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孟加拉湾的叶绿素 a,海表温度和风速的趋势

摘要

孟加拉湾(BoB)是一个高能量活跃的地区,其短期内的动态变化将对浮游环境产生巨大影响."风泵"能够在 BoB 海域导致垂直的混合从而影响海表温度和叶绿素浓度.本文对 2006——2016 年的月平均 Aqua-MODIS 叶绿素 a(chl-a)浓度数据和 Sea WiFS 月度气候态数据进行了分析,研究了叶绿素浓度的时间/季节变化和温度以及风速的关系.基于季风期间的 chl-a 变异与海表温度(SST),评估了在 BoB 海域它们之间的关系和变化.chl-a 浓度值的趋势分析表明,该区域的垂直混合非常低,冬季最高,夏季最低.冬季最大 chl-a 浓度值为 0.50 mg/m^3,并且从 2 月开始下降到夏季季风期间.与冬季季风相比,夏季季风期间叶绿素表现出较低的浓度.在夏季季风期间,特别是在 7 月和 8 月,由于云层密集,卫星传感器无法准确捕获 chl-a 浓度值.chl-a 浓度和 SST 之间相关系数 R^2 值为 0.218 1.

关键词

叶绿素;风泵;孟加拉湾,海表温度;上升流

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0　导读

本文原文为英文,希望感兴趣的读者进一步关注原文.

孟加拉湾(BoB)是一个高能量活跃的地区,其短期内的动态变化将对浮游环境产生巨大影响."风泵"是指风力驱动的海洋上层洋流和水体运动以及随后的生态效应的影响,它可改变海洋中关键元素的运动和循环,从而影响海洋生态系统中的初级生产等.本文研究了叶绿素 a(chl-a)浓度的时间/季节变化及其与海表温度(SST)和"风泵"的关系.本文对于 10 年(2006—2016 年)的月平均 Aqua-MODIS chl-a 数据和 Sea WiFS 月度气候态数据进行了分析.基于季节的 chl-a 浓度变异与 SST,评估了在 BoB 海域它们之间的关系和变化.

chl-a 浓度值的趋势分析表明,该区域的垂直混合非常低,冬季最高,夏季最低.冬季最大 chl-a 浓度值为 0.50 mg/m^3,并且从 2 月开始下降到夏季季风期间.与冬季季风相比,夏季季风期间叶绿素表现出较低的浓度. 高 chl-a 浓度可能是由于印度洋地区冬季水平平流增强造成的,从而影响 BoB 海区的生物生产力.观测发现在 2013 年 chl-a 浓度的最大值达到 0.50 mg/m^3,其原因是 2013 年 12 月在 BoB 西南部形成的热带气旋(Madhi)横穿了 BoB 西部地区.Ekman 抽吸速率指数是理解这个时期垂直混合的重要指标.

在 9 月到次年 1 月期间,风引起的混合导致温度的降低和 chl-a 浓度增加.冬季季风期间,深层和表层水混合使表层营养物质增加,温度也降低.SST 下降,解释了 BoB 地区冬季季风(12 月)内出现最大 chl-a 浓度的原因,也解释了表层和深层水的混合导致营养物质供应到上层并提高表层的生产力的现象.在夏季季风期间,特别是 7 月和 8 月,卫星传感器无法准确捕获 chl-a 浓度值,原因是夏季季风期间云层密集.由于云量覆盖像素问题,冬季季风和季风转换期是最适合研究 BoB 区域的叶绿素 a 浓度的时间,因为这种空间验证的像素可用性远高于夏季季风期间.

本研究显示了叶绿素 a 浓度与海表温度的相关性($R^2=0.218\ 1$, $p<0.05$)以及风速之间的相关性($R^2=0.193\ 1$, $p<0.05$).BoB 海区呈现中度的正相关,最可能的原因是海区强烈的分层,特别是夏季季风期间.和其他印度洋海区相比,BoB 的风场类型会刺激较小的上涌,因此,随着 chl-a 浓度的增加而出现正相关.与其他海区一样,风速也被认为是 BoB 引起垂直混合最有效的能量驱动.

The propensity of chlorophyll-a, sea surface temperature and wind speed in the Bay of Bengal

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Abstract The Bay of Bengal (BoB) is a high energy active region, dynamics of BoB varies during short term with huge effect over the planktonic environment. "Wind pump" induces vertical mixing in the BoB region, which affects the sea surface temperature (SST) and chlorophyll-a (chl-a). This study demonstrates the temporal/seasonal variation of chl-a concentration and its relationship to SST and wind speed. Monthly averaged Aqua-MODIS chl-a data for a period of 10 years (2006–2016) and Sea WiFS monthly climatology data were analyzed. Based on monsoonal chl-a and SST variability, we appraised their relationship and variations over the BoB. Trend analysis of chl-a concentration values shows that vertical mixing is very low in this region with weak annual phase, which reaches its maximum in winter and minimum in summer. About 0.50 mg/m^3 is observed during winter as the maximum chl-a concentration value and then decreases since February until summer monsoon period. Summer monsoon period is identified as lack of chl-a concentration, compared to winter monsoon period. In summer monsoon period, especially in July and August, satellite sensors couldn't capture chl-a concentration values accurately due to the dense cloud cover. The R^2 value for relationship between chl-a concentration and SST is observed to be 0.218 1.

Key words chlorophyll a; Wind Pump; Bay of Bengal; sea surface temperature; upwelling

1 Introduction

Marine plants and phytoplankton are the major photosynthetic sources in the ocean surface, which significantly influence the fluctuation of atmospheric Carbon Dioxide (CO_2) (global carbon cycle) and primary productivity of the ocean systems. The major process is the synthesis of organic carbon using inorganic CO_2 that varies in different climatic ambience[1-2]. When validating or assessing the primary productivity in the ocean, chlorophyll-a (chl-a) concentration is a vital parameter[3]. Many nutrients such as nitrite, phosphate, silicate, etc. are highly usable (within the photic zone, where phytoplankton occur in abundance) in phytoplankton environment especially upper layers of the ocean[4]. Distribution and density of phytoplankton depend on the nutrient level in the ocean surface and sunlight availability, but the mixing of water, occasional fronts, ocean circulation, cyclones, and upwelling also affect the intensification of phytoplankton distribution[2,5-6]. Especially, "wind pump"[7] is a major factor for phytoplankton distribution in the ocean. Defined as the impacts of wind-driven ocean currents on water transport and subsequent ecological effects, "wind pump" changes the movement and the cycling of key elements in the ocean thus affects the primary production, in marine ecosystems[6] these natural phenomena are varying according to their own time scales (annually or seasonally) and chl-a concentration fluctuates almost equally with them. But there is lack of studies and assessments of chl-a relationship with physical properties in different regions of the ocean[8].

Upwelling and vertical mixing induced by "wind pump" are the most significant factors in surface layers of the ocean which regulate the majority of phytoplankton (chl-a) biomass[7]. This biomass depends on several limiting factors that is suggested by correlations such as the relationship between wind speed and chl-a concentration, as well as wind speed and SST which are negatively correlated in the world ocean as typically[9]. Fluctuations of wind speed regulate the depth of upper mixed layer and also increase vertical nutrient mixing which cools the upper layer of the ocean[10-12]. Spreading of SST in the Indian Ocean is very significant because western part of the Indian Ocean is highly abundant with cooler water, although the western part of Pacific and Atlantic oceans are hot. Physical, chemical and biological properties in the Arabian Sea region and the BoB region are comparatively different as western part of the BoB receives an enormous freshwater supply which results in low salinity during monsoonal periods. Therefore, the thermocline is deeper in the western part of the BoB and upwelling is comparatively less considering other regions of the Indian Ocean[13-14].

The BoB is a very significant and important region of the northern Indian Ocean due to the abundant existence of short term and long term seasonal cyclones and eddies formation. Therefore, upwelling is highly induced during these periods[10,14]. The BoB overall chl-a is comparatively higher than that in southern Indian Ocean around the equatorial region[15]. This study targets to evaluate the temporal (seasonal) variability of chl-a concentration and SST, as well as the effect of wind speed variation, further to study their interrelationship over the BoB region in the northern Indian Ocean territory using statistical methods[2,16]. Satellite-derived data and reanalysis data from specific data providers will be used as major data sources.

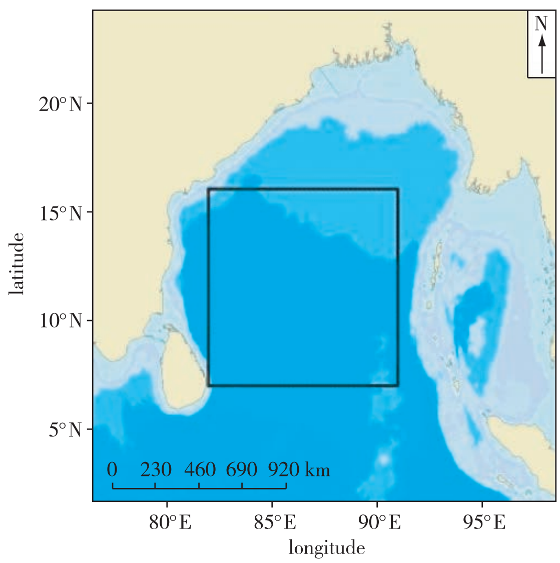

Fig. 1 Study area (black square) in the BoB of the northern Indian Ocean spreading from latitude 7-16°N and longitude 82-91°E

2 Data and methods

The study area extends around the BoB in the northern Indian Ocean (7-16°N and 82-91°E) and the variability of chl-a and SST in this area were studied (Fig.1). The moderate-resolution imaging spectroradiometer (MODIS) _ Aqua ocean color based monthly composite level-3 standard mapped image (SMI) at 9 km spatial resolution data were downloaded from National Aeronautics and Space Administration (NASA) Ocean Color (http://oceancolor.gsfc.nasa.gov). Time duration is July 2006 - Dec 2016. "Chlorophyll concentration data are calculated with MODIS algorithm (OC3M) and averaged in global ocean region. The OC3M algorithm is: $\log_{10}(CHL) = 0.283 - 2.753R + 1.457R^2 + 0.659R^3 - 1.403R^4$ where $R = \log_{10}[\max(R_{rs}(443), R_{rs}(488))/R_{rs}(551)]$"[17]. Chl-a values are derived from the recorded radiance using the OC2 algorithm in MODIS-Aq. Chl-a concentration[18]. Over 10 mg/m^3 chl-a values were not evaluated for this analysis because such values are sporadic. Furthermore, Sea-viewing Wide Field-of-view Sensor (Sea WiFS) monthly climatology 1°×1° data were downloaded from University of Hawaii website (http://apdrc.soest.hawaii.edu).

The 0.25°×0.25°-pixels resolution monthly averaged SST data were downloaded from WindSat monthly averaged data products, Version-7.0.1 from the University of Hawaii website (http://apdrc.soest.hawaii.edu) for July 2006 - December 2016. Since there weren't precise values for June and July of 2007, average SST value was used for these two missing values.

Monthly averaged wind speed data were downloaded from National Centers for Environmental Prediction (NCEP) reanalysis data using University of Hawaii website (http://apdrc.soest.hawaii.edu). Pixels resolution is 2.5°×2.5° and time duration was the same as above.

3 Results

3.1 Chl-a concentration variation in the BoB

The area-averaged chl-a concentration in the BoB area during the period of July 2006-December 2016 is showed in Figure 2. Considering this studied time

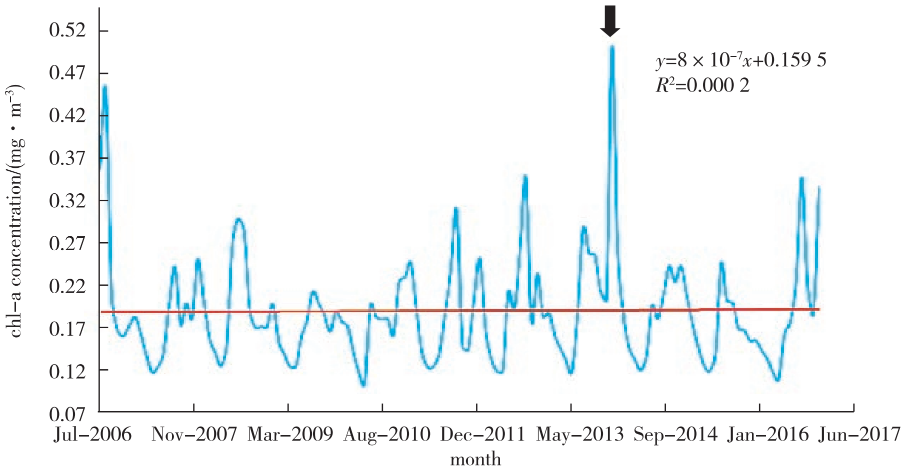

Fig. 2 Area averaged monthly time series of chl-a concentrations with moderately increasing linear trend for the BoB for the period of 2006-2016(The highest chl-a concentration value (showed in black arrow; 0.50 mg/m^3) is observed in December 2013)

period, the chl-a concentration is varied from 0.10 mg/m^3 to 0.50 mg/m^3. The lowest of the areal average of chl-a concentration of 0.10 mg/m^3 is noted in May 2010 and the highest of 0.50 mg/m^3 noted in December 2013. According to Figure 2, five major peaks are identified (0.50 mg/m^3 in December 2013, 0.45 mg/m^3 in August 2006, 0.36 mg/m^3 in July 2006, 0.35 mg/m^3 in September 2012 and 0.35 mg/m^3 in September 2016).

3.2 Error of cloud cover pixel

In literature review, many researchers suggested the noticeable cloud cover period during the summer monsoon period (especially June to August). Therefore, this cloud cover decreases the satellite observations and accuracy of satellite data[12,19]. In this study, a lack of pixel data during July and August is also found (figures are not provided) from 2006 to 2016. Figure 3 also shows high chl-a concentrations during July and August. This observation coincides with above researcher's suggestions. This problem may be due to the lack of pixel data to take accurate average value.

3.3 SST and chl-a concentration

In this study, SST data during 2006-2016 are also observed to clarify the variability of chl-a concentration. SST variation is in sinusoidal distribution during this time period and varied in the range of 27.9-31.4 ℃ (Fig.4). The minimum SST value (27.9 ℃) is noted during January 2007 and January 2014, and the maximum value of SST (31.4 ℃) is noted in April 2010.

Moderately sensible correlation between surface chl-a concentration and SST are identified ($R^2=0.218\,1$, $p<0.05$) (Fig.5).

3.4 Chl-a concentration and wind speed

Chl-a concentration and wind speed are moderately correlated in this area ($R^2=0.193\,1$, $p<0.05$, significant at 95%) (Fig.6). Chl-a concentration is increasing with increase of wind speed.

4 Discussion

4.1 Variability of chl-a concertation

High chl-a concentration is found during September to January. This high chl-a concentration may be induced by the nutrient upwelling which is caused by the sea level anomalies and winds[12]. "Wind pump" influences on water movements which changes the transport and the cycling of major elements in the ocean[6,20]. Furthermore, open ocean upwelling which is also motivated by Ekman pumping increases the chl-a concentration by cyclones which are very copious during winter monsoon periods that triaged increase nutrients concentrations to upper layers in the BoB region[14]. Variability of chl-a (Fig.2) for period 2006-2016 illustrates that the year 2013 has the maximum value (0.50 mg/m^3) of chl-a concentration. In December 2013, category-2 tropical cyclone ("Madhi") formed in the southwestern BoB and crossed over the western BoB area (https://www.nasa.gov/content/goddard/92b-

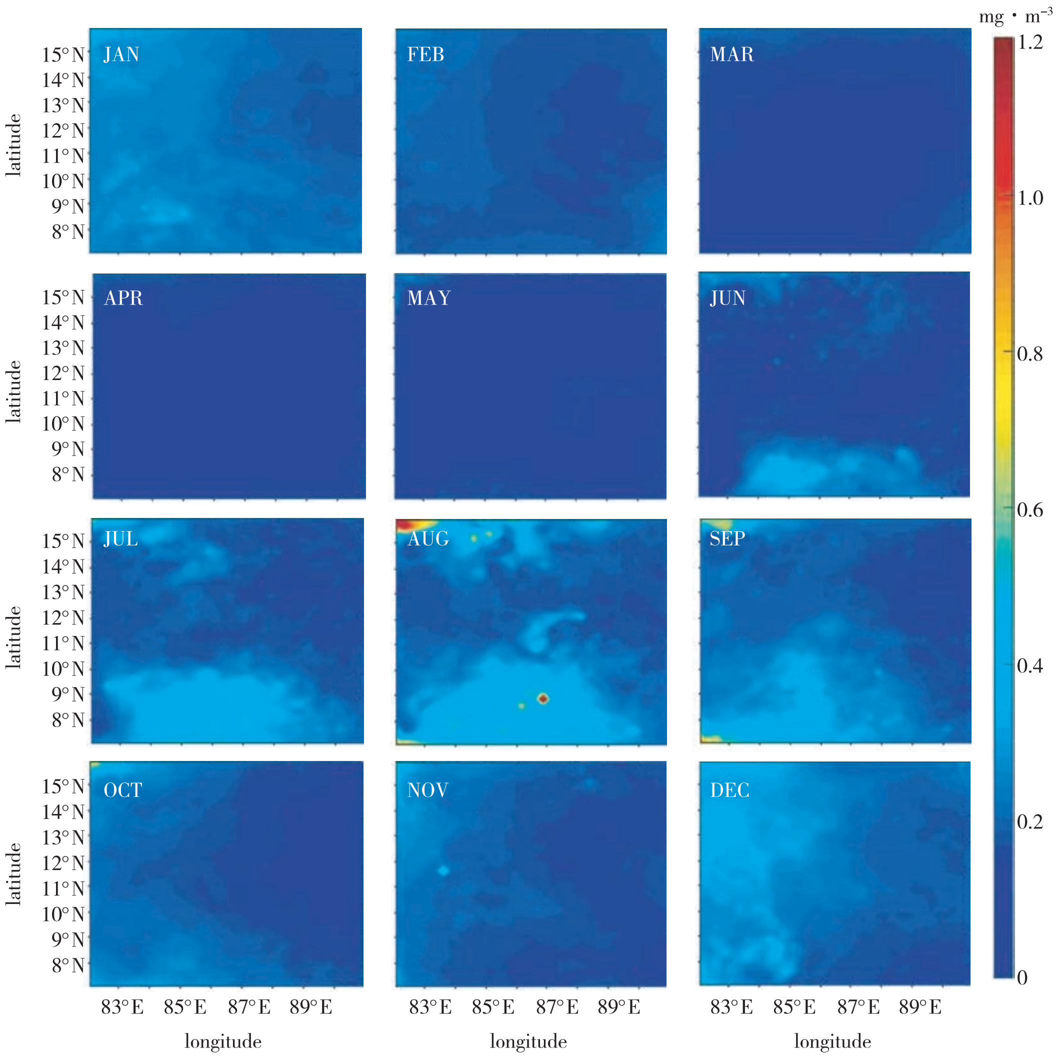

Fig. 3 Monthly averaged chl-a concentration in the study area, with summer cloud cover pixel error shown in July and August (below 10°N) (Sea WiFS monthly climatology)

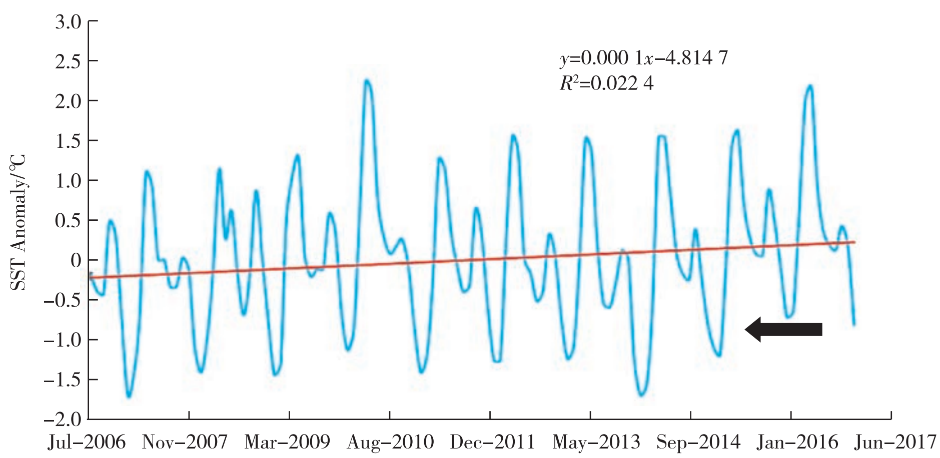

Fig. 4 Area averaged monthly time series of SST show an increasing linear trend in the studied region. Maximum sea surface value is observed in April 2010 (31.4 ℃). The black arrow shows the minimum SST anomaly during the study period

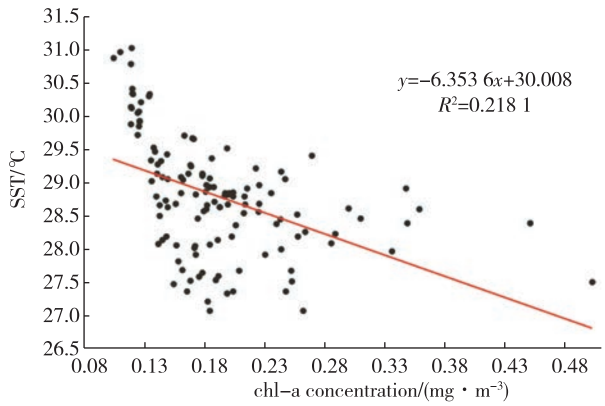

Fig. 5 Scatter plot of the monthly chl-a concentrations versus SST ($R^2=0.218\ 1$, $p<0.05$)

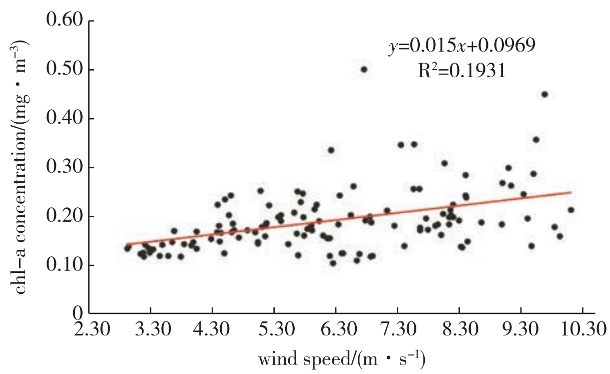

Fig. 6 Scatter plot of the monthly chl-a concentrations versus wind speed ($R^2=0.193\ 1$, $p<0.05$)

northern-indian-ocean/). Ekman pumping velocity index is an important character for understanding the vertical mixing in this period[21]. This could be the most appropriate reason to explain the above high chl-a value.

Due to the cloud cover pixel error in monthly climatology, chl-a concentration in the lowest part of the study region during July 2006 and August 2006 may be poorly averaged. The resulted chl-a concentration and wind speed correlation shows positive trend (increase) and these results suggest the upwelling induced by wind energy mechanism (moderately). Kumar et al., (2002) evaluated the less productivity in the BoB than in the Arabian sea during the summer monsoon period and mentioned that surface layer of the BoB is strongly stratified by frequent rainfall, river inputs and weak wind patterns over the BoB. Though the summer monsoon is impotent to corrode the stratified layer, which leads to the reduction in vertical mixing[22]. Figure 3 shows low chl-a concentration during May to June, but during July to September chl-a concentrations are very high as earlier (during summer monsoon). It could be due to the aforementioned cloud cover pixel issue during the period from July to August.

4.2 Monsoonal effect and SST on chl-a concentration

Upper layer chl-a concentration is identified as lower during the years 2006-2010 compared to the other years and then increases during 2010-2013; the inconsistency of chl-a graph for 2006-2016 displays that the year 2013 has recorded the highest value ($0.50\ mg/m^3$) but it tends to decrease from 2014 to 2015, and appears to increase again after June 2016. Due to cloud cover pixel errors winter monsoon and the inter-monsoon period is most suitable to study chl-a concentration in the BoB area because the spatially validated pixel availability is much higher than that in summer monsoon season. During winter monsoon period productivity is higher in the BoB than during summer monsoon period mainly due to the stratified upper water column (excluding natural cyclones formation). Most probably the occurrence of cold eddies controls the nutrient mixing to the surface ocean during the winter monsoon. The surface cooling is increased by the net heat loss from the sea surface. Relatively heavy winds induce the wind mixing and effect on the water column which also induce a proficient nutrients supply by cold eddies. Chl-a concentration in upper layers is chiefly dependent on stratification and wind mixing. Then, the chl-a concentration in the subsurface layer of the ocean is dependent on the existence of mesoscale eddies[23-24]. Importantly, surface water consists high concentration of dissolved oxygen than bottom water. As well, warm water is incapable of holding more dissolved oxygen than cold water, which may explain above results[25]. But there is no strong evidence of this impact on BoB region. Overall, a minor increasing trend of chl-a concentration is identified during 2006-2016 over the study area, which is evident from the statistical values ($R^2=0.000\ 2$, $p<0.05$).

During the study period, SST trend is positive but not significant (Fig.4), which is opposed to interpretations over the western Indian Ocean[26]. SST is a most important factor (other than wind stress) for vertical upwelling and winter mixing in the western Indian ocean. As well as the SST decline during winter monsoon (about 3 ℃) describes the occurrence of maximum chl-a within the winter monsoon (December) over the BoB region. Reducing SST levels further explain additional mixing of surface water and deep water which cause the supply of nutrients to the upper layers and enhance the productivity of surface layers[27]. Kumar et al. suggested that SST be considered as a proxy for factors which induce high chl-a concentration in the central equatorial Indian Ocean[16] but R^2 value is observed as 0.22 between chl-a concentration and SST in the current relationship study. Therefore, it couldn't be clearly suggested as a proxy for variables on chl-a concentration in the BoB region as in central equatorial Indian Ocean.

4.3 "Wind pump" effects on chl-a concentration

Wind stress is possibly the most important force effect on the upper layer of the ocean[28]. Generally, many scientists suggested that wind speed and chl-a concentration shows a strong positive relationship in open ocean[12,29-30], while the BoB region showed moderately positive relationship between chl-a and wind speed. Maybe the reason for the latter is the strong stratification which forms especially during the summer monsoon. Mixing behavior of wind and chl-a does not depend on each other alone. The course of winds could induce the upwelling or downwelling[31]. Wind patterns in the BoB stimulate minor upwelling considering other parts of the Indian Ocean, therefore, a positive correlation can be observed with wind and the increase in chl-a concentration. This can be considered as one of the "wind pump" effects[7].

5 Conclusion

During 2006－2016 the chl-a concentration illustrates moderate increasing trend in the BoB region. High chl-a concentration possibly occurs due to the enhanced horizontal advection during winter over the Indian Ocean region. This phenomenon affects biological productivity in the BoB region. The behavior of heavy winds and eddy featured cyclone formation are responsible for the nutrient uplifting to the surface areas and mixed layer enhancement through the cool thermocline water, via "wind pump" effects.

During September to January an increase in chl-a concentration occurs by this wind mixing and moderately cooling result. During winter monsoon high chl-a concentration can be observed due to the rich nutrients which are resulted by the deep and surface water mixing led by the decline in SST. Therefore, inhibiting the comparison between winter monsoon and summer monsoon.

This study shows both relationship between chl-a concentration and sea surface temperature (R^2 = 0.218 1, $p < 0.05$), and between chl-a concentration and wind speed ($R^2 = 0.193\ 1$, $p<0.05$). Moderate positive relationships are shown in BoB region. Most probable reason is the strong stratification especially in summer monsoon. Wind speed is considered as the most effective energy force in the vertical mixing in the BOB like other oceanic regions.

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