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ASSESSING SPATIAL AND TEMPORAL VARIABILITY IN PHYTOPLANKTON CONCENTRATION THROUGH CHLOROPHYLL-a SATELLITE DATA: A CASE STUDY OF NORTHERN ARABIAN SEA

IMRAN AHMED KHAN[1], LUBNA GHAZAL[2], MUDASSAR HASSAN ARSALAN[3], MUHAMMAD FAHEEM SIDDIQUI[4*] AND JAMIL HASAN KAZMI[2]

[1]*Govt. Degree Science & Commerce College Landhi, Korangi 6 Karachi,*
Department of Geography, University of Karachi, Karachi 75270, Pakistan.
[2]*Department of Geography, University of Karachi, Karachi 75270, Pakistan.*
[3]*Institute of Space and Planetary Astrophysics, University of Karachi, Karachi 75270, Pakistan.*
[4]*Department of Botany, University of Karachi, Karachi 75270, Pakistan.*
[*]*Corresponding author e-mail: mfsiddiqui2011@yahoo.com; imranak32@hotmail.com*

Abstract

This study focuses on applying remote sensing technology to identify and assess seasonal and intra-annual variation of phytoplankton availability. A standard MODIS algorithm for Chlorophyll-a, is used to obtain a variation of phytoplankton with the help of MODIS time series images from April 2011 to March 2012 that describe the situation for a whole year, we also used periodical data for each three months, *i.e.*, from April 2011 to June 2011, July 2011 to September 2011, October 2011 to December 2011 and finally January 2012 to March 2012. Chlorophyll-a (Chl-a), products were retrieved from the sensor data that demonstrates the spatio-temporal variability of phytoplankton concentration in the northern Arabian sea near the coastline and open sea water of Pakistan, India, Iran and Oman. High concentration of Chl-a, were observed during two periods August to September and February to March respectively. It was also revealed that Chl-a, concentration was almost identical between the latitude 20 and 21 degrees N throughout the year.

Key words: Phytoplankton, Chlorophyll-a (Chl-a), Spatio-temporal, MODIS algorithm, Remote sensing monitoring, Arabian sea, Marine plants.

Introduction

Phytoplankton are the foundation of the marine food chain. They help to sustain the life in the ocean through photosynthesis. They are equally significant to life on land due to the production of more than half of Earth's oxygen supply. They also play a critical role in the carbon cycle as they consume carbon dioxide from the ocean during photosynthesis and emit oxygen as a by-product. The monitoring of the extent, magnitude and distribution of phytoplankton has been the prime interest to scientists, researchers, and aquatic resource managers for decades. An understanding of the marine plants and their distribution enable researchers to draw conclusions about water body's health, composition, and ecological status. Marine resources are very important as researchers are always engaged in finding new ways of exploring marine potential in order to make best use of them for the benefit of mankind. Standard monitoring of marine plants in Arabian Sea along the coast of developing countries such as Pakistan and other South Asian countries is not novel (Banse and McClain, 1986; Brown *et al.,* 1985; Banse, 1984, and 1987; Saifullah, 1994 and 1979). Although shallow and deep water appraisal of biological parameters is integral for the development and management of environment, ecology and many related economic activities such as fishing and trade (Piontkovski, 2012; Latif *et al*., 2013).

Ecological management is essential for our lives and economy, for that determination of Chlorophyll-a (Chl a) distribution in the coastal waters it is important to understand the physical conditions of the area. Chl-a is a vital pigment for photosynthesis in phytoplankton. Generally Phytoplankton are microscopic, and their movement is depended to the water currents (Moisan *et al*., 2012; Piontkovski, 2012). Understanding the spatial and temporal pattern of Chl-a, in this region is important because the presence of these organic matter affect the marine ecosystem, especially in the enhancement of marine plants and animal productivity in the coastal region, especially in estuaries (Moisan *et al*., 2012).

Currently, the concentration of the Chl-a is being used as an indicator for primary productivity and to understand the changes at various places (Richardson &Ledrew, 2006; Yoder, 2000). The concentration of these pigments in the water column is mainly caused by the abundance of phytoplankton in the water column (Yoder *et al.,* 2002). A high quantity of phytoplankton and productivity lead to enhanced concentration of green pigments in the water column (Ras *et al.,* 2008; Tang *et al.,* 2004). They are the primary foodstuff manufacturers in the aquatic environment and commonly are known as algae.

Growth of phytoplankton is reliant upon solar radiation and nutrient materials. They are able to incorporate as well as release materials to the surrounding water. Therefore, they have a significant effect upon the quality of water. Interest has increased due to their possible role in regulating climate by production and consumption of greenhouse gases (Falkowski *et al*., 1998). Phytoplankton productivity is one of the primary forces regulating our planetary climate. For instance, via impacts on atmospheric carbon dioxide levels, that is closely linked to the oceanic concentrations. For example, gases can diffuse across the air-sea interface, many of which are synthesized and emitted by certain phytoplankton species or groups (Diersing, 2009).

Phytoplankton community is diverse and comprises on the order of tens of thousands of marine phytoplankton species (Jeffrey &Vesk, 1997). On regional scales, phytoplankton biogeography is controlled by the physical, chemical, and meteorological characteristics that force ecosystem dynamics to function accordingly. Understanding of the cyclical relationship of phytoplankton groups and how the production of greenhouse gases relates to temperature and productivity provides a better understanding of their association to the climate (Falkowski *et al.,* 2004; Pan *et al.,* 2013). Changes in phytoplankton community structure could potentially provide an early warning for climate-driven perturbations in marine ecosystems (Hallegraeff, 2010).

The spatio-temporal distribution of the Chl-a, provides a way to explain the changing environmental conditions. There is a dire need for accurate information and relevant data of marine environment, including plants for our lives and sustainable development. Remote sensing technology is playing an enormous role due to its high frequency of observations along with the possibility of spatio-temporal monitoring and evaluation of the position and movements of marine plants and other organisms. The remote sensing system guided to the essential understanding and data concerning their finding and prevailing conditions (Kampel *et al.,* 2009).The capability of satellite remote sensing in providing global coverage has been an advantage for the measurement of Chl-a, in the marine environment. In marine remote sensing, Chl-a, is being used as a proxy to the existence of phytoplankton (Kampel *et al.,* 2009). In this regard Martin (2004) reported Satellite data is an efficient source which provides synoptic coverage without accessing to the remote areas in short span of time. Remotely sensed repeated monitoring of the presence of phytoplankton is the most efficient method to study the marine ecology and the environment. Satellite based spectroscopy of marine Chlorophyll in the visible spectrum (wavelength between 400-700 nm) is an effective technique to appraise the abundance (Chauhan *et al.,* 2002; Radiarta &Saitoh, 2008) and it is used to estimate Chl-a concentration for estimating phytoplankton (Behrenfeld *et al.,* 1997).

Measurements of Chlorophyll concentrations through Satellite rely on the absorption and scattering characteristics of phytoplankton; the way optical properties affect the underwater light field; and the reflectance (Rrs) or radiance (nLw) values measured by the satellite sensor (Behrenfeld, 1997). Photosynthetic organisms absorb electromagnetic radiation predominately in the blue, blue-green, and red portions (bands) of the visible spectrum, depending on pigment composition. The maximum absorption by algal pigment is around 440 (nm). As particles, they scatter light, and the shape of the scattering spectrum is dependent on phytoplankton size (which is highly variable - from 0.7 mm to 100 mm), composition, and absorption of the spectrum. Fluorescence by phytoplankton is observed around 680 nm.

Information about Chlorophyll concentration is obtained by using appropriate algorithms that relate measurements of remote sensing reflectance spectra either directly to Chlorophyll concentration (observed algorithms), or to optical properties of phytoplankton and other optically active materials in the water based on radiation transfer and theoretical relationships. Satellite based estimation of surface concentrations of Chl-a, and associated pigments have contributed significantly in gaining a better understanding of the spatial and temporal variations of phytoplankton biomass and biological activity in the world's oceans and the role of phytoplankton in the climate system (Desa *et al.,* 2001).

With this background, the prime objective of this study is to expose researchers of various fields, such as phyto-geography, marine biology and environment to aware of about the free of cost satellite based products to enrich their experience. Secondly, to provide a detailed spatio-temporal analysis of Chl-a concentration in the northern Arabian Sea with NASA data portal (NASA GES DISC Giovanni, 2013). As large scale studies of such phenomenon are not accurately conducted through conventional means in this region and would require plenty of time and resources, in which developing countries are already lagging behind.

Study area: The study area is spread over from 57 to 73 degree east longitude and from 16 to 30 degree north latitude. This geographical location of northern Arabian Sea is shared by coastal lands of Pakistan, Iran western part of India and the eastern coast of Oman (Fig. 1). The Arabian Sea has extreme climatic parameters because of seasonal variations in the environmental conditions, especially the air and water temperatures (Desa *et al.,* 2001; Sarangi *et al.,* 2005 and Piontkovski *et al.,* 2011). The study area has a unique biodiversity, including several common and rare species of algal blooms such as seasonal brown, green, and red algal flora represent important components of the region. Upwelling effects result in highly productive pelagic waters and high plankton productivity along the Oman Coast that supports an enormous diversity of small herbivorous (Piontkovski *et al.,* 2012; Al-Hashmi *et al*., 2010).

Materials and Methods

Chlorophyll-a data from NASA missions such as Sea-viewing Wide Field-of-View sensor (SeaWiFS), and data from the Moderate Resolution Imaging Spectroradiometer (MODIS), were analyzed with the Goddard Earth Sciences Data and Information Services Center (GES DISC) online data analysis system Giovanni (Berrick *et al.,* 2009). MODIS is a remote sensing instrument on board space-borne satellites Terra and Aqua. Terra travels from north to south across the equator in the morning, while Aqua travels from south to north over the equator in the afternoon. The two satellites can view the whole earth's surface every 1-2 days. MODIS can acquire electromagnetic energy in 36 groups of wavelengths (36 spectral bands). The data are used to observe and improve understanding of changes at and above the earth's surface, including the oceans' surfaces.

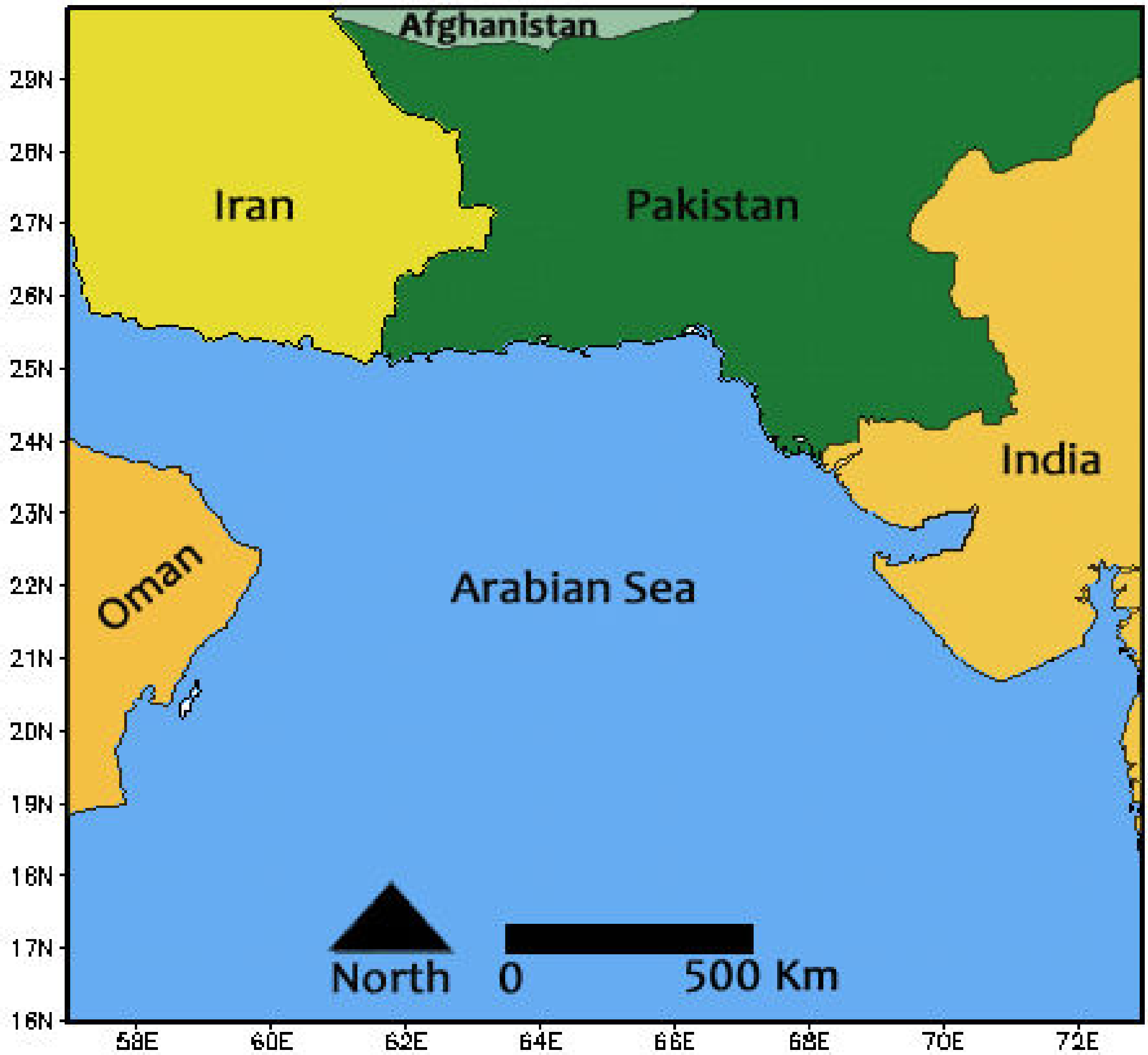

Fig. 1. Northern Arabian Sea (Study area).

As a source of Ocean Color Radiometry data, Water Quality Portal is used (NASA GES DISC Giovanni, 2013). MODIS-Aqua and SeaWiFS data is obtained from this portal. There are several variables available at the portal. For the study, we downloaded only level 3, Chl-a data of MODIS with 4 km^2 spatial resolution. Variability of the time series of monthly Chl-a, colored dissolved organic matter (CDOM), euphotic depth, rainfall and Sea surface temperature (SST) images were determined by using MODIS algorithm analysis. The MODIS algorithm (OC3) utilizes the processes (Carder *et al.,* 2004), which is performed by applying the calculation in the following manner.

MODIS Chlorophyll Algorithm (OC3).
Chl_a = 10**(0.283 - 2.753*R + 1.457*R^2 + 0.659*R^3 - 1.403*R^4)

where:
R = log10((Rrs443 > Rrs488) / Rrs551)
Rrs = nLw / F0; remote sensing reflectance
F0 = extraterrestrial solar irradiance
nLw = water leaving radiance at 443, 488, 551

We scrutinize Chl-a, data along with several associated variables such as Colored dissolved organic matter (CDOM), rainfall data, sea surface temperature (SST) and euphotic depth From April 2011 to March 2012. We also utilized periodical data for each three months, *i.e.*, from April 2011 to June 2011, July 2011 to September 2011, October 2011 to December 2011 and finally January 2012 to March 2012 respectively.

Results

Fig. 2, shows Intra-annual spatial distribution of Chl-a, CDOM, rain fall and euphotic depth from April 2011 to March 2012. Fig. 2a explains the concentration of Chl-a, that is higher in the north and western part of the study area as compared to southern and southeastern parts. High values of Chl-a, especially along the coastal belts are ranging from 2.5-30 mg/m^3 and it keeps on reducing from 0.7-0.2 mg/m^3. A small patch of Chl-a, is seen in the northern Arabian sea in the coastal deep sea on the Makran coast of Pakistan. Fig. 2b describes that

CDOM distribution is higher in east and southeastern direction, especially near Indian and Pakistan coast, though low values are observed Omani and Iranian coast. Fig. 2c characterizes the mean rainfall distribution in the entire study area, which is ranging from 5-150 mm while the western part receives much lesser rain than that of eastern parts that is 5-63.5 mm and 63.5-150 mm respectively. It is because of the direction of the wind in the monsoon season in summer. Fig. 2d is showing the spatial distribution of euphotic depth, north western parts are shallower than the south eastern part near India. By comparing all four variables of Fig. 2, it is evident that higher level of Chl-a concentration is found in those shallow waters with low euphotic depth and high rainfall, additionally high organic matter bring together only within the coastal belt of north and eastern side of the study area that is the region of south Asian countries. However, there is no significant association turnout in the remaining areas.

Fig. 3 defines the association of variables among sea surface temperature (SST), Chl-a, and CDOM. It confirmed the inverse relationship between SST and Chl-a (Fig. 3a), while positive association is observed with Chl-a, and CDOM (Fig. 3b); and CDOM and SST (Fig. 3c).

Fig. 4 is showing the map based relationship among all selected variables. Fig. 4a shows a correlation map between Chl-a, and CDOM. It is observed that strong values are found between these two variables in the study area, especially in the middle and southern part of the Arabian Sea. Fig. 4b map shows correlation between Chl-a, and euphotic depth that having no significant region except narrow coastal belts of south Asian countries *i.e.* India and Pakistan. Fig. 4c, on the other hand is showing a significant correlation between CDOM and euphotic depth in the entire area with high values near Omani and Iranian coastal water makes strong correlation. Similarly Fig. 4d shows correlation between Chl-a, and SST which is generally not significant, but good enough near Indian and Pakistani coastal belts.

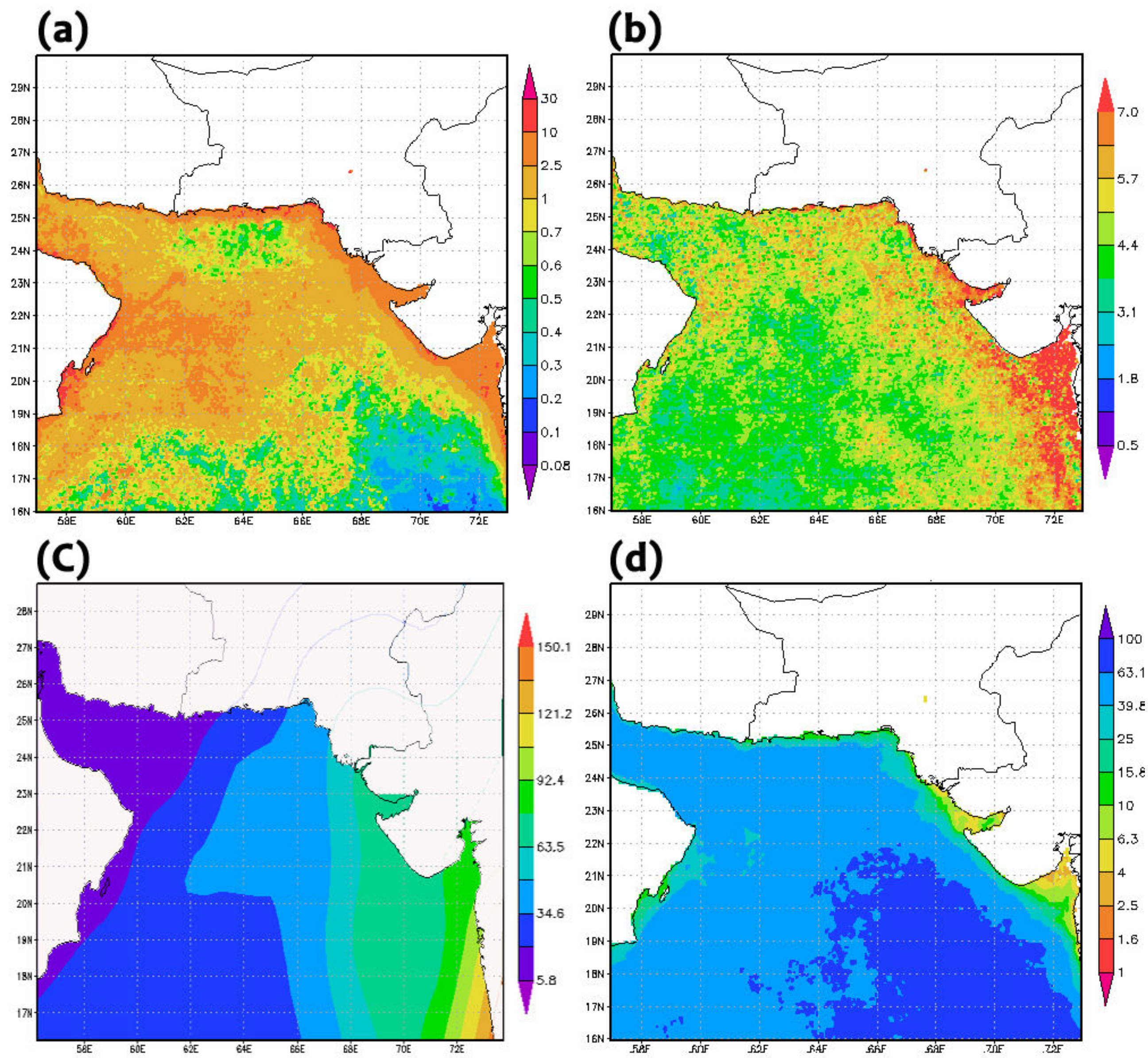

Fig. 2. Intra-annual spatial distribution of the variables from April 2011 to March 2012 (a) Chl-a (mg/m3); (b) Colored dissolved organic matter CDOM (unit less); (c) Occurrence of Rainfall (mm); (d) Euphotic depth (m).

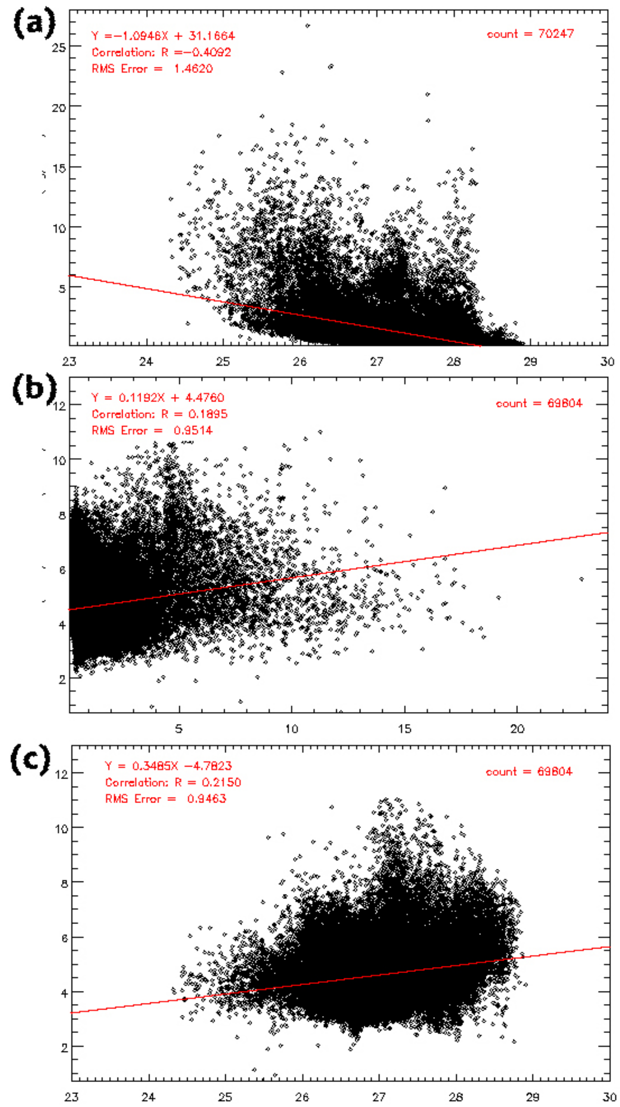

Fig. 3. Correlations among variables; (a) correlation between Chlorophyll a (Chl-a) and sea surface temperature (SST); (b) correlation between Chlorophyll a (Chl-a) and colored dissolved organic matter (CDOM); (c) correlation between sea surface temperature(SST) and colored dissolved organic matter (CDOM).

Fig. 5 shows the three months periodical distribution of Chl-a, from April 2011 to March 2012. Generally concentration of Chl-a, is highest in the extreme north of Arabian sea near the narrow coastal belt of India, Pakistan, Iran and Oman all the year round. It keeps on reducing as we move towards the open sea. Seasonally, high concentration is found during the period of July to September and January 2012-March 2012. It is reported by other studies also performed by Brock *et al.* (1992) that an increased concentration of phytoplankton along the Omani coast in the northwestern Arabian Sea is observed from May through September. It extends into the open sea by upward nutrient fluxes forced by coastal upwelling and offshore Ekman pumping. Sarangi *et al.* (2005) and Dwivedi *et al.* (2006) also reported the algal bloom in the North Arabian Sea develops every year during February to March and it is correlated to northeasterly trade winds and sea surface temperatures. There are several reasons for these peak values, including monsoon rainfall. During this season, torrential rain changes the composition of shallow marine water as more amount of phytoplankton reaches to deltaic regions through rivers and surface runoff. Fig. 5c reveals the fact that during October to December 2011, the concentration of Chl-a, goes down as less rainfall occur during these months. On the other hand, during January 2012 to March 2012 an increase has been found in the concentration of Chl-a (Fig. 5d).

Fig. 6 is showing intra annual variation of Chl-a. The minimum value is 0.02 mg/m3 in the month of May and maximum value 98 mg/m3 is seen in the month of September (refer Fig. 6a and 6b). Mean maximum Chl-a, is observed in the month of February that is around 35 mg/m3 (Fig. 6c), while the highest value of standard deviation is in September (Fig. 6d).

Discussion

Among the wide range of temporal changes of physical, chemical, and biological variables, featuring the Arabian Sea ecosystems, the seasonal variation is one of the most prominent discrimination. Seasonal changes are driven by a vigorous system of monsoonal winds in the region. The winter (Northeast) monsoon affects the region from December to March. The summer (Southwest) monsoon is developed from June to September. In winter, the air over land becomes cooler and denser than air over the ocean, which creates a high atmospheric pressure over the continent and a low pressure over the ocean (Caron *et al.,* 1999). The resulting pressure gradient leads to northeasterly wind flow, *i.e.* the northeast monsoon from November to March, directed from continent to the ocean south of the equator. As the year progresses, increased heating reduces the high pressure over the continent. By summer, a high atmospheric pressure is formed over the ocean and the wind direction is reversed to a southwesterly wind flow (June–September), directed from ocean to continent (Barlow *et al.,* 1999).

Variation of Phytoplankton is exceptionally vital for the development of estuarial eco-systems. Phytoplankton productivity is one of the main forces regulating our planetary climate for via impacts on atmospheric carbon dioxide levels, which are closely linked to the oceanic carbon dioxide concentrations. Phytoplankton absorb carbon dioxide during photosynthesis, lesser Chl-a values means lesser Phytoplankton that leads to a greater amount of carbon from the atmosphere get dissolved in the ocean as carbonic acid that may contribute to ocean acidification *i.e.* lowering the pH level and to the thrashing of marine life that due to from acidification. However, excessive water column productivity, expressed by high Chlorophyll a concentrations, can supply large amounts of easily decomposable organic matter to the sediments. The decomposition of algal biomass can increase the diurnal amplitude of water column pH and dissolved oxygen fluctuations, and in some cases may lead to anoxic and hypoxic events. Moreover, high Chl-levels indicate large numbers of phytoplankton and free floating macro algae, which can shade sea grass meadows leading to a decline in sea grass distribution. The above changes can translate into changes in animal and plant species diversity.

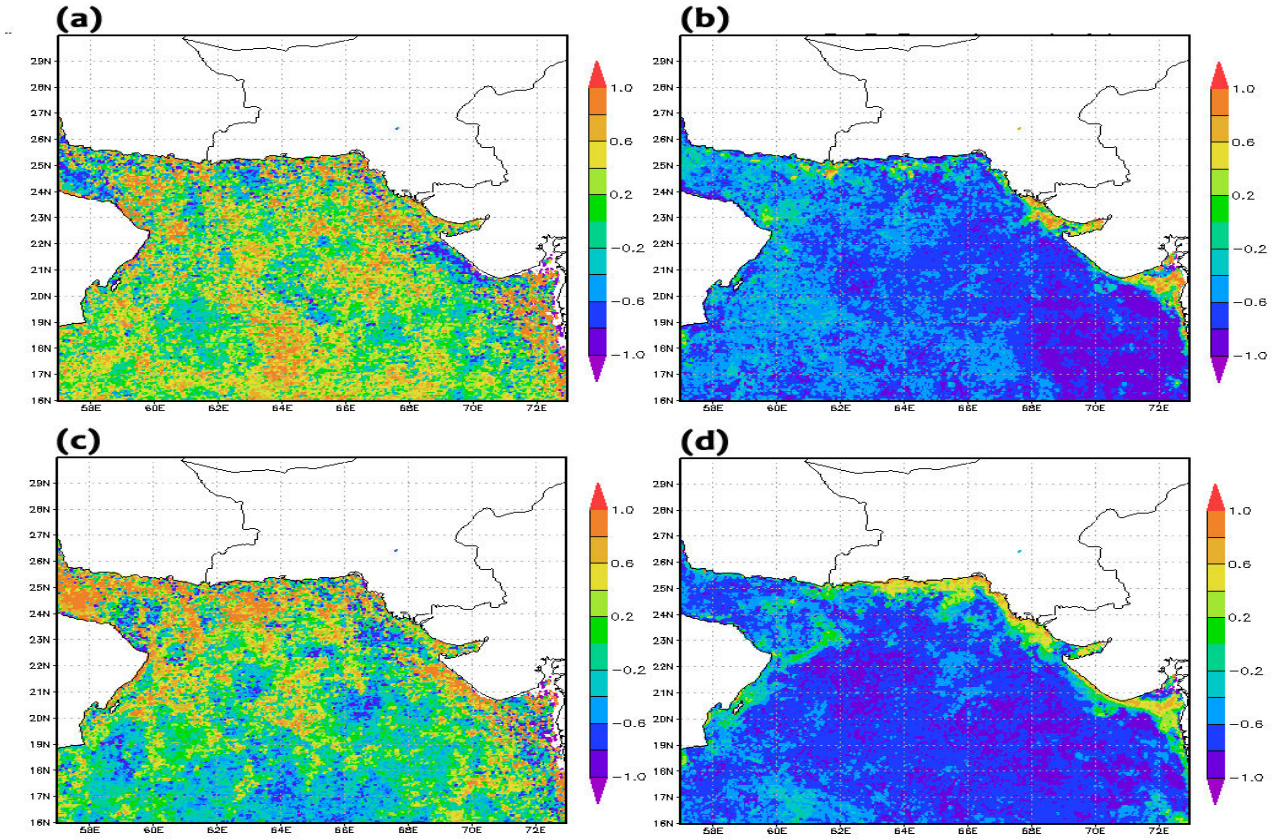

Fig. 4.Correlation based map among variables; (a) correlation between Chlorophyll a(Chl-a) and colored dissolved organic matter(CDOM); (b) correlation between Chlorophyll a (Chl-a) and Euphotic depth; (c) correlation between colored dissolved organic matter (CDOM) and Euphotic depth; (d) correlation between Chlorophyll a (Chl-a) and sea surface temperature (SST).

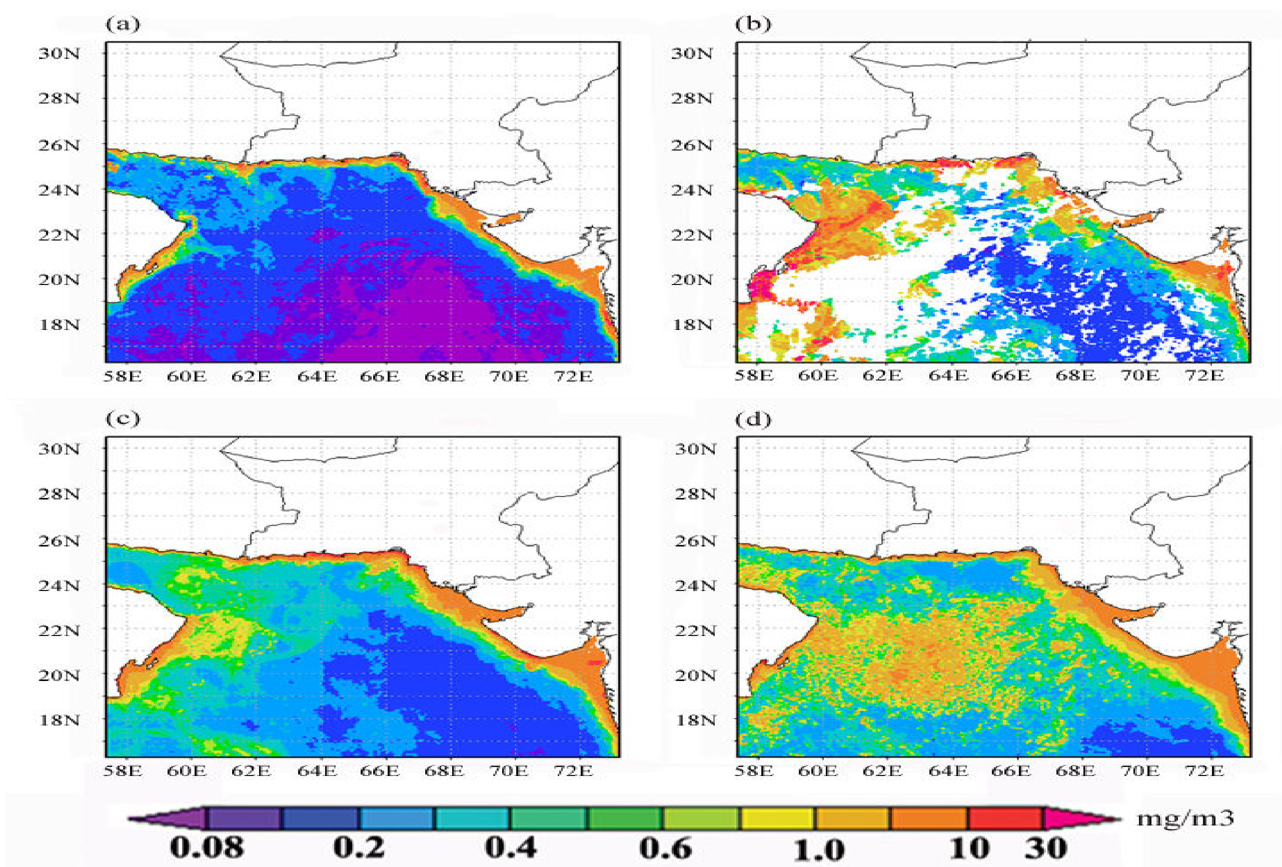

Fig. 5. Spatio-Temporal distribution of Chl-a; (a) April 2011 to June 2011 (b) July 2011 to September2011 (c) October 2011 to December 2011 (d) January 2012 to March 2012.

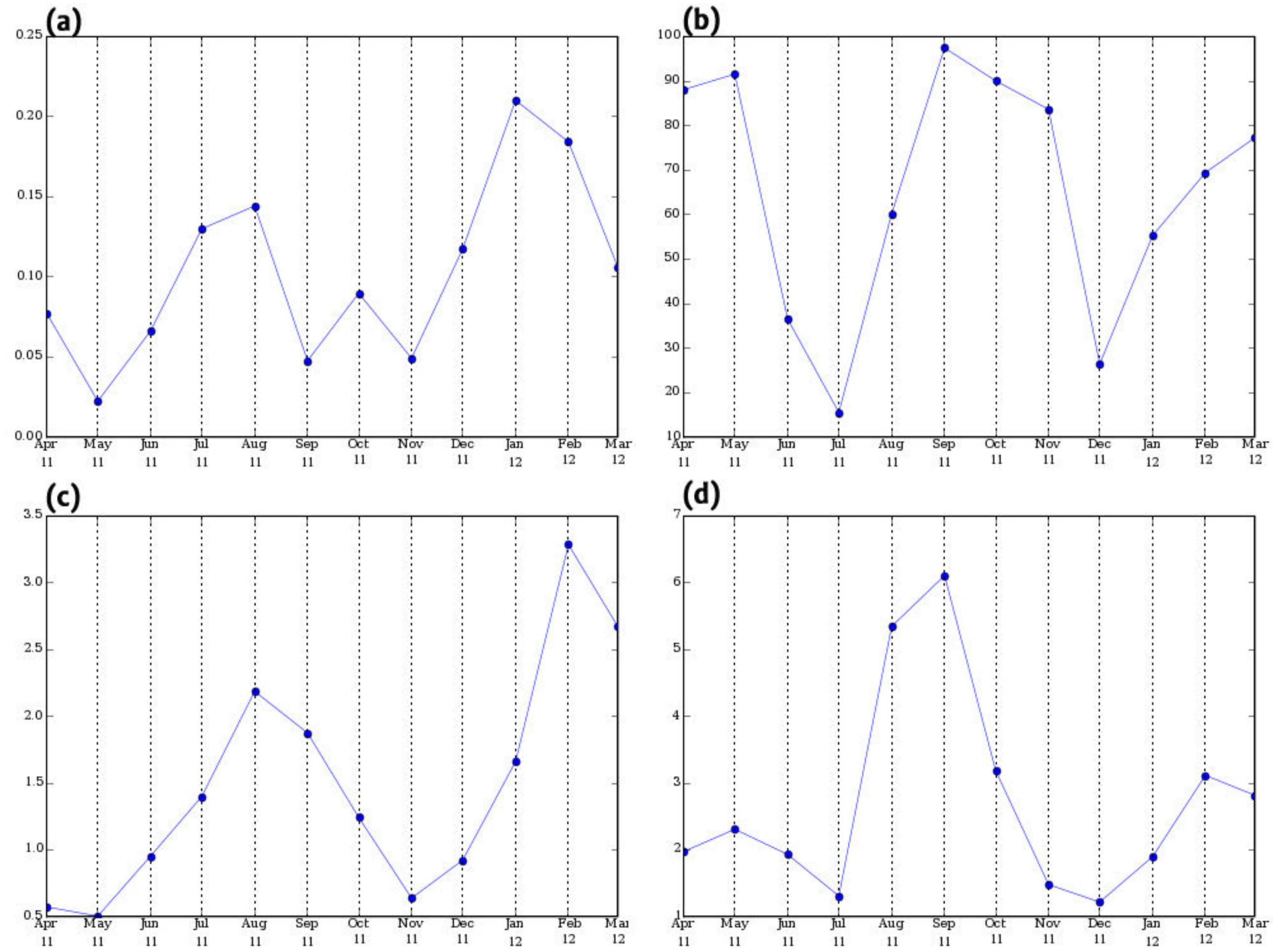

Fig. 6. Intra annual variation of Chl-a in mg/m3 (a) Minimum values of Chl-a (b) Maximum values of Chl-a (c) Mean values of Chl-a (d) Standard deviation values of Chl-a.

Concerning geographical location along the coastline, Arabian Sea ecosystems are subjected to different modes of physical forcing (Veldhuis *et al.,* 1997). The summer monsoon stimulates an upwelling along the southeastern coast, facing the western Arabian Sea. The deviation prevents the development of the summer coastal upwelling in the Sea of Oman (Al-Hashmi *et al.,* 2010). The upwelling takes place in the other season however. In winter, the Northeast monsoon sets up the upwelling along the northern (Iranian) coast. Over time, advected by basin scale circulation and meso-scale eddies high productive waters of the northern coast reach the southern regions of the sea.

The temporal variability of phytoplankton biomass appears to be dependent primarily on physical processes occurring at wide spatial and temporal scales (Wahbah & Zughul, 2001; Harrison *et al*., 1997). The observed data provide information of Chl-a, at the ocean surface either seasonally or between a certain period and may vary due to input from land and the influence of oceanographic physical processes such as surface wind. There are various sources of Chlorophyll and nutrient input to the ocean, including discharge from the river, estuaries and coastal pollution from land one exemplar is fertilizer pollution runoff into the ocean that enable nitrogen and other nutrients into water that contribute more Phytoplankton(Lee *et al.,* 2003).

Conclusions

The study was conducted to analyze the spatio - temporal dynamics of phytoplankton through Chl-a, Satellite data in the coastal belt of south Asian countries and to determine the relevant factors influencing its variability.

The large aptitudes of bio-optical datasets were used to evaluate data on Chl-a (representing phytoplankton biomass) from Moderate Resolution Imaging Spectro radiometer (MODIS) algorithms in the Northern Arabian Sea. Aqua MODIS satellite data from April 2011 to March 2012 of Chl-a distribution were analyzed. Concentration of Chl-a, was found higher near coastal belts of the study area, that depicts that there is great potential for the development of fishing Industry and hatcheries of shrimps. The study also concludes the significance of remote sensing for exploring marine environment, resources and efficient and sustainable ecological management. It has also been revealed that integration of various remote sensing datasets could play a vital role for the ecological studies that might readily be used for fisheries departments to evaluate the role of Phytoplankton in establishing the potential of fisheries hotspot.

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