Photosynthetic characteristics and primary productivity of phytoplankton in the Arabian Sea and the Indian Ocean during the NE monsoon season

Toru Hirawake*, Takashi Ishimaru* and Hiroo Satoh*

Abstract: Chlorophyll a distribution, photosynthetic characteristics and primary productivity of phytoplankton were investigated in the Arabian Sea and eastern part of the Indian Ocean during the NE monsoon season (January 1984). Concentration of chlorophyll a at surface waters varied from 0.05 mg m⁻³ in the South Equatorial Current region to 0.71 mg m⁻³ in the Somali Current region. Standing stock of chlorophyll a within the euphotic zone ranged from 7.0 to 20.5 mg m⁻³. A clear subsurface chlorophyll maximum (SCM) was observed in the layer at depth of 15 to 120 m that was 2-3 % penetration of the incident light. Depth of the SCM varied according to depths of the euphotic zone and mixed layer. The amounts of chlorophyll a in the SCM occupied more than 60% of the chlorophyll a standing stock within the euphotic zone. Photosynthesis-Irradiance curves illustrated clear differences of photosynthetic characteristics. Initial slope of the curve (a) varied from 0.009 to 0.034 mgC (mg chl. a)⁻¹ h⁻¹ (μmol quanta m⁻² s⁻¹)⁻¹ at the surface and from 0.002 to 0.208 mgC (mg chl. a)⁻¹ h⁻¹ (μmol quanta m⁻² s⁻¹)⁻¹ at the SCM. The maximum value of a (0.208) indicates the evidence of the dark adaptation of phytoplankton at the most southern site. Both a and maximal photosynthetic rate (Pmax) were very low at the SCM in the Equatorial Countercurrent region (Pmax = 2.1 mgC (mg chl. a)⁻¹ h⁻¹) and the South Equatorial Current (Pmax = 1.2 mgC (mg chl. a)⁻¹ h⁻¹). These low values suggested that phytoplankton at the SCM had lost their activity. Primary production varied largely from 0.08 to 0.76 gC m⁻² day⁻¹. The maximum production was estimated in the Somali Current region, that was attributed to the high ability of photosynthesis as shown on the P-I curve. Light utilization index ($\Psi$) also indicated the large variance of water column quantum yield within our studied area and high ability of production in the Somali Current region.

1. Introduction
The Arabian Sea and the Indian Ocean were under the influence of monsoons. The monsoons, SW during June–August and NE during December–February, and currents play a very important role in determining the variability of phytoplankton productivity and biomass (Krey, 1973; Yentsch and Phinney, 1993). Primary productivity and biomass of phytoplankton in these area were measured concentrically during the International Indian Ocean Expedition (IIOE; 1959–1965) by numerous research vessels. The level of primary production as the results of the IIOE were reported by Ryther et al. (1966) in the western part of this region and by Saiko (1965) in the eastern part, and summarized by Krey (1973) and Aruga (1973).

After the days of the IIOE, some investigations of photosynthetic characteristics, primary production and chlorophyll a standing stocks in the Arabian Sea has been carried out by ship or satellite (e.g. Banse and McClain, 1986; Banse, 1987; Yentsch and Phinney, 1993; Goes et al., 1993; Pant, 1993; Brock et al., 1993) focused on the interested phenomena such as upwelling and phytoplankton bloom.

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Photosynthetic characteristics shown by Photosynthesis–Irradiance curve (P–I curve) are important factors controlling the photosynthetic activity of phytoplankton in their natural environment (CÔTE and PLATT, 1984) and the parameters are being used in models for estimating primary production from remotely sensed data (e.g. PLATT et al., 1988). In the Indian Ocean, however, these parameters have apparently not reported to date. New ocean color sensors such as SeaWIFS and OCTS must need the parameters that are not interpolated.

During the cruise of the T/V Umitaka-Maru III of Tokyo University of Fisheries in January 1994, we made a measurements of primary productivity of phytoplankton in the Indian Ocean included the Arabian Sea. In this paper, the authors present the photosynthetic characteristics and primary productivity of phytoplankton during the NE monsoon season.

2. Material and Methods
A series of investigation was carried out on the cruise from the Gulf of Oman to Fremantle, Australia (Fig. 1).

Water temperature and salinity were measured with a CTD (ICTD, FSI) : OCTOPUS system (OCTO–Parameter Underwater Sensor; ISHIMARU et al., 1984) at 17 stations. The sensor of salinity was calibrated with salinometer.

Primary productivity of phytoplankton was measured at 14 stations except Stns. 05, 06 and 08. Seawater samples for primary productivity were collected using Van Dorn bottles from the sea surface and from the depth of subsurface chlorophyll maximum (SCM) recognized by the data of in situ fluorometer equipped with an OCTOPUS system. Additional water samples were collected using a Rossete Multi Water Sampler equipped with an OCTOPUS System for measurement of chlorophyll a standing stock of phytoplankton.

For measurement of phytoplankton chlorophyll a, 200 ml of water sample was filtered through glass fiber filter (Whatman GF/F, φ 25 mm). The filter was immediately soaked in
N, N-Dimethylformamide (DMF) and extracted pigments in the dark (Suzuki and Ishimaru, 1990). Concentration of chlorophyll a was determined fluorometrically with Turner Designs 10-005R fluorometer within a few days after the soaking (Parsons et al., 1984).

Photosynthetic activity of phytoplankton was measured by the stable 14C isotope method (Hama et al., 1988). Water samples were transferred into 2000 ml clear poly carbonate bottles. After adding NaH13CO3 (approximately 10% of total carbonate, ISOTEC Inc.), the samples were incubated for 4 hours in water bath controlled at surface water temperature under natural light (full sunlight, 46, 21, 11, 6% and dark). After the incubation, the water samples were filtered through glass fiber filters (Whatman GF/F, φ 47mm) precombusted at 450°C for 4 hours. The filters were treated with fume of HCl to remove traces of inorganic carbon, and the isotope ratios of 13C and 14C were determined by infrared absorption spectrometry (Sato et al., 1985) with a 14C analyzer (EX 130, JASCO). The photosynthetic activity was calculated by the equation of Hama et al. (1983), and the rate at each depth was calculated on the basis of P-I curve fit to the model of Eilers and Peeters (1988) with a nonlinear curve-fitting minimization that uses a Gauss-Newton method. The equation of the model takes the form:

\[ p = I / (aI + bI + c) \]

where \( p \) is photosynthetic rate, \( I \) is irradiance, and \( a, b, \) and \( c \) are the fitted parameters. Photosynthetic characteristics were calculated with the formulas: initial slope \( (a) = 1 / c \), optimal intensity \( (J_0) = (c / a)^{0.5} \), maximal photosynthetic rate \( (P_{max}) = [b + 2(ac)^{0.5}]^{-1} \), and intensity of onset of light saturation \( (J_{sat}) = P_{max} / a \).

Photosynthetically available radiation (PAR) was measured with a LI-190SB air quantum sensor and a LI-192SB underwater quantum sensor (LI-COR inc.), and recorded with an LI 1000(LI-COR inc.) quantum meter.

Primary production in water column was estimated by integrating the value multiplied the photosynthetic rate by chlorophyll a concentration at each depth over the entire euphotic zone. Daily value of production was calculated on the basis of integrated PAR during the incubation period and during the whole day (Wetzel and Likens, 1991).

3. Results

Hydrographic condition

Based on the surface currents (e.g. Molinari et al., 1990), studied area was distinguished into total of four regions: Somali Current region (SC, Stns. 01–05); Equatorial Countercurrent region (ECC, Stns. 07–13); South Equatorial Current region (SEC, Stns. 14–16); and West Australian Current region (WAC, Stn. 17).

Spatial distributions of water temperature, salinity and στ in the upper 200 m of water column are shown in Fig. 2a, 2b and 2c, respectively. Although the salinity was homogeneous vertically, physical features indicated the stratification between 50 and 130 m except in the SC region. Especially, thermocline was developed in the ECC region as illustrated in Fig. 2a. The thermocline weakened at 10°S where ECC and SEC formed a front. Low salinity band (<35 PSU) was observed at 10°S (Fig. 2b) and separated the high salinity water mass. In the SC region, water mass was well mixed. In contrast with low temperature (<26°C) and high salinity (>36 PSU) near the Gulf of Oman, warm (>28°C) and low saline (<34 PSU) water mass was observed along the west coast of India.

Chlorophyll a distribution and photosynthetic characteristics

Spatial distribution of chlorophyll a concentration in the upper 200 m of water column is shown in Fig. 2d, and the surface values and standing stock of chlorophyll a for each region are listed in Table 1. Chlorophyll a concentration at the sea surface was low (0.05–0.71 mg m⁻³). The surface water from the SCC to WAC regions had extremely low (0.05–0.09 mg m⁻³) chlorophyll a concentrations. Although the highest surface value (0.71 mg m⁻³) was observed at Stn. 01 in the Somali Current region, shallower station of the same region had relatively low values.

Chlorophyll a standing stock within the euphotic zone ranged from 7.0 mg m⁻³ at Stn. 15 in the SEC region to 20.5 mg m⁻³ at Stn. 01 in
Fig. 2. Vertical sections of (a) water temperature, (b) salinity, (c) $\sigma_t$, and (d) chl a concentration in the Arabian Sea and the Indian ocean. Blank area denotes no data.

Table 1. Surface chl a concentration and standing stock within euphotic zone of chl a, primary production, solar radiation incident upon surface, and light utilization index in the different regions showing range and mean. Values in parentheses are mean.

<table>
<thead>
<tr>
<th>Region</th>
<th>Station</th>
<th>Surface (mg m$^{-3}$)</th>
<th>Standing Stocks (mg m$^{-3}$)</th>
<th>Primary Production (gC m$^{-2}$ day$^{-1}$)</th>
<th>Solar Radiation (mol quanta m$^{-2}$ day$^{-1}$)</th>
<th>$\Psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Somali Current</td>
<td>01-05</td>
<td>0.19-0.71(0.40)</td>
<td>8.5-20.5(12.7)</td>
<td>0.28-0.76(0.45)</td>
<td>28.0-34.2(30.4)</td>
<td>0.88-1.27(1.06)</td>
</tr>
<tr>
<td>Equatorial Countercurrent</td>
<td>07-13</td>
<td>0.09-0.14(0.12)</td>
<td>8.7-15.2(12.4)</td>
<td>0.09-0.20(0.14)</td>
<td>23.9-43.3(35.1)</td>
<td>0.22-0.63(0.36)</td>
</tr>
<tr>
<td>South Equatorial Current</td>
<td>14-16</td>
<td>0.05-0.09(0.08)</td>
<td>7.0-13.0(10.1)</td>
<td>0.08-0.11(0.10)</td>
<td>43.1-50.6(45.8)</td>
<td>0.18-0.29(0.22)</td>
</tr>
<tr>
<td>West Australian Current</td>
<td>17</td>
<td>0.08</td>
<td>11.8</td>
<td>0.29</td>
<td>35.7</td>
<td>0.69</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.19</td>
<td>12.0</td>
<td>0.23</td>
<td>36.1</td>
<td>0.55</td>
</tr>
<tr>
<td>C.V. (%)</td>
<td></td>
<td>89.7</td>
<td>27.3</td>
<td>80.8</td>
<td>21.1</td>
<td>67.6</td>
</tr>
</tbody>
</table>

*light utilization index [gC(gchlA)$^{-1}$ (mol quanta m$^{-2}$)$^{-1}$]
the SC region. The averaged value in the SC region was relatively higher (12.7 mg m$^{-2}$) than those in the other regions. Although surface chlorophyll $a$ concentrations had a wide range within the studied area (89.7% C.V.), variation of standing stocks with region was small (27.3% C.V.).

In the layer at depths of 15 to 40 m in the SC region and at 50 to 120 m in the other regions, distinct subsurface chlorophyll maximum (SCM) was observed (Fig. 2d). Maximal concentrations at the SCM layer ranged 0.27–0.99 mg m$^{-2}$ in the SC region and 0.25–0.50 mg m$^{-2}$ in the other regions. The SCM occupied more than 60% of the chlorophyll $a$ standing stock (Table 1) within the euphotic zone. Comparison of peak depth and range of the SCM, depth where PAR is reduced to 1% of the surface ($Z_{ru}:$ euphotic zone depth), and mixed layer depth (MLD) is shown in Fig. 3. In the present study, range of the SCM is determined on the basis of Gaussian Curve fit (LEWIS et al., 1983; PLATT et al., 1988) modified by MATSUMURA and SHIMOTO (1993), and MLD is defined as the first depth at which the temperature is 10°C less than that at 10 m (RAO et al., 1989). Peaks of the SCM were lower part of the euphotic zone, that were 2–3% penetration of the surface light except Stn. 15. The SCM changed its vertical distribution according to a relative position of MLD and $Z_{ru}$. In the SC region, mixed layer (41–86 m) included whole of euphotic zone (34–58 m) and the SCM was approximately within the MLD and/or euphotic zone. MLD in the ECC region was close to $Z_{ru}$ and turned upside-down where top and bottom of the SCM (except Stn. 13 at about 10°S where is a front as mentioned above) were positioned at above and at below of both depths, respectively. In the SEC and the WAC regions more southern than the front of 10°S, $Z_{ru}$ was completely lower than MLD. The SCM in these regions was distributed lower than MLD and expanded up to extremely weak light layer deeper than $Z_{ru}$.

P-I curves at sea surface and SCM in the each region and the parameters of photosynthetic characteristics were shown in Fig. 4 and listed in Table 2, respectively. P-I curves illustrated a clear difference of photosynthetic characteristics between the surface and SCM, and between the regions. All curves at the sea surface show a weak photoinhibition, though, $P_{max}$ of the surface were 1.3–5.4 times as high as for the SCM.
Fig. 4. Photosynthesis-Irradiance curves at surface and SCM fitted to all data in the (SC) Somali Current region, (ECC) Equatorial Countercurrent region, (SEC) South Equatorial Current region, and (WAC) West Australian Current region.

Table 2. Parameters showing photosynthetic characteristics of phytoplankton in different regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>Surface</th>
<th>SCM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Station</td>
<td>(a)</td>
</tr>
<tr>
<td>Somali Current</td>
<td>01-05</td>
<td>0.034</td>
</tr>
<tr>
<td>Equatorial Countercurrent</td>
<td>07-13</td>
<td>0.018</td>
</tr>
<tr>
<td>South Equatorial Current</td>
<td>14-16</td>
<td>0.014</td>
</tr>
<tr>
<td>West Australian Current</td>
<td>17</td>
<td>0.009</td>
</tr>
</tbody>
</table>

*initial slope \((\text{mgC (mg chl.a)}^{-1}\text{h}^{-1}) \times \text{umol quanta m}^{-2}\text{s}^{-1})^{-1}\)

*maximal photosynthetic rate \((\text{mgC (mg chl.a)}^{-1}\text{h}^{-1})\)

*optimal intensity \((\text{umol quanta m}^{-2}\text{s}^{-1})\)

*intensity of onset of light saturation \((\text{umol quanta m}^{-2}\text{s}^{-1})\)
Primary productivity in the Indian Ocean

\[ P_{\text{net}} \] was especially high in the SC region that was 1.6–1.9 times at the surface (11.6 mgC (mg chl. a)\(^{-1}\) h\(^{-1}\)) and 1.8–6.3 times at the SCM (7.5 mgC (mg chl. a)\(^{-1}\) h\(^{-1}\)) as high as for the others. \( a \) of the surface (0.034 mgC (mg chl. a)\(^{-1}\) h\(^{-1}\) (µmol quanta m\(^{-2}\) s\(^{-1}\)) in the SC region is also highest value, that shows most productive surface water. As shown by the values of \( I_s \) (834–954 µmol quanta m\(^{-2}\) s\(^{-1}\)) and \( I_l \) (338–660 µmol quanta m\(^{-2}\) s\(^{-1}\)) of the surface, phytoplankton at the surface was adapted to strong insolation. While at the SCM, photoadaptation to dark was not observed except the WAC region. The SCM in the WAC had high value of an \( a \) (0.208 mgC (mg chl. a)\(^{-1}\) h\(^{-1}\) (µmol quanta m\(^{-2}\) s\(^{-1}\))\(^{-1}\)) showing high activity at low light intensity. Although \( I_s \) at the SCM in the ECC region was relatively low (156 µmol quanta m\(^{-2}\) s\(^{-1}\)), low \( P_{\text{net}} \) (2.1 mgC (mg chl. a)\(^{-1}\) h\(^{-1}\)) denies a dark adaptation. Phytoplankton at the SCM of the SEC was reduced its activity more than those in the ECC. It appears that high \( I_s \) and \( I_l \) in this region indicate light adaptation. But this is only a lost of activity because of the remarkably low \( a \) (0.002 mgC (mg chl. a)\(^{-1}\) h\(^{-1}\) (µmol quanta m\(^{-2}\) s\(^{-1}\))\(^{-1}\)) and \( P_{\text{net}} \) (1.2 mgC (mg chl. a)\(^{-1}\) h\(^{-1}\)).

**Primary production and light utilization index**

Distribution of daily primary production was shown in Fig. 5, and the values for the each region were shown in Table 1. The studied regions had a widely one order range of primary production (0.08–0.76 gC m\(^{-2}\) day\(^{-1}\)). The highest value of production was obtained in Stn. 01 in the SC region. Production in the SC region, of which mean production was 0.45 gC m\(^{-2}\) day\(^{-1}\) with the range of 0.28–0.76 gC m\(^{-2}\) day\(^{-1}\), was 1.5–4.5 times in mean value as high as the others. The waters in the ECC region were low productive (0.09–0.20 gC m\(^{-2}\) day\(^{-1}\)), and more oligotrophic water was observed in the SEC region as shown in the value of primary production (0.08–0.11 gC m\(^{-2}\) day\(^{-1}\)). Although the WAC region keep close to the SEC region, that had relatively high value (0.29 gC m\(^{-2}\) day\(^{-1}\)) because of the high photosynthetic activity of phytoplankton in the SCM layer.

Total water column light utilization index \( \Psi \) (Falkowski, 1981) for each region was shown in Table 1. \( \Psi \) was estimated from the expression:

\[
\Psi = P_{\text{net}} \times \Psi_{\text{chla}}
\]

where \( P \) is the daily primary production of water column in gC m\(^{-2}\) day\(^{-1}\), \( B \) is the chlorophyll \( a \) standing stock in g chl. a m\(^{-2}\), and \( I_l \) is solar radiation at the sea surface (Table 1) in mol quanta m\(^{-2}\) day\(^{-1}\). Averaged value of \( \Psi \) for all regions was 0.55 gC (g chla)\(^{-1}\) (mol quanta m\(^{-2}\) day\(^{-1}\)) with 67.6% (C.V.) of variation. In the SC
region, mean value of $\Psi$ was 1.06 gC (g chl $a^{-1}$) (mol quanta m$^{-2}$)$^{-1}$ with the narrow range (0.88–1.27 gC (g chl $a^{-1}$) (mol quanta m$^{-2}$)$^{-1}$) that is 15% in C.V., and the value was the highest within the all studied regions. The index $\Psi$ was fallen into the averaged value of 0.22 gC (g chl $a^{-1}$) (mol quanta m$^{-2}$)$^{-1}$ in the SEC region (26% C.V.), and relatively high in the WAC region (0.69 gC (g chl $a^{-1}$) (mol quanta m$^{-2}$)$^{-1}$). In the ECC region, the highest variance of $\Psi$ was observed (50% C.V.).

4. Discussion

Distinct physical features in the studied are the front and the low salinity band which had observed also during the IOE (Wyrtki, 1971; 1973). Wyrtki (1973) suggested that the low salinity band is characteristic of the front formed at 10°S and separates the high salinity water mass of the northern Indian Ocean from the subtropical high salinity water of the sub-tropical gyre. Low saline water along the west coast of India is also typical of the SC region. This water mass marks the northward flowing equatorial surface waters (ESW; Goes et al., 1993) from the southwestern Bay of Bengal (Bruce et al., 1994). Surface salinity maps demonstrated by Wyrtki (1971) also showed the intrusion of low-salinity water from the Bay of Bengal into the Arabian Sea. Moreover, low chlorophyll water mass observed in this region was originated from the Bay of Bengal associated with the ESW (Goes et al., 1993).

Clear differences in chlorophyll distribution, photosynthetic characteristics and primary production were observed, that is according to four regions distinguished by surface currents. In the SC region of the Arabian Sea, these values were distinctly higher than those in the other regions. Moreover $a$ and $P_{aa}$ in this region ($a = 0.034, P_{aa} = 11.6$ at Surface; $a = 0.027, P_{aa} = 7.5$ at SCM) was higher than values : $a = 0.017$ mgC (mg chl $a^{-1}$) $^{-1}$ h$^{-1}$ (umol quanta m$^{-2}$ s$^{-1}$)$^{-1}$ (convert water to mols of quanta assuming $1W = 4.6 \mu$mol quanta s$^{-1}$) and $P_{aa} = 5.37$ mgC (mg chl $a^{-1}$) $^{-1}$ h$^{-1}$ published by Sathyendranath et al. (1996) in the Somali Basin (southwest of Stn. 01). Similar to the conditions in the Somali Basin during the NE monsoon (January 1993) reported by Veldhuis et al. (1997), the MLD exceeded the $Z_{oc}$ So that, it is considered that the nutrients is supplied enough to keep a high activity compared with it in the other regions. The SC region in this study is including the shallow waters, that is also a reason of high $a$ and $P_{aa}$. However, primary production at the shallow stations (0.28–0.41 gC m$^{-2}$ day$^{-1}$) was lower than the result of Somali Basin (Veldhuis et al., 1997) because of the low standing stocks.

In the ECC region, the MLD was closed to the $Z_{oc}$ and almost of the SCM was distributed along the $Z_{oc}$ at depth more than 50m. The SCM in the SEC and the WAC region were also along the $Z_{oc}$ and entirely beneath the MLD situated at approximately 50m. As long as seen in these results, the SCM was depended on light intensity, but the dark adaptation was observed only in the WAC and activity of phytoplankton were very low as shown in the values of $a$ and $P_{aa}$ in the SEC ($a = 0.014, P_{aa} = 2.1$) and SEC ($a = 0.002, P_{aa} = 1.2$). The results of Jits (1965) also illustrated that productivity along the 110°E was infinitesimal at the depth more than about 50m. Saino (1965) suggested from the results of the tank experiments that the chlorophyll at the depth of the SCM had almost lost their photosynthetic ability. He more implied that the SCM is not the result of the passive accumulation of senescent phytoplankton but represents an accumulation of actively growing phytoplankton (Saino, 1973). The SCM in the ECC and the SEC appeared in our study might avoid the nutrients impoverished surface water mass and strong solar radiation.

Distinct difference and variability in water column light utilization index ($\Psi$) were appeared in like manners of productivity and P–I curve parameters. The index means water column averaged quantum yield for photosynthesis and has been used as important factor of productivity model estimate the depth–integrated primary production (Falkowski, 1981; Platt, 1986; Morel, 1991). The value of $\Psi$ changes with a variety of environments (Platt, 1986) such as the values of Falkowski (1981) ($\Psi = 0.43$), Yoder et al. (1985) ($\Psi = 1.5$), Campbell and O'Reilly (1988) ($\Psi = 1.47$), and Balch et al. (1988) ($\Psi = 0.27$). The averaged
value obtained of our study ($\Psi = 0.55$) was lower than the world-wide averaged value of 0.96 gC (g chl. a)$^{-1}$ (mol quanta m$^{-2}$) (BALCH and BYRNE, 1994). However the value in the SC region ($\Psi = 0.88-1.27$) is relatively high within values of the world oceanic waters (e.g. FALKOWSKI, 1981), and same level as much as the values by $^{14}C$ based experiments in the Somali Basin ($\Psi = 0.84-1.59$; VELDHUIS et al., 1997) in spite of the difference in the technique and method that induces large error (BALCH and BYRNE, 1994). In contrast with the SC region, $\Psi$ in the SEC region ($\Psi = 0.18-0.29$) was one of the lowest value in the world oceans. In case we try to estimate the primary production of water column from satellite derived data, it is difficult to regard our studied regions as only one area where has constant value of $\Psi$, due to its large variance. In other words, it was appropriate that a variable $\Psi$ and photosynthetic characteristics ($\alpha$, $P_{max}$, $I_s$, $I_a$) were ramified into four region based on the surface currents.

Although we presented chlorophyll distribution, productivity and photosynthetic characteristics of phytoplankton in the Arabian Sea and the eastern Indian Ocean related to the hydrographic condition and the light penetration, the obtained primary production data are only shipboard estimates that are "point" or "line". It is hoped that the primary production in this area will estimated in more broad-scale from satellite to resolve the global carbon cycle.

It is ideal that simple mathematical model is utilized to estimate the integrate primary production from remotely sensed data. The simplest productivity models estimate primary production as a function of sea surface chlorophyll (e.g. EPPLEY et al., 1985). This simplest relationship for the Arabian Sea and the Indian Ocean (HIRAWAKE et al., 1996) has a strong correlation ($r^2 = 0.90$ for the same dataset as this study), but the model induced a large error in the sites where primary production depends on the standing stock within the SCM layer or chlorophyll concentration was high. It is expected that a more complicated model is attempted for such regions. Although the complex approach also need information on the photosynthetic characteristics, there was very little about these parameters in our studied area, especially from the ECC to WAC region. It is clear that the photosynthetic characteristics presented in this study are very precious data on the next step in the primary production model.

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