & Unnikrishnan A S, The monsoon currents in the north Indian Ocean, *Prog Oceanogr*, 52 (1) (2002) 63-120.

4 Madhupratap M, Kumar S P, Bhattathiri P M A, Kumar M D, Raghukumar S, *et al.*, Mechanism of the biological response to winter cooling in the northeastern Arabian Sea, *Nature*, 384 (6609) (1996) 549-552.

5 Banse K, Seasonality of phytoplankton chlorophyll in the central and northern Arabian Sea, *Deep-Sea Res Part A, Oceangr Res Paper*, 34 (5-6) (1987) 713-723.

6 Naqvi S W A & Jayakumar D A, Ocean biogeochemistry and atmospheric composition: Significance of the Arabian Sea, *Curr Sci*, 78 (3) (2000) 289-299.

7 Barber R T, John M, Robert C B, Louis A C, David H, *et al.*, Primary productivity and its regulation in the Arabian Sea during 1995, *Deep-Sea Res Part II: Topical Studies in Oceanogr*, 48 (6-7) (2001) 1127-1172.

8 Naqvi S W A, Naik H, Pratihary A K, DeSouza W, Narvekar P V, *et al*., Coastal versus open-ocean denitrification in the Arabian Sea, *Biogeosciences*, 3 (2006) 621-633.

9 Measures C I & Vink S, Seasonal variations in the distribution of Fe and Al in the surface waters of the Arabian Sea, *Deep-Sea Res Part II: Topical Studies in Oceanogr*, 46 (8-9) (1999) 1597-1622.

10 Moffett J W, Tyler J G & Wajih S A N, Reduced iron associated with secondary nitrite maxima in the Arabian Sea, *Deep-Sea Res Part I: Oceanogr Res Papers*, 54 (8) (2007) 1341-1349.

11 Naqvi S W A, Moffett J W, Gauns M U, Narvekar P V, Pratihary A K, *et al.*, The Arabian Sea as a high-nutrient, low chlorophyll region during the late Southwest Monsoon, *Biogeosciences*, 7 (2010) p. 2091.

12 Bruland K W, Kristin J O & James P C, Reactive trace metals in the stratified central North Pacific, *Geochim Cosmochim Acta*, 58 (15) (1994) 3171-3182.

13 Capone D G, Jonathan P Z, Hans W, Birgitta B & Edward J C, *Trichodesmium*, a globally significant marine Cyanobacterium, *Science*, 276 (5316) (1997) 1221-1229.

14 Martin J H & Gordon R M, Northeast Pacific iron distributions in relation to phytoplankton productivity, *Deep-Sea Res Part A, Oceangr Res Papers*, 35 (2) (1998) 177-196.

15 Martin J H, Glacial-interglacial CO_2 change: The Iron Hypothesis, *Paleoceanogr*, 5 (1) (1990) 1-13.

16 Tindale N W & Pease P P, Aerosols over the Arabian Sea: Atmospheric transport pathways and concentrations of dust and sea salt, *Deep-Sea Res Part II: Topical Studies Oceanogr*, 46 (8-9) (1999) 1577-1595.

17 Prijith S S, Rajeev K, Bijoy V T, Nair S K & Mannil M, Multi-year observations of the spatial and vertical distribution of aerosols and the genesis of abnormal variations in aerosol loading over the Arabian Sea during Asian Summer Monsoon Season, *J Atmos Sol-Terr Phy*, 105 (2013) 142-151.

18 Winker D M, Mark A V, Ali O, Yongxiang H, Kathleen A P, *et al.*, Overview of the CALIPSO mission and CALIOP data processing algorithms, *J Atmos Ocean Tech*, 26 (11) (2009) 2310-2323.

19 Prijith S S, Babu S S, Lakshmi N B, Satheesh S K, Moorthy K K, Meridional gradients in aerosol vertical distribution over Indian Mainland: Observations and model simulations, *Atmos Environ*, 125 (2016) 337-345.

20 Gregg W W & Casey N W, Modeling coccolithophores in the global oceans, *Deep-Sea Res Part II: Topical Studies Oceanogr*, 54 (5-7) (2007) 447-477.

21 Gregg W W, Cécile S, Rousseaux & Franz B A, Global trends in ocean phytoplankton: a new assessment using revised ocean colour data, *Remote Sens Lett*, 8 (12) (2017) 1102-1111.

22 Banerjee P & Prasanna K S, ENSO modulation of interannual variability of dust aerosols over the northwest Indian Ocean, *J Climate*, 29 (4) (2016) 1287-1303.

23 Wiggert J D & Murtugudde R G, The sensitivity of the southwest monsoon phytoplankton bloom to variations in aeolian iron deposition over the Arabian Sea, *J Geophys Res*, 112 (2007) p. C5.

24 Srinivas B M M S & Ashwini K, Impact of anthropogenic sources on aerosol iron solubility over the Bay of Bengal and the Arabian Sea, *Biogeochemistry*, 110 (1) (2012) 257-268.

25 Duce R A, The impact of atmospheric nitrogen, phosphorus, and iron species on marine biological productivity, In: *The role of air-sea exchange in geochemical cycling*, edited by Buat-Ménard P, (Springer, Dordrecht), 1986, pp. 497-529.

26 Roy R, Chitari R, Kulkarni V, Krishna M S, Sarma V V S S, *et al*., CHEMTAX-derived phytoplankton community structure associated with temperature fronts in the northeastern Arabian Sea, *Journal Mar Sys*, 144 (2015) 81-91.

27 Chinni V & Singh S K, Dissolved iron cycling in the Arabian Sea and sub-tropical gyre region of the Indian Ocean, *Geochim Cosmochim Acta*, 317 (2022) 325-348.

28 Nishioka J, Hajime O & Daisuke T, Evidence of an extensive spread of hydrothermal dissolved iron in the Indian Ocean, *Earth Planet Sci Lett*, 361 (2013) 26-33.

29 Takeda S, Akiyoshi K & Kyoko K, Effects of nitrogen and iron enrichments on phytoplankton communities in the northwestern Indian Ocean, *Mar Chem*, 50 (1-4) (1995) 229-241.