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Comparison of summer chlorophyll *a* concentration in the South China Sea and the Arabian Sea using remote sensing data

YAO Jinglong[1, 2], YANG Lei[1], SHU Yeqiang[1], ZENG Lili[1], SHI Rui[1], CHEN Ju[1], ZU Tingting[1], CHEN Chuqun[1, 3*]

[1] State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China

[2] China-Sri Lanka Joint Center for Education & Research, Chinese Academy of Sciences, Guangzhou 510301, China

[3] University of Chinese Academy of Sciences, Beijing 100049, China

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Abstract

The South China Sea (SCS) and the Arabian Sea (AS) are both located roughly in the north tropical zone with a range of similar latitude (0°–24°N). Monsoon winds play similar roles in the upper oceanic circulations of the both seas. But the distinct patterns of chlorophyll *a* (Chl *a*) concentration are observed between the SCS and the AS. The Chl *a* concentration in the SCS is generally lower than that in the AS in summer (June–August); the summer Chl *a* concentration in the AS shows stronger interannual variation, compared with that in the SCS; Moderate resolution imaging spectroradiometer (MODIS)-derived data present higher atmospheric aerosol deposition and stronger wind speed in the AS. And it has also been found that good correlations exist between the index of the dust precipitation indicated by aerosol optical thickness (AOT) and the Chl *a* concentration, or between wind and Chl *a* concentration. These imply that the wind and the dust precipitation bring more nutrients into the AS from the sky, the sub-layer or coast regions, inducing higher Chl *a* concentration. The results indicate that the wind velocity and the dust precipitation can play important roles in the Chl *a* concentration for the AS and the SCS in summer. However aerosol impact is weak on the biological productivity in the west SCS and wind-induced upwelling is the main source.

Key words: chlorophyll *a*, dust precipitation, Arabian Sea, South China Sea, nutrients

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1 Introduction

Oceans cover about 71% of the earth's surface, playing an important role in the climate change through their various physical and biogeochemical processes. The physical, chemical and biological processes are generally coupled and controlled by the physical forcing parameters of the ocean. The growth of phytoplankton depends on the availability of light and nutrients such as nitrogen, phosphorous, iron, etc. These nutrients are made available to phytoplankton by various sources such as river discharges, the atmospheric deposition, the offshore Ekman transports upwelling processes and mixed-layer dynamics of oceans. Of these, the atmospheric deposition is the main source of nutrients for most of the pelagic oceanic regions (Duce and Tindale, 1991; Erickson et al., 2003; Fan et al., 2006; Kayetha et al., 2007).

The Arabian Sea (AS), located mainly in the tropical zone of the Northern Hemisphere, is a unique oceanic region mostly influenced by the surrounding continents from the three sides and the semi-annual monsoonal reversals make the AS one of the highly productive regions over the world oceans (Madhupratap et al., 1996; Tang et al., 2002). Patra et al. (2007) discussed the atmospheric deposition of mineral dust as a major source of nutrients, attributed occurrences of the chlorophyll blooming in the northern Arabian Sea to aerosol depositions, whereas earlier studies (Tang et al., 2002) have presented evidence of cold SST eddies and supply of nutrients due to vertical mixing. The enhanced chlorophyll blooms also could be associated with the disturbed ocean surface stratification (Luis and Kawamura, 2002) at the time of dust storms. Moreover, a previous study (Singh et al., 2008) indicated successfully that one good consistency was received between the enhancement of the phytoplankton chlorophyll *a* (Chl *a*) concentration and the dust precipitations indexed by a satellite-derived aerosol optical thickness (AOT) in the Arabian Sea.

The South China Sea (SCS) is mostly located also in the tropical zone of the Northern Hemisphere, where there are similar physical forcing features on seasonal reverse monsoons and seasonal reverse basin-wide circulations during different seasons In contrast, the SCS belongs mainly to the oligotrophic region (Liu et al., 2002; Li et al., 2006; Zhao and Tang, 2007), where phytoplankton is not productive generally with low Chl *a* concentra-

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*Corresponding author, E-mail: cqchen@scsio.ac.cn

tion (<0.2 mg/m^3) or low primary productivity all the year around. Aerosol impact on biogeochemistry was also preliminarily studied in the SCS (Lin et al., 2007).

In recent years, because of changes in wind shear, land cover and precipitation patterns, the amount of dust uplifted and long range transport of the mineral dust is found to be quite variable. The mineral dust is found to enhance a phytoplankton population (Kayetha et al., 2007; Baker et al., 2003; Cropp et al., 2005; Mahowald et al., 2005), and in turn the increase of the phytoplankton population may lead to the ecological imbalance over oceanic regions. In this paper, we have made efforts to clarify spatial and temporal patterns of dust precipitations and other oceanic parameters and study their impact on the Chl *a* concentrations using moderate resolution imaging spectro-radiometer (MODIS) data and other satellite data including QuikSCAT wind and TRMM SST from December 2003 to December 2008. The detailed analysis of the MODIS Chl *a* concentration and the AOT will be used to investigate whether an enhancement in chlorophyll concentrations is linked to the dust precipitations reflected by the AOT as well as strong wind in the AS.

2 Study area, data and methods

2.1 *Study area and data sampling*

The SCS and the AS are both located mostly in the tropical regions of the Northern Hemisphere, from 0° to 24°N (Fig. 1), where southwesterly summer monsoon is prevailing and northeasterly winter monsoon is dominated in most of the two seas. Considering the obvious distinctness of the phytoplankton biomass between the SCS and the AS, we will investigate the dynamical mechanism producing the two different phytoplankton patterns in the present study. Our work is stressed on the west regions of both SCS and AS, where the variation of Chl *a* concentration as well as the wind, the AOT is more notable.

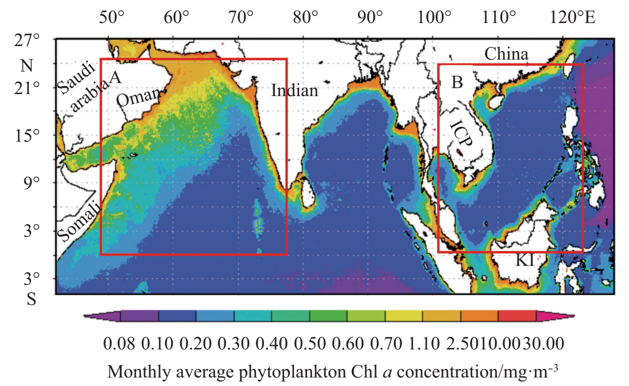

Fig. 1. The locations of the study area (shown as Boxes A and B) and the monthly phytoplankton Chl *a* concentrations averaged for July 2002 to December 2008. Box A represents Arabian Sea and Box B represents South China Sea; ICP is short for Indo-China Peninsula and KI is short for Kalimantan Island.

2.2 *Satellite products*

The MODIS monthly products (Level-3) (http://oceancolor.gsfc.nasa.gov/) of resolution 9 km×9 km are used to study the summer variations and the effect of dust storms during 2003–2006. MODIS products contain various geophysical parameters as multi-layered data. In the present study, the Chl *a* concentration (mg/m^3) and the AOT have only been extracted from the above products in the SCS and the Arabian Sea. The possible influence of dust precipitation is studied through investigating the deposition of aerosol (i.e., AOT) associated with the dust events over the AS and the SCS.

The fusion of daily SST (TMI_AMSRE) was derived from the tropical Rainfall Measuring Mission (TRMM) microwave imager (TMI) and the advanced microwave scanning radiometer-EOS (AMSR-E). They have a resolution of 0.25°×0.25°. Owing to the cloud-penetrating capacity of both TMI and AMSR-E, the two measurements together can overcome influence of cloudy conditions (Wentz et al., 2000). Therefore, the TMI_TRMM and the AMSR-E fusion SST products are also used in this study.

Surface wind velocity (SWV) data are based on the microwave scatterometer SeaWinds on QuikSCAT satellite that measures the surface wind over the oceans (Liu et al., 2000). The monthly QuikSCAT data from the NASA (http://poet.jpl.nasa.gov) were used. Using MODIS monthly data sets, the Chl *a* concentrations, the AOT and the SST as well as the QuikSCAT wind over the oceanic regions, over which the influence of the dust and wind fields, are studied and an attempt is made to reveal the difference of phytoplankton biomass between the SCS and the AS.

2.3 *Methodology*

2.3.1 *Chl a concentrations, AOT and SST*

In the present study, we use monthly products because there were generally relatively sparse valid observations of Chl *a* concentration due to cloudy weather conditions. Here, the Chl *a* concentrations, the AOT and the SST were averaged over summer season (1 June to 31 August) for every year, respectively. The summer mean images (June–August) are presented in every year. Through analyzing the interannual variation of Chl *a* concentration as well as the AOT and the SST, the characteristics of Chl *a* concentration and the mechanism of its response to oceanic conditions will be discussed.

2.3.2 *Surface wind velocity (SWV)*

It is well-known that the monsoons play generally important roles in the upper oceans through mixing, upwelling, circulation and other disturbances induced by the SWV. Thus, here we will present the summer wind distribution of wind field in the present study and discuss the influence of the SWV on the SCS and the AS. Similar to the processing of the Chl *a* concentration, the images of the SWV were painted for the same period (summer: 1 June to 31 August) from 2003 to 2008.

Furthermore, in order to analyze the influence of offshore transport of coastal nutrient-rich water triggered by winds, we will also introduce Ekman volume transport to present offshore transport of coastal water and the contribution of the wind fields in our chosen regions where the strong winds are prevailing and roughly parallel to the coastline:

$$U_{\rm V} = \frac{1}{\rho_0 f}\tau, \tag{1}$$

$$f = 2\Omega \sin\psi, \tag{2}$$

$$\tau = \rho_{\rm a} C_{\rm d} U^2, \tag{3}$$

$$C_{\rm d} = \frac{(0.6 + 0.07U)}{1000} \quad (6\ {\rm m/s} \leqslant U \leqslant 26\ {\rm m/s}), \tag{4}$$

where U_V is the volume transport vertical to the coastlines; τ is the sea surface wind stress vertical to the coastlines; ρ_0 is the density (assuming 10^3 kg/m^3 here) of ocean water; ρ_a is the air density (1.25 kg/m^3); ψ is a latitude degree (°); Ω is the rotation rate of the earth (Ω=7.292×10^{-5} rad/s); U is the wind velocity; and C_d is the drag coefficient of wind.

3 Results

3.1 *Time series of satellite data*

To investigate further the relationship between the Chl *a* concentration and the oceanic conditions, we chose two boxes (8°–13°N, 105°–115°E) and (8°–13°N, 50°–60°E) in Fig. 2a for time series during summer respectively for the SCS and the AS, where the variations of Chl *a* concentration, were more notable. The time series of the Chl *a* concentration, the AOT, the SWV, and the SST were averaged over the boxes for summer from 2003 to 2008, where the changes were more evident.

Both the AS and the SCS (Fig. 2) are situated roughly in the same tropical zones with similar latitude scopes; the AS is generally a high productive region, in most of which the annual mean concentration of Chl *a* concentration (Figs 1 and 2) is over 0.4 mg/m^3. However, The SCS belongs mostly to typical oligotrophic region where low phytoplankton biomass (Fig. 1) appears in most areas of the SCS (Chl *a* concentration less than 0.2 mg/m^3). The significant difference of Chl *a* concentration between the AS and the SCS will be presented in the paper.

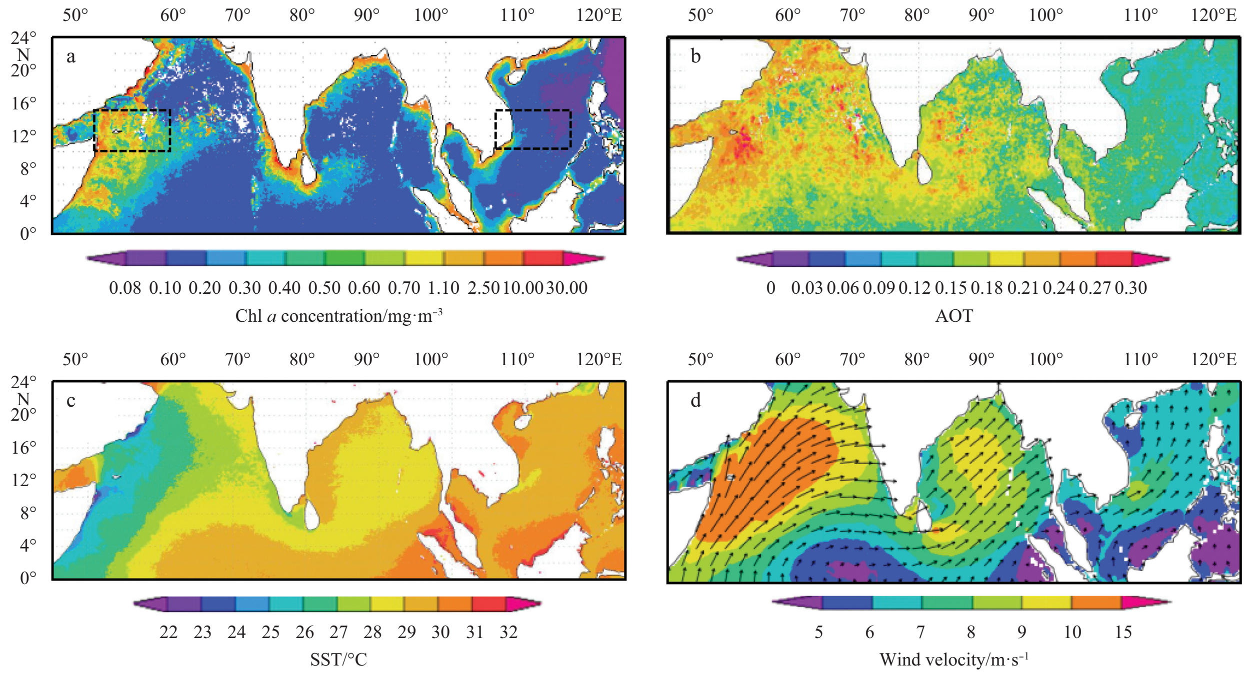

Fig. 2. The summer climatology averaged for 1 June to 31 August durding the period of 2003–2008 over the study area. a. Chl *a* concentration, b. AOT, c. SST and d. surface wind velocity. Boxes in Fig. 2a are the sampling areas of Chl *a* concentration in the AS and the SCS, respectively.

3.2 *Summer Chl a concentrations*

The Chl *a* concentration (Fig. 1) is high (>0.3 mg/m^3) in the whole AS, and is over 0.4 mg/m^3 in west of the AS, especially higher (Fig. 2) in nearshore regions east of the Somalia Peninsula in summer. The Chl *a* concentration (Figs 1 and 2) in west of the AS is generally higher than that in east of the AS. There is the similar spatial tendency with high (low) concentration in west (east) of the two seas. However, the Chl *a* concentration (Figs 1 and 2) in the SCS is generally low (<0.2 mg/m^3) in most of the offshore regions, except a little higher (about 0.3 mg/m^3) southeast of Vietnam. In summer, higher Chl *a* concentrations (Fig. 2) are observed in the AS than those in the SCS, especially higher southwest of the AS. And the Chl *a* concentration in the AS presented more evident interannual variation, compared with that in the SCS.

3.3 *Distribution of AOT*

According to the MODIS-derived aerosol data, the AOT at 869 nm shows evidently the spatial and temporal variation of aerosol in both two regions (Fig. 3). The AOT is thick (roughly greater than 0.24) in most of the AS with thicker AOT (>0.27) in the west of the AS. In contrast with the AS, the AOT in the SCS is generally thinner (<0.15), and thicker south than north of the SCS in summer.

3.4 *SST distribution in the AS and the SCS*

In summer, the SST (Fig. 4) in the AS is low (23–28°C), while the SST is uniformly higher (28–31°C) in the SCS. The SST in the AS is obviously lower with a decrease of 0–6°C, compared with that in the SCS. In the AS, the SST is lower in the west than that in the east roughly with a mean gap of 3°C. The similar tendency occurs in the SCS, nevertheless, the SST difference between the west SCS and the east SCS is not obvious, compared with that in the AS.

3.5 *Sea surface wind velocity*

The SWV (Fig. 5) are roughly over 9 m/s in the whole AS, even up to 15 m/s in the west AS. The wind vectors are along the direct from the southwest to the northeast roughly parallel to the west coastlines in the west AS (i.e., the coastlines from the Somali Pen-

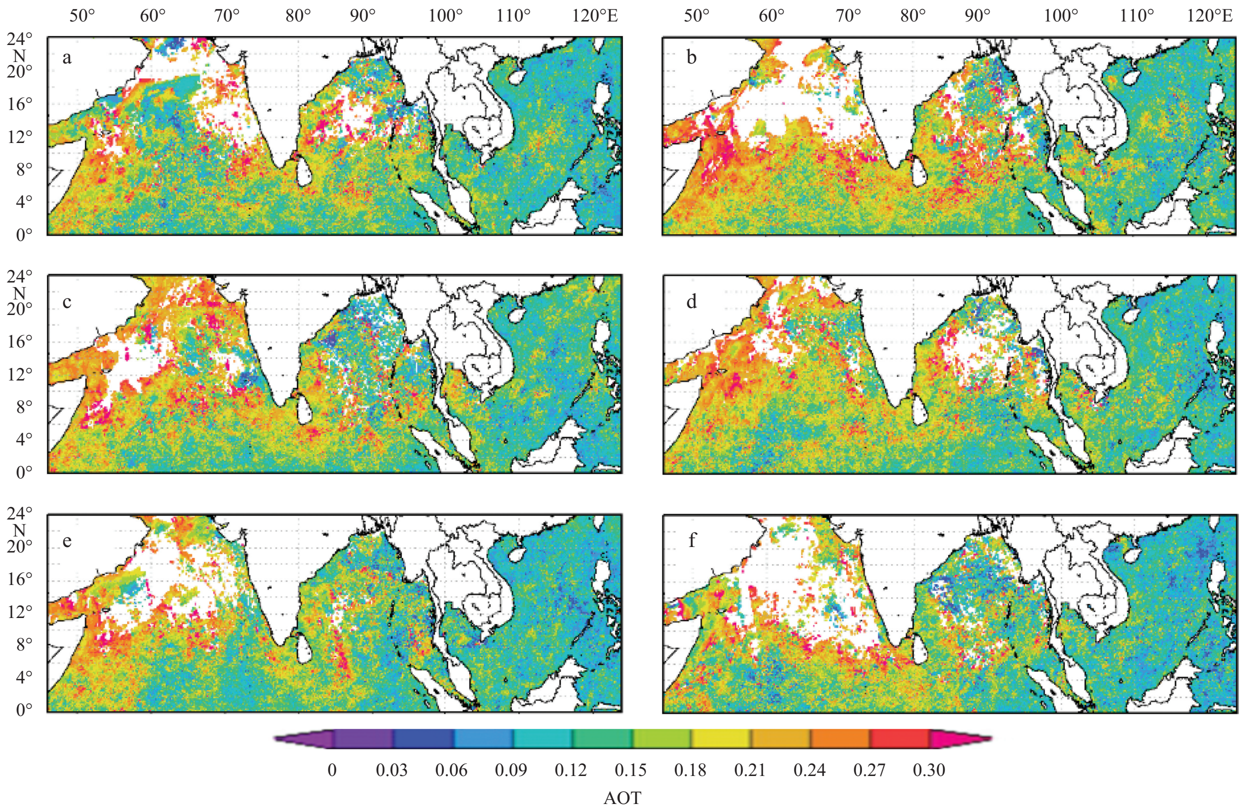

Fig. 3. The summer AOT averaged for 1 June to 31 August over the study area during the period of 2003–2008. Figures 3a–f indicate 2003–2008, respectively.

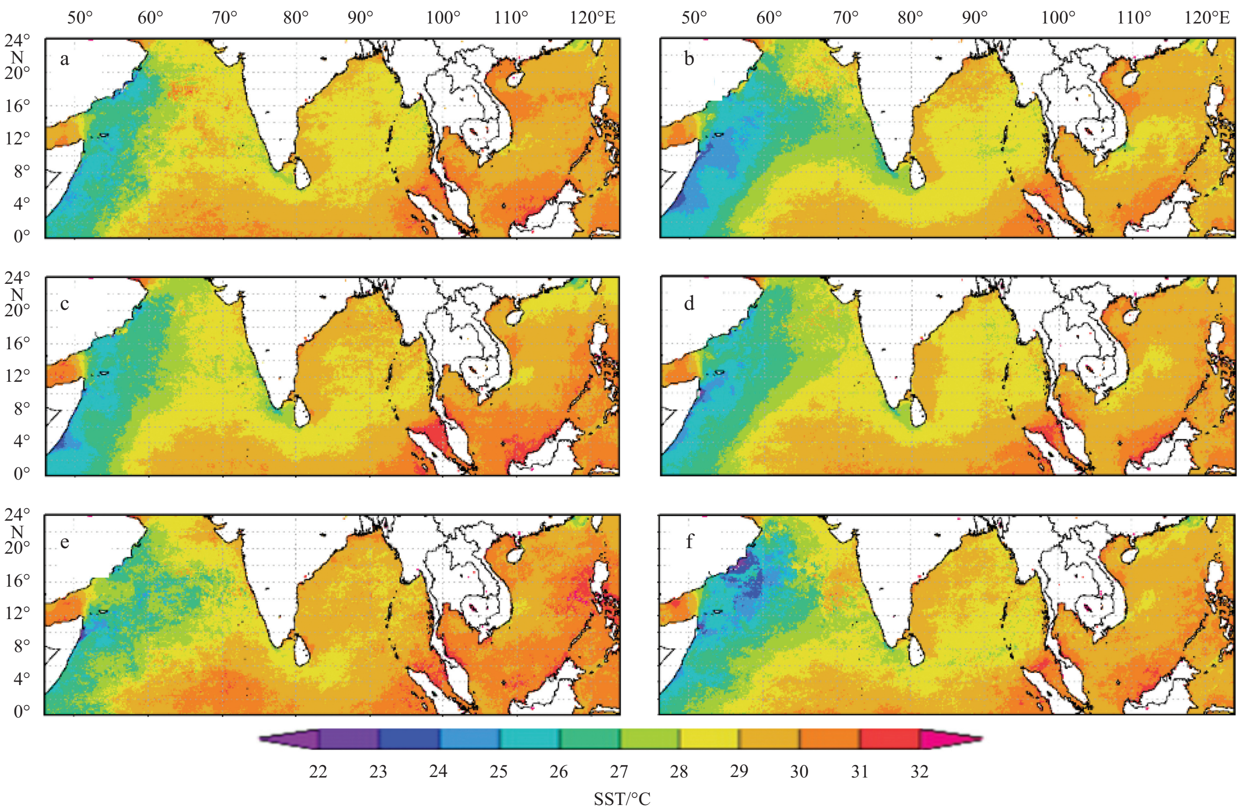

Fig. 4. The summer SST averaged for 1 June to 31 August during the period of 2003–2008 (a–f) using AMRE-TRMM merged products. Figures 4a–f indicate 2003–2008, respectively.

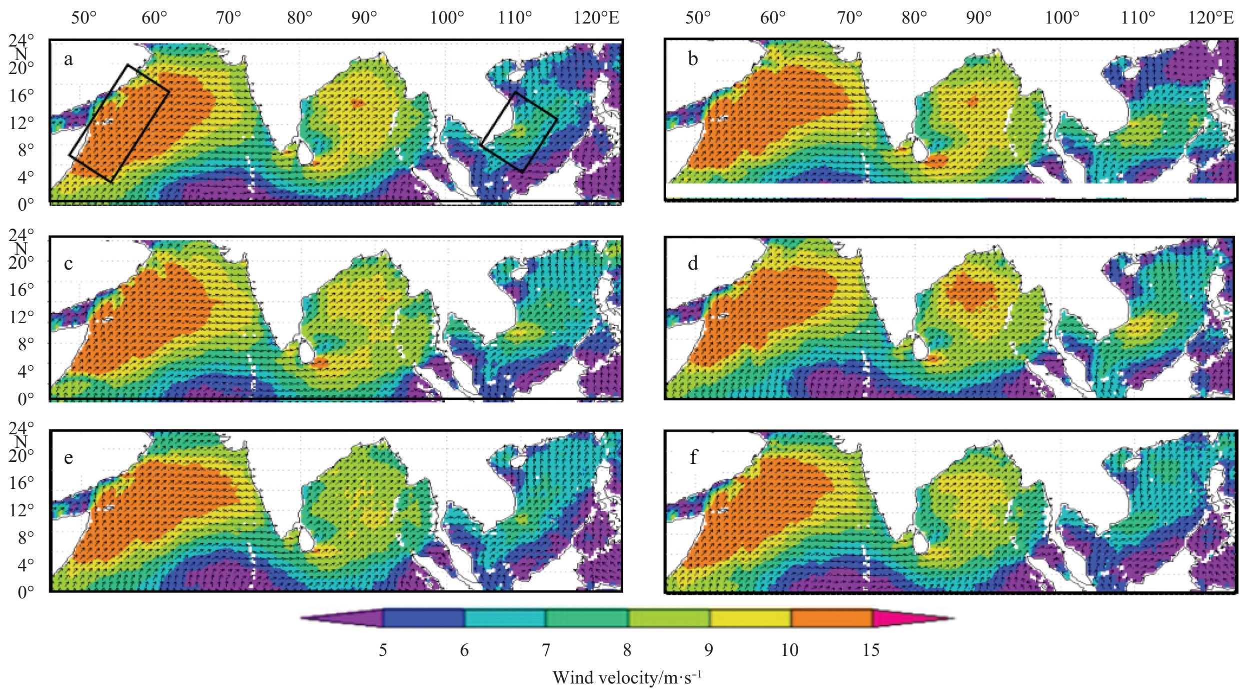

Fig. 5. The summer QuikSCAT-derived wind velocity averaged for 1 June to 31 August during the period of 2003–2008. Figures 5a–f indicate 2003–2008, respectively.

insula to Oman, left box in Fig. 5a) and points to the east in the east AS (east of 65°E). In contrast with the AS, the wind velocity is almost weaker (<7 m/s) in the whole SCS, only a little stronger (9–10 m/s) in the southeast of Vietnam with a southwest direction parallel to the Vietnam's coastline (right box in Fig. 5a).

3.6 *Time series of summer Chl a concentration and oceanic conditions*

The time series (Fig. 6) of the Chl *a* concentration, the SST, the AOT and the wind velocity were calculated on the study area (Fig. 1) averaged for 1 June to 31 August from 2003 to 2008. The mean Chl *a* concentration in Box A is over 1.14 mg/m^3, about 3.85 times of that (about 0.3 mg/m^3) in Box B. And the SST in the AS is lower 3.44°C than that in the SCS. In the AS, there is a high aerosol level illustrated by the AOT (0.23 for the AS, compared with 0.14 for the SCS). The wind velocity are also evidently stronger in the AS (the mean velocity about 12 m/s) than those (the mean velocity about 7.7 m/s) in the SCS. On the basis of the above wind velocity and Eqs (1)–(4), we can estimate that the offshore Ekman mass transport vertical to the coastlines in the west AS is about three times of that in the SCS.

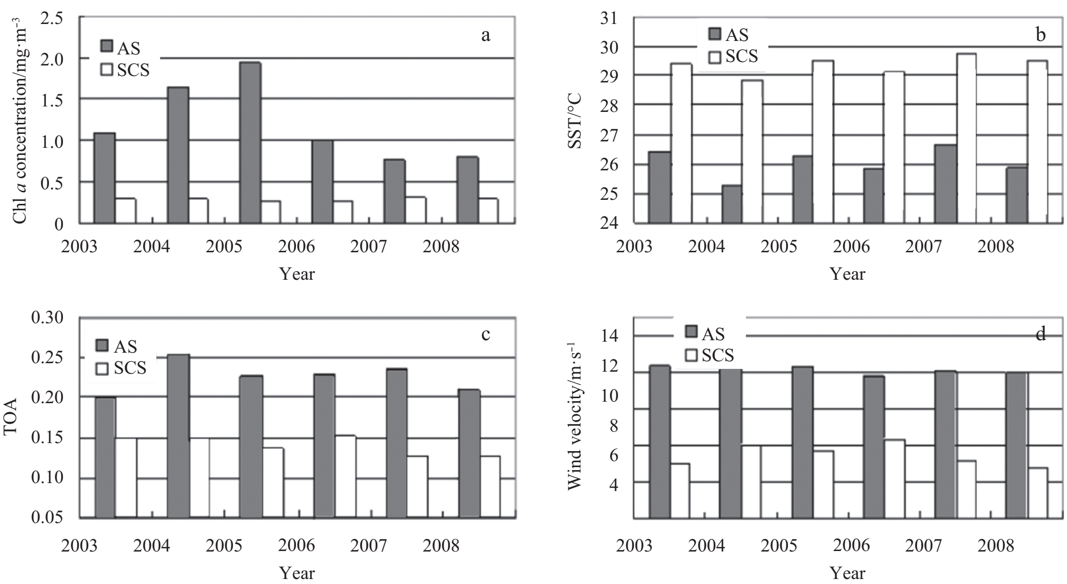

Fig. 6. The summer time series averaged for 1 June to 31 August over the study area from 2003 to 2008. a. Chl *a* concentration, b. SST (°C), c. AOT, and d. wind velocity.

4 Discussion

4.1 *Higher phytoplankton biomass in the AS than in the SCS*

According to the present study between the AS and the SCS, the high Chl *a* concentrations (>0.2 mg/m^3) are common features in the AS, especially higher (>0.4 mg/m^3) in the area near the west AS during summer, associated with the strong wind speed (>10 m/s), the low SST and the thick AOT; However, compared with these in the AS, the lower Chl *a* concentration features are very obvious in most of the SCS, where the weak wind speed, the high SST and the thin AOT prevail generally. Thus, the higher productive biomass in the AS may be triggered due to the higher atmospheric deposition illustrated by the AOT, and stronger winds which can induce strong upwelling/mixing entrainment and lower SST, compared with those in the SCS.

The upwelling triggers generally low SST due to the upward transport of low-temperature deep water, which reflects intensities of upwelling in turn. Previous studies suggested that mixing and coast/offshore upwelling associated with summer southwest wind may play an important role in the decrease of the SST and the Chl *a* concentration enhancement in both the SCS and the AS (Van Couwelaar, 1997; Bartolacci and Luther, 1999; Woodward et al., 1999; Lee et al., 2000; Fischer et al., 2002; Xie et al., 2003; Banzon et al., 2004; Smith and Madhuprata, 2005; Zhao and Tang, 2007). Tang et al. (2002) were attributed the chlorophyll blooms in the northwest AS to cold eddies with low SST, which induced upwelling and vertical mixing to raise nutrients from the sublayer. Whereas recent studies by Patra et al. (2007) suggested that the atmospheric deposition of the mineral dust may be one of the major sources of nutrients, inducing the chlorophyll blooms in the northern Arabian Sea. Singh et al. (2008) indicated also that dust precipitations including dust storms played an important role in the Chl *a* concentration enhancement of the northern AS.

4.2 *Roles of SWV and aerosol deposition*

In order to quantitatively discuss the influence of the wind velocity and the atmospheric depositions on the AS and the SCS, the time series of oceanic conditions and Chl *a* concentration were produced respectively in the regions of the west AS and the west SCS (Boxes A and B in Fig. 1). The time series for the study area indicated that Chl *a* concentration, the AOT, and the wind velocity in the AS are respectively 2.0–4.0 times, 1.3–2.0 times, 1.5–2.0 times of those in the SCS, respectively. In addition, the SST in the AS is about 3.44°C less than that in the SCS. The better correlation of the Chl *a* concentration with the SST was presented in both the AS and the SCS, with correlation coeficients of –0.32 and –0.48, respectively. The above correlation implied that the SST is relatively one good index of upwelling in our study area. The results also affirm the speculation in Section 4.1. Furthermore, according to the wind velocity parallel to the coastlines, we can estimate that the wind-induced offshore Ekman mass transport vertical to the coastlines in the west AS is about 2.0–3.0 times of that in the west SCS, suggesting significant supply of more nutrients-rich water into offshore regions of the AS. The regression analysis displayed also a good positive tendency between the Chl *a* concentration and the wind velocity/the AOT, of which the correlation (r=0.61, p<0.05) between the Chl *a* concentration and the wind velocity is better than that (r=0.58, p<0.05) between the Chl *a* concentration and the AOT, suggesting that the wind velocity may also be one of the important factors inducing the high Chl *a* concentration besides the AOT in the AS. It is well-known that nutrients are generally positively correlated with the Chl *a* concentration in the oligotrophic oceans (Sunda and Huntsman, 1997; Hutchins and Bruland, 1998; Jickells et al., 2005; Meskhidze et al., 2005; Yuan and Zhang, 2006). The atmospheric general circulation and the wind velocity at 850 hPa (Fig. 7) displayed that the wind summer pattern and the processes of the atmospheric circulation with one strong southeasterly wind from Northeast Africa joining the strong anticyclonic atmosphere circulation over the west AS, illustrating further that wind can play an important role in coastal upwelling, but also in transport of the dust particles from Northeast Africa (Singh et al., 2008). The results indicate also that the wind velocity may play more important role in the higher Chl *a* concentration in the west AS. In addition, due to the lower SST in the AS being more favorable to mixing/entrainment under the influence of the same wind field, the lower SST in the AS may lead to more supply of nutrients than that the higher SST in the SCS, which may exert also certain effect on the high Chl *a* concentration in the AS. And in the SCS, the wind velocity shows also good correlations with Chl *a* concentration, with the correlation coefficients of 0.5 (p<0.05). However the negative correlation between the Chl *a* concentration and the AOT is not significant (r=–0.15 (p>0.05)), coincided with the result of Lin et al. (2009), who thought that aerosol impact on Chl *a* concentration in the region is minor and monsoon-induced upwelling is the main source to support the biological productivity, based on the monthly MODIS-derived AOT data. And previous studies (Liu et al., 2002; Xie et al., 2003; Zhao and Tang, 2007) indicate also that upwelling is prevailing in summer in the west SCS. Therefore aerosol dust indexed by the AOT in summer is not important in the west SCS, and the SWV may play one vital role in the phytoplankton biomass through upwelling induced by the wind parallel to the coastlines and wind stress curls, as well as wind-induced mixing. In contrast, the more effective dust fertilizing is mainly in the AS through natural aerosol deposition, which leads to the positive relation between the AOT and the Chl *a* concentration because the rainfall (<200 mm/a) is seldom in the AS all the year round (Baumgartner and Reichel, 1975). In the future study, we will further investigate the influence of rainfall on the AOT in the SCS.

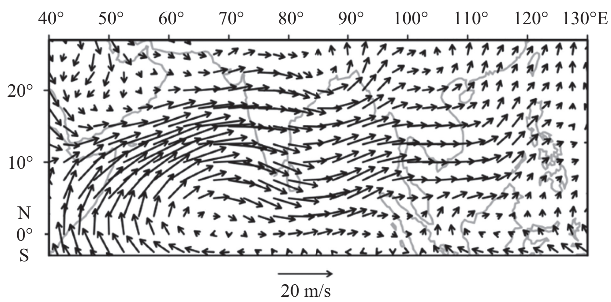

Fig. 7. Atmospheric general circulation and wind velocity at 850 hPa (at the height of 1 500 m) in summer.

5 Conclusions

Stronger wind speed, higher AOT and lower SST are obvious in the AS, compared with these in the SCS, these factors may cause higher phytoplankton biomass in the AS than that in the SCS. The wind velocity plays possibly one more important role in the high phytoplankton biomass through the mixing entrainment and offshore Ekman transport than the aerosol precipitation in the AS. The wind velocity can exert an important influence on phytoplankton in the SCS, and the negative correlation between the AOT and the Chl *a* concentration may be caused by rainfall, which brought dust indexed by the AOT into the ocean, reducing the aerosol concentration indexed by the AOT in the sky.

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