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Research Article

Vertical Patterns of Early Summer Chlorophyll a Concentration in the Indian Ocean with Special Reference to the Variation of Deep Chlorophyll Maximum

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Vertical patterns of early summer chlorophyll *a* (Chl *a*) concentration from the Indian Ocean are presented, as well as the variations of depth and size-fractioned Chl *a* in the deep chlorophyll maximum (DCM). A total of 38 stations were investigated from 12 April to 5 May 2011, with 8 discrete-depth samples (7 fixed and 1 variable at real DCM) measured at each station. Depth-integrated Chl *a* concentration ($\sum$Chl *a*) varied from 11.5 to 26.8 mg m^{-2}, whereas Chl *a* content at DCM ranged from 0.17 to 0.57 μg L^{-1} with picophytoplankton (<3 μm) accounting for 82% to 93%. The DCM depth varied from 55.6 to 91 m and shoaled latitudinally to northward. Moreover, our results indicated that the $\sum$Chl *a* could be underestimated by up to 9.3% with a routine sampling protocol of collecting samples only at 7 fixed depths as the real DCM was missed. The underestimation was negatively correlated to the DCM depth when it varied from 55.6 to 71.3 m ($r = -0.63$, $P < 0.05$) but positively correlated when it ranged from 75.8 to 91 m ($r = 0.68$, $P < 0.01$). This indicates that in the Indian Ocean the greater the departure of the DCM from 75 m depth, the greater the underestimation of integrated Chl *a* concentration that could occur if the real DCM is missed.

1. Introduction

Photosynthetic marine phytoplankton species play a pivotal role in oceanic biological processes, producing particulate and dissolved organic carbon [1]. Such photosynthetic processes also reduce the partial pressure of CO_2 in surface seawater and ultimately result in the drawdown of atmospheric CO_2 [2]. In surface oceans, a series of environmental factors are known to control the biomass and distribution of phytoplankton. Light intensity influences phytoplankton growth and productivity through driving or photoinhibiting photosynthesis [3, 4], while vertical mixing affects carbon fixation ability by balancing the damage and repair at high or low light levels [5, 6]. The available trace metals (e.g., copper and iron) also lead to variations in phytoplankton biomass or size communities [7–9]. The temperature that often regulates surface ocean stratification can reduce the exchange of nutrients between deep nutritious water and surface water, depressing nutrient status within the euphotic zone and influencing species composition [10]. Changes in physico-chemical environments (e.g., light, mixing, temperature, or nutrients) would thus influence phytoplankton community structure and alter their vertical distributions in the water column [10, 11].

In pelagic oceans, the deep chlorophyll maximum (DCM) that appears between the nutrient-depleted upper and light-limited lower layers of the euphotic zone is usually characterized by high phytoplankton biomass and production [12–15]. Contributions of the DCM to integrated chlorophyll *a* (Chl *a*) and primary production have been estimated up to 90% and 30% of total [12, 13]. As a result, many studies tend to focus on the DCM layer

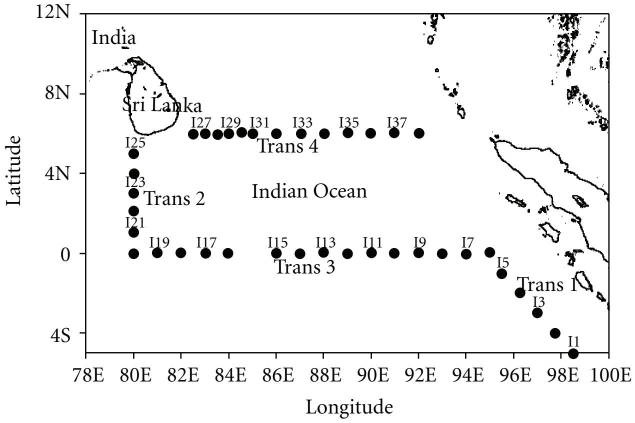

Figure 1: Map of the Indian Ocean, showing the sampling sites (solid circles) during the cruise dated from 12 April to 4 May, 2011.

in marine investigations, for example, in the South China Sea [10, 16], Atlantic or Pacific Oceans [15, 17]. Regionally, the Indian Ocean hosts a unique oceanographic process caused by semiannually reversing monsoon winds [18–20], leading to a great variation in vertical stability and nutrients fluxes as well as depth of upper mixed layer (UML) [21–23]. Corresponding to such changes in mixed layer depth and nutrient regeneration, thickness and depth of the DCM therein would be changed greatly [24, 25], as well as phytoplankton community structure [15]. It is of general interest to understand such biological characteristics of the DCM; however, little has been documented in the Indian Ocean [15]. In this study, we investigated the vertical patterns of Chl *a* concentration in this tropical region and looked into the size communities of the DCM layer.

2. Materials and Methods

2.1. Study Area and Sampling Protocol. During a cruise dated from 12 April to 4 May 2011, we measured the profiles of chlorophyll *a* (Chl *a*) concentration in the Indian Ocean. A total of 38 stations were settled at intervals of 55 to 110 km along four transacts: transacts 1, 2 in latitude and transacts 3, 4 in longitude (Figure 1). At each station, discrete seawater samples were collected from 7 fixed depths (0 m, 25 m, 50 m, 75 m, 100 m, 150 m, and 200 m) with a Rosette sampler fitted with 5 L Niskin Bottles and mounted on a Sea-Bird Electronics CTD (SBE-911 plus, USA); this sampling protocol is broadly used (e.g., [26, 27]). To vividly track the variable deep chlorophyll *a* maximum (DCM), one more water sample was taken from a depth of maximal fluorescence that was determined by a CTD-mounted fluorometer (termed hereafter real DCM). All 8 collected samples were treated within 10 min for determination of Chl *a* content and phytoplankton species composition as described below.

2.2. Chl a Determination. To determine Chl *a* concentration, 800 mL seawater from each depth of each station was filtered onto a Whatman GF/F glass fiber filter (25 mm), which was immediately wrapped in aluminum foil, frozen, and stored at −20°C for later extraction and measurement. The content of Chl *a* was measured fluorescently using a Turner Design 10 fluorometer after a complete extraction with 90% acetone (v/v) for 24 h in the dark at 4°C. Chl *a* concentration was calculated according to Parsons et al. [28]. For determination of picophytoplankton cells fraction ($<3\,\mu$m), prefiltered ($3\,\mu$m pore-size polycarbonate filter) samples were filtered onto a Whatman GF/F filter, and the measurement of Chl *a* was performed as described above.

2.3. Species Analyses. For phytoplankton species analyses, the seawater sample was fixed with Lugol's solution to a final concentration of 1.5% [28]. After one-liter sample was concentrated to 30 mL by settling for 24 h and gently siphoning supernatant, identification and numeration of the species were conducted under a regular microscope for a whole 0.5 mL sample with Utermöhl's method [29].

2.4. Data Analysis. Chl *a* concentration of the water column was integrated as [30]

$$\sum \mathrm{Chl}\,a = \int_0^{200} [\mathrm{Chl}\,a], \tag{1}$$

where $\sum \mathrm{Chl}\,a$ ($\mathrm{mg\,m^{-2}}$) is the depth-integrated Chl *a* concentration, whereas [Chl *a*] is the Chl *a* concentration ($\mu\mathrm{g\,L^{-1}}$) at one depth.

Underestimation (%) of the depth-integrated Chl *a* when missing the real DCM was calculated as

$$\mathrm{Uest}\,(\%) = \frac{\left(\sum \mathrm{Chl}\,a - \sum' \mathrm{Chl}\,a\right)}{\sum \mathrm{Chl}\,a} \times 100\%, \tag{2}$$

where Uest (%) is the underestimation of depth-integrated Chl *a* due to the real DCM missing and $\sum$Chl *a* and $\sum'$ Chl *a* ($\mathrm{mg\,m^{-2}}$) are the depth-integrated Chl *a* calculated using the Chl *a* density collected from 7 fixed and 1 variable depths (i.e., real DCM) or just using that from 7 fixed depths (miss the real DCM), respectively.

We combined data from transacts 1 and 2 together in Figure 2 to more clearly show a latitudinal variation of

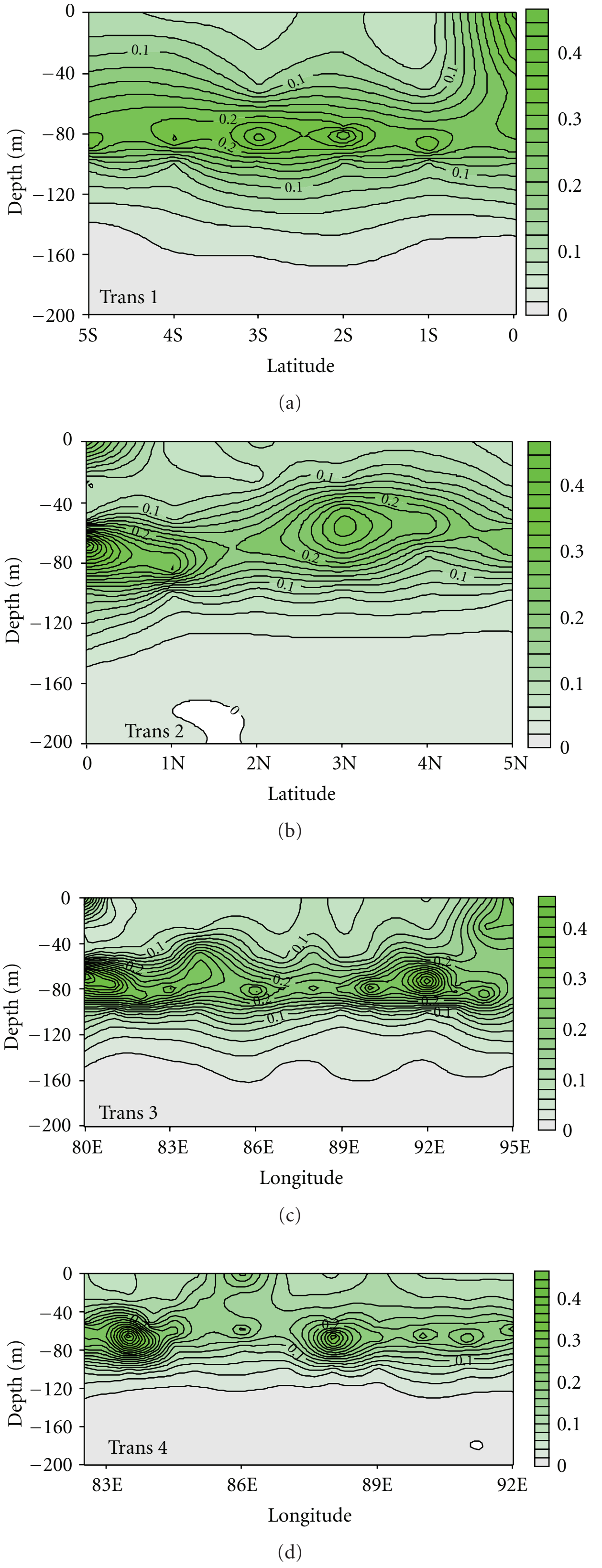

Figure 2: Vertical patterns of chlorophyll *a* concentration (Chl *a*, μg L^{-1}) along the four transects, showing the variations in the latitudinal ((a) and (b)) and longitudinal ((c) and (d)) scales.

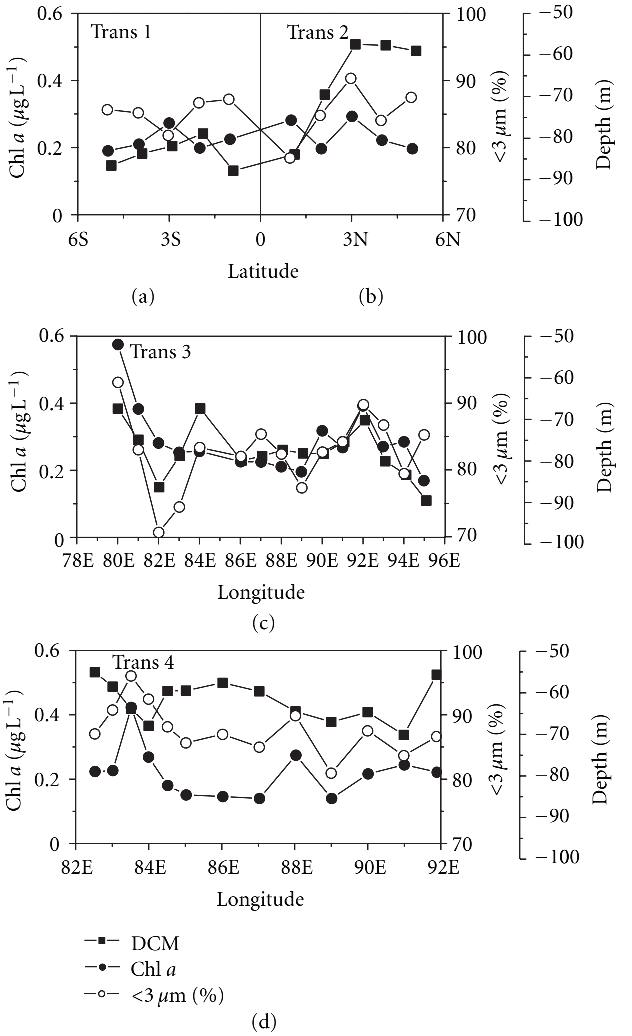

Figure 3: Variability of the Chl *a* concentration (μg L^{-1}), proportion of picocells fraction (%) and depth (m) of the DCM: in latitude ((a) and (b)) and longitude ((c) and (d)).

Chl *a*. One-way analysis of variance (ANOVA) was used to determine the significant differences among the estimated parameters ($P < 0.05$); the correlation between variables was established using a Kendall's *t*-test with 95% confidence band.

3. Results

Contours of Chl *a* for the four transacts in the Indian Ocean throughout 12 April to 4 May 2011 are shown in Figure 2. Chl *a* concentration displayed a drastic change with increasing depth, with surface values being less than 0.10 μg L^{-1} in most cases (except at stations I6 and I20); it increased to a maximum of over 0.20 μg L^{-1} at the DCM and then decreased to less than 0.01 μg L^{-1} at the bottom (Figure 2). The most conspicuous feature relating to the pattern of vertical Chl *a* distribution was the location of the DCM, which varied greatly and shoaled latitudinally to northward (Figures 2(a) and 2(b)).

Great variability of Chl *a* content at the DCM as well as its depth was found for the study period (Figure 3). Chl *a* varied greatly from 0.17 to 0.57 μg L^{-1} at stations I35 and I20, respectively, where picophytoplankton (<3 μm) accounted for 82% and 93% of total Chl *a* (Figure 3). Most of the microscopically identified phytoplankton groups were dinoflagellates (e.g., *Amphidinium carterae*, *Gyrodinium* spp., *Gonyaulax* spp. and *Prorocentrum* sp.) and diatoms (e.g., *Chaetoceros* spp.), although the cyanobacterium *Trichodesmium hildebrandtii* was numerically important at some stations (e.g., I6 and I7). In particular, depth of the DCM displayed a high variability in a latitudinal scale and shoaled from 91 to 55.6 m to northward (Figures 3(a) and 3(b)); however, less variability was shown in a longitudinal scale (Figures 3(c) and 3(d)). The DCM depth in transact 3 (equatorial water) was 79 ± 6.4 m, approximately 16 m deeper than that of transact 4 (6°N water, 63 ± 5.0 m) (Figures 3(c) and 3(d)).

Depth-integrated Chl *a* concentration ($\sum$Chl *a*) ranged from 11.5 to 26.8 mg m^{-2} if including the real DCM at stations I32 and I7, respectively (Figure 4(a)). Exclusion of the real DCM caused 0.65% to 9.3% underestimation of the $\sum$Chl *a* (Figure 4(b)) where the depths of DCM were 75.8 m (I10) and 91 m (I5), respectively. A significant relationship was found when the underestimated $\sum$Chl *a* was plotted against the DCM depth (Figure 4(b)), that is, the underestimation was negatively correlated to the depth when it varied from 55.6 to 71.3 m ($r = -0.63$, $P < 0.05$) and positively correlated when it ranged from 75.8 to 91 m ($r = 0.68$, $P < 0.01$). This indicates that a greater departure of the DCM from 75 m would cause a greater underestimation of primary production if the real DCM is missed as seen in previous investigations where samples were collected at only 7 fixed depths.

4. Discussion

In this paper, we present the vertical patterns of chlorophyll *a* concentration in the Indian Ocean, where the DCM depth shoaled latitudinally to northward. The routine depth-integrated Chl *a* content as reported previously (e.g., [26, 27]) could be underestimated by up to 9.3% due to missing of the real DCM. The underestimation was negatively correlated to the DCM depth if it was less than 75 m but positively correlated if it was over 75 m.

The DCM layers frequently appear in oligotrophic waters of the Indian Ocean over the summer period, with a high variability in depth and magnitude as shown here (Figures 2–4) or in other studies [10, 15, 31]. Changes in water turbulence, nutrient-flux, and light intensity could be responsible for the changes in DCM location, thickness, and Chl *a* content. In the investigated water, seasonal transition of southwest to northeast monsoons underwent a drastic vertical turbulence in the water column [20, 21, 23]. Dynamics of the mixed layer caused by winds, together with eddies, influenced the supply of nutrients from below the thermocline, powering the growth of phytoplankton and ultimately affecting the DCM formation and maintenance (i.e., biomass and distribution) [15, 23, 31, 32]. Moreover, nutrients, for example, biogenic silica, that are often species-specific could be another cause for the presence of diatom populations at the DCM [33]. Solar radiation that provides energy for photosynthesis could also regulate phytoplankton community structure and locations in the euphotic zone [17, 34]. This might also explain the more shallow DCM depth in the 6°N waters compared to equatorial waters in the Indian Ocean (Figures 3(c) and 3(d)), as well as its latitudinal shoaling to northward during the early summer period (Figures 3(a) and 3(b)).

The proportion of small picophytoplankton markedly decreased with the DCM depth (Figure 5). Solar irradiation was known to be lower at the DCM with much more short-waveband blue light [35]; only larger phytoplankton cells can utilize short-waveband energy for photosynthesis [4, 36]. Growth of smaller cells at this layer might thus be inferior to their larger counterparts, leading to a negative correlation of pico-cells in proportion to the DCM depth ($r = -0.53$, $P < 0.01$). On the other hand, the nutrient status in the DCM was usually pulsed-supplied by vertical mixing [32, 37]; therefore, the growth of larger plankton cells could be superior to smaller ones due to their possession of nutrient storage vacuoles [38], resulting in the higher proportion in deeper DCM (Figure 5). Atmospheric conditions such as cloudiness could be another cause for the variation of DCM locations [22]; however, sunny days prevailed over the investigated waters during the study period, and the cloudiness would thus have had little effect on the locations of DCM.

Depth, thickness, and Chl *a* content of the DCM often change greatly in the spatial (Figures 2 and 3) or temporal scales [15, 16, 21] due to the changes in environmental factors [31, 34, 37]. Considering that the DCM contributes to a large portion of total primary production [12, 13], the depth-integrated biomass of phytoplankton tended to be underestimated if missing the real DCM using the routine sampling protocol of collecting samples at only several fixed depths. According to our results, the depth-integrated Chl *a* could be underestimated by up to 9.3% due to missing the real DCM in the Indian Ocean; it could be higher when the DCM location departs more from 75 m depth.

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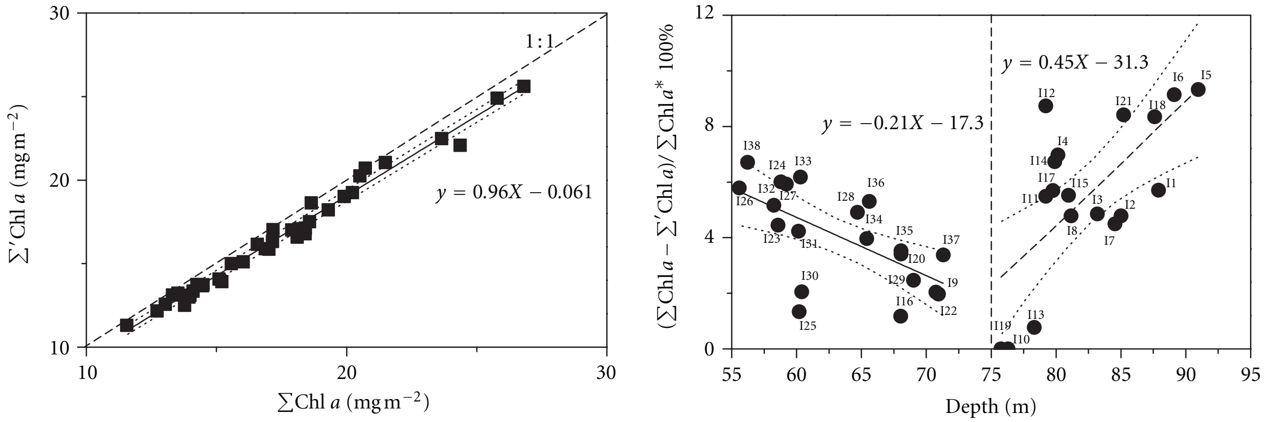

(a)

(b)

FIGURE 4: (a) Integrated Chl *a* ($\sum' \text{Chl } a$, mg m^{-2}) not including the real DCM as a function of that including it ($\sum \text{Chl } a$), with the solid line showing the significant relationships ($r = 0.99$, $P < 0.01$, $n = 38$). (b) The underestimated $\sum \text{Chl } a$ (%) when missing the real DCM as a function of its depth (m), with the lines indicating the significant relationship (solid line, $r = -0.63$, $P < 0.05$, $n = 20$; dashed line, $r = 0.68$, $P < 0.01$, $n = 18$).

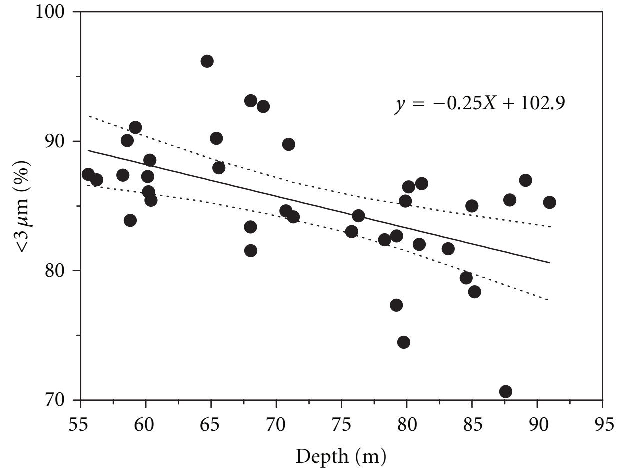

FIGURE 5: Contribution (%) of picocells fraction to total Chl *a* at the DCM as a function of the DCM depth. The solid line shows the significant relationship ($r = -0.53$, $P < 0.01$, $n = 38$).

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