ESTIMATION OF SEASONAL VERTICALLY INTEGRATED PRIMARY PRODUCTIVITY IN AMBON BAY USING THE DEPTH-RESOLVED, TIME-INTEGRATED PRODUCTION MODEL

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ABSTRACT

Seasonal vertically integrated primary productivity (IPP) in eight stations of Inner Ambon Bay (IAB) and nine stations of Outer Ambon Bay (OAB) was estimated using the depth-resolved, time-integrated production model and vertical-a distribution model which was mainly dependent on chlorophyll-a profile. The profile was modeled as Gauss function in which its parameters were determined by minimizing the difference between the model and the average of *in situ* chlorophyll-a concentration from 2008 to 2012. The data was collected by UPT BKBL-LIPI Ambon during monitoring program in Ambon Bay. Based on this model, the results showed that the primary productivity during the southeast monsoon was to some degree higher than that of other seasons. The main factors causing the higher IPP in this season were upwelling phenomenon and high rainfall intensity. From the results, it could be concluded that run-off gave more impacts in IAB than in OAB while upwelling in Banda Sea affected the IPP more in OAB than that in IAB. Then, the existence of the sill located between IAB and OAB inhibited the mixing of IAB and OAB waters so that the levels of IPP and chlorophyll-a concentration in IAB were higher than that of in the OAB.

Keywords: chlorophyll-a, integrated primary productivity, Ambon Bay

INTRODUCTION

The vertical profile of chlorophyll-a is one of the important indicators of phytoplankton biomass and therefore is often used as a parameter in determining water column primary productivity (Platt and Sathyendranath, 1988; Gong et al., 2000; Siswanto et al., 2005). Furthermore, the estimation of the profile is relatively an easy thing. Its concentration in water surface can be determined by operating remote sensing technology. In deeper water, the fluorescence sensor attached in CTD (Conductivity, Temperature and Depth Sensors) can be used to estimate the concentration until the depth of more than 200 meters.

Phytoplankton activities are influenced strongly by temperature, nutrients and light intensity (Reynolds, 1987; Henriksen et al., 2002). On the other hand, physical processes such as upwelling, stratification and turbulence can influence the magnitude and shape of the chlorophyll-a vertical profile (Pitcher et al. 1992; Richardson et al., 2002). Those conditions lead to variation of chlorophyll-a vertical profile and primary productivity in different seasons. It is suggested that the profile can be modeled as a shifted gaussian function that the parameters vary widely with regions and seasons (Platt and Sathyendranath, 1988; Sathyendranath et al., 1989; Platt et al., 1991). The use of this model gives better estimation of integrated primary productivity (IPP) than calculating a uniform vertical structure of phytoplankton biomass which ignores the contribution of the chlorophyll-a maximum (Richardson et al., 2002).

In this study, we identified the characteristic of chlorophyll-a profile and estimated the IPP in Ambon Bay in four seasons (southeast monsoon, transition I, northwest monsoon, and transition II). This region was an important spawning and catchment area for pelagic fishes. Therefore, the study of IPP was important for understanding of recruitment fluctuation of those fishes. The parameterization of chlorophyll-a vertical profile was made to generalize the characteristic of the profile in Ambon Bay so that it gave benefits to estimating the IPP not only during the period of this study but also other periodes when field measurement was not possible to be provided. The fluorescence vertical profile was parameterized using the Gaussian equation. Then, the IPP in four seasons was estimated by using the depth-resolved, time-integrated production model that strongly depended on the vertical profile of chlorophyll-a in Ambon Bay.

METHODOLOGY

Obeservation sites

The observation has been carried out in Ambon Bay at 17 stations i.e. eight stations in the inner bay and nine stations in the outer bay (Fig. 1). The maximum depth of the Inner Ambon Bay (IAB) was about 40 m while it was more than 200 m in the Outer Ambon Bay (OAB). There was a sill (channel with narrow width) with the depth varied between 8 and 12 m, about 800 m long and 600 m wide connecting the inner and outer bay (Fig. 2).

Data collection

The observation of environment condition in Ambon Bay has been conducted by LIPI Marine Laboratory-Ambon since 2008. Prior to 2012, the measurements were taken 3–6 times per year. In 2012, it has been recorded every month. Physical, chemical and biological parameters were collected. Compact CTD - ASTD 687 was used to collect the parameters that included temperature, salinity,

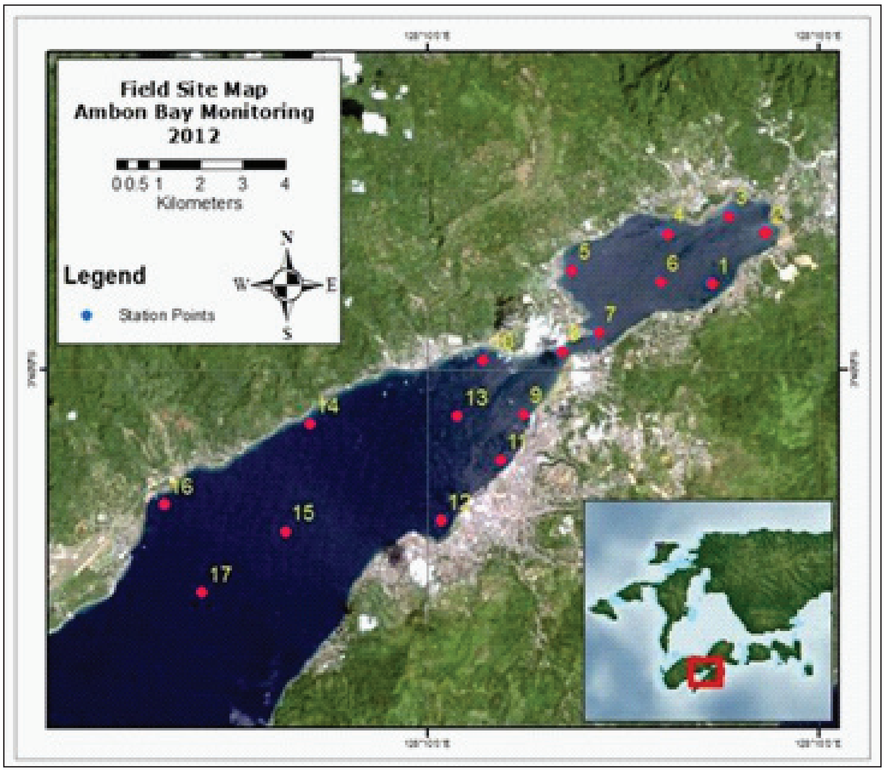

Figure 1. Location of water sampling in Ambon Bay.

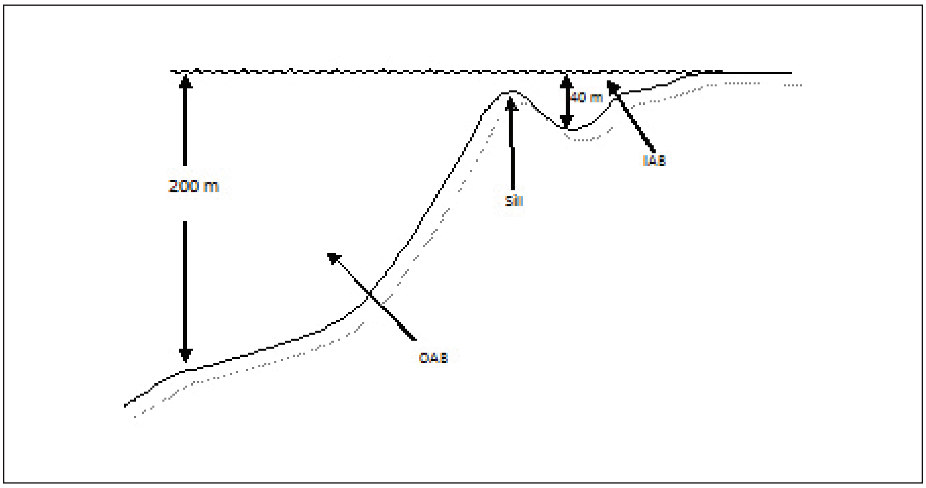

Figure 2. Vertical cross section of Ambon Bay. There are more than 20 rivers that end up in Ambon Bay., The water turbidity is strongly intensified during the rain season especially during the southeast monsoon. The discharged freshwater is likely to bring large amount of nutrients as Ambon was geologically young (Miller, 1999) and still experience in relatively rapid rates of erosion.

chlorophyll-a concentration and turbidity. In the inner bay, the measurement was performed up to the seabed, while in the outer bay the maximum depth of measurement was 40 meters water depth. The CTD data was recorded *in situ* within every second when it went down to the bottom such data were used in this study) or went up to the surface. Therefore, in each 1 meter interval the number of recorded data could be different depending on the speed of CTD movement. In order to reduce the measurement noises, the average of recorded data was taken in each meter. In addition, the meteorological data such as precipitation has been collected from Meteorological, Climatological and Geophysical Agency, Ambon.

Data analysis

The chlorophyll-a profile was fitted to the shifted Gaussian function model. The four parameters were determined by minimizing the difference between the model and the *in situ* chlorophyll-a concentration from 2008 to 2012. These data were used as reference to find the parameters of the Gaussian function as described in the next section. Then, the model of chlorophyll-a was applied as an input to estimate IPP, using the depth-resolved, time-integrated production model. The calculations were conducted during four seasons i.e. the southeast monsoon (July), transition I (October), the northwest monsoon (February), transition II (May). As for verification, these results of the calculation were compared with the results of Kemili and Putri (2012) who also estimated IPP around Banda Sea waters using satellite chlorophyll-a data. Even though there was no *in situ* measurement to verify for both Chl-a fluorescence measured by portable CTD and IPP model, but the final results (IPP) were as expected and would be detailed in discussion section.

The IPP in the water column has been estimated using the depth-resolved, time-integrated production model as shown by the following equation (Siswanto et al., 2005)

$$IPP = \int_{z=0}^{z_{eu}} Chl(z) \times P_{opt}^{B} \times \frac{E(z)}{E_{max}} \times \exp\left(1 - \frac{E(z)}{E_{max}}\right) dz \qquad (1)$$

where IPP, Chl (z), P^B_{opt} , E(z) and E_{max} is the total intergrated productivity (mgC $m^{-2}d^{-1}$), the maximum Chl-a normalized carbon fixation rate within the water column (mgC mgChl-$a^{-1}d^{-1}$), the relative vertical distribution of C fixation as a function of depth (dimensionless), the irradiance at depth z (Einstein $m^{-2}d^{-1}$), and the irradiance at the inflection point between light-limited and light-saturated phases (Einstein m–2d–1), respectively.

The Gaussian function of chlorophyll-a vertical distribution was proposed as follows (Platt and Sathyendranath, 1988; Sathyendranath et al., 1989; Platt et al., 1991)

$$Chl(z) = B_0 + \frac{h}{\sigma\sqrt{\pi}} exp\left(-\frac{(z-z_m)^2}{2\sigma^2}\right) \quad (2)$$

where B_0, h, σ, z_m, is a background Chl-*a* (mg m^{-3}), total Chl-a above the background (mg m^{-3}), standard deviation (m) that control the thickness of Chl-*a* maximum layer, and the depth of the peak, respectively (Fig. 3).

The variables of the Gaussian function for each season were determined by using a MATLAB simplex search method from Lagrias *et al*. (1998). In this method, the difference ϵ between the observed chl-a concentration and the Gaussian function was minimized so that the function fits to the real data as represented by:

$$\epsilon = \sum_z (Chl(z)_{in\ situ} - Chl(z)_{model}) \quad (3)$$

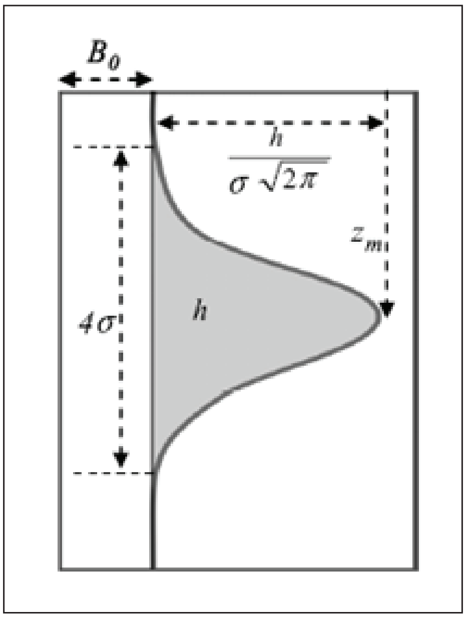

Figure 3. Shifted Gaussian distribution showing four parameters (B0, h, σ and zm), used to describe Chl-a vertical profiles (Siswanto et al. 2005).

P^B_{opt} was influenced by temperature, light-emitted and photo-inhibited carbon fixation rates photosynthetic parameters (Behrenfeld and Falkowski, 1997). However, it can be parameterized only by temperature because the other parameters were secondary important that can be ignored as shown by the following equation from Behrenfeld and Falkowski (1997):

$$P^B_{opt}(T)=3.27*10^{-8}\times T^7+3.4132\times10^{-6}*T^6-1.348\times10^{-4}\times T^5+2.46\times10^{-3}\times T^4-0.0205\times T^3+0.0617\times T^2+0.2749\times T+1.2956 \quad (4)$$

This parameter was well behaved for sea surface temperature ranging from -1°C to 29°C.

The parameters of E_{max} have been modeled empirically by Siswanto, *et al*. (2005) as:

$$E_{max} = -11.04 + 3.07\times E_0 - 0.13E_0^2 + 0.002\times E_0^3$$
$$E_z = E_0 e^{-k_{PAR}\times z} \quad (5)$$
$$k_{PAR} = 0.047 + 0.063\times Chl_0$$

in which E0, Chl0, kPAR is surface irradiance, surface Chl-a, and attenuation coefficient of photosynthetically active radiation, respectively.

RESULTS

The data and model of chlorophyll-*a* vertical distribution in the Inner Ambon Bay, the sill and the Outer Ambon Bay is represented by stations 1, 7 and 15, respectively (Fig. 4, 5 and 6). In general, the model could explain the variation of the observation at about 90% for all stations in all seasons. Only some models (out of 20) could explain the variation of the observation data at about 60 %. There were three different reasons for the situation. One reason was that some of the observed profiles showed two peaks while the model only showed a single peak. Another reason was that some observed profiles were not symmetrical while the model demonstrated symmetrical profile. The last reason was that some of observed data still showed noise even though the average value was taken in the same way as the other data.

In general, the concentration of chlorophyll-a in IAB was higher than that of in the OAB and the peak positions varied among different seasons. The highest concentration occurred in July and the peak of profiles was nearly at the surfaces (Fig. 4−6). In the inner bay, the highest concentration was about 4 mg.cm^{-3} as shown in station 1 (Fig. 4). This condition might be due to its location that was close to the estuary with abundant nutrients from river discharged. Beside the geologically young land, the increase of illegal loggings in this area has caused erosion and thus large amount of sediments were discharged into this estuary during the southeast monsoon with high precipitation reaching 22 mm. Meanwhile, in other stations during the same season, the peaks were only about 1.5 mg.m^{-3}.

In other seasons, the peaks were lower than 1.5 mg.cm^{-3} in the inner bay while it was lower than 1 mg.cm^{-3} in the outer bay. In these seasons, the peak levels were located more than 5 m below the water surfaces. The peaks in October were generally closer to the surfaces than those in February. Moreover, in the northwest monsoon season the width of the peaks, σ, was generally larger than that of in the southwest monsoon and in contrast, the total Chl-a within the peak tended to be less than that of during the southwest monsoon. This condition changed the profile from having a sharp/gentle peak to one with a gentle peak/almost uniform throughout the water column (Fig. 4−6).

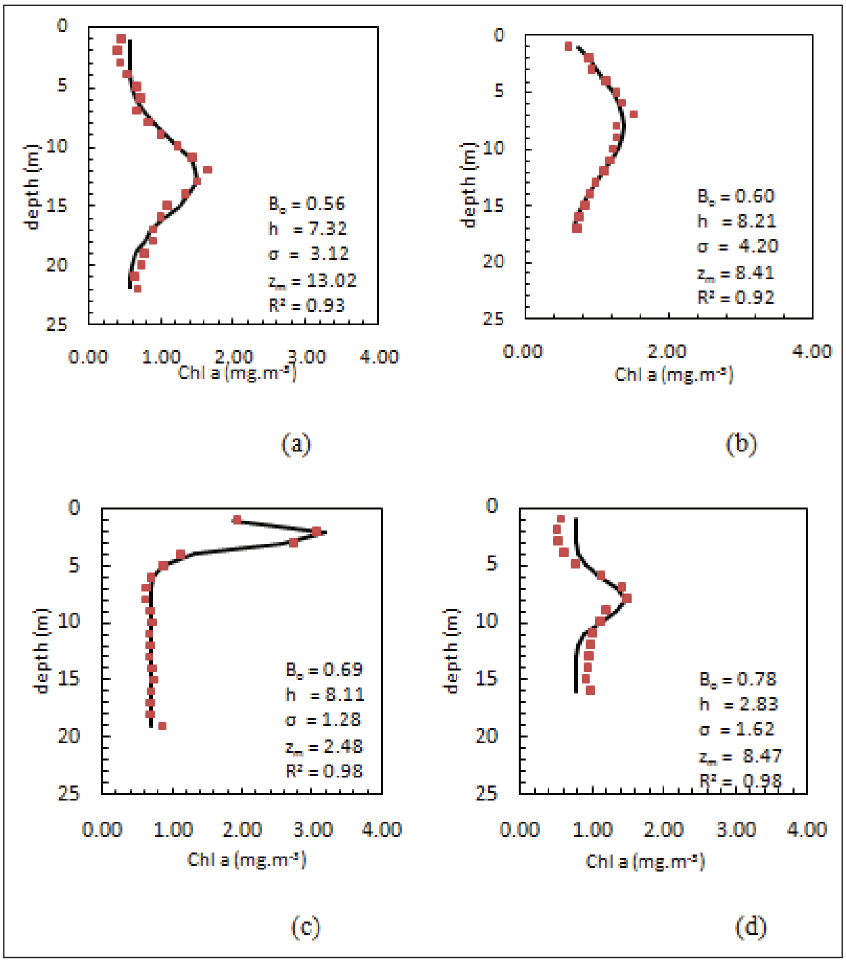

Figure 4. Vertical distribution of chlorophyll-a concentration (mg/m3) at station 1 : Northwest monsoon (a), Transition II (b), Southeast monsoon (c), Transition I (d)(— model, ■ observation data)..

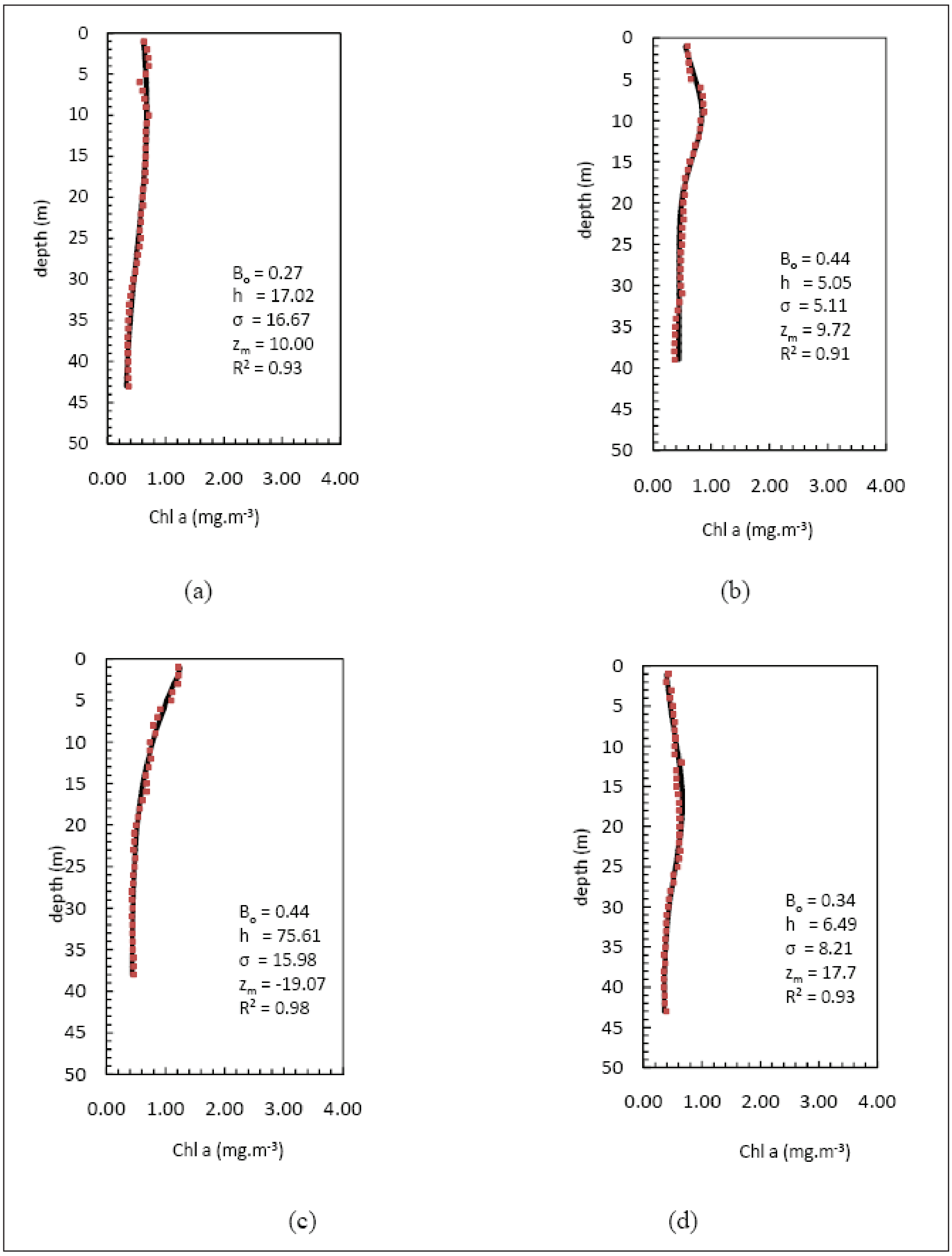

Figure 5. Vertical distribution of chlorophyll-a concentration (mg/m3) at station 7 : northwest monsoon (a), Transition II (b), southeast monsoon (c), Transition I (d)(— model, ▪ observation data).

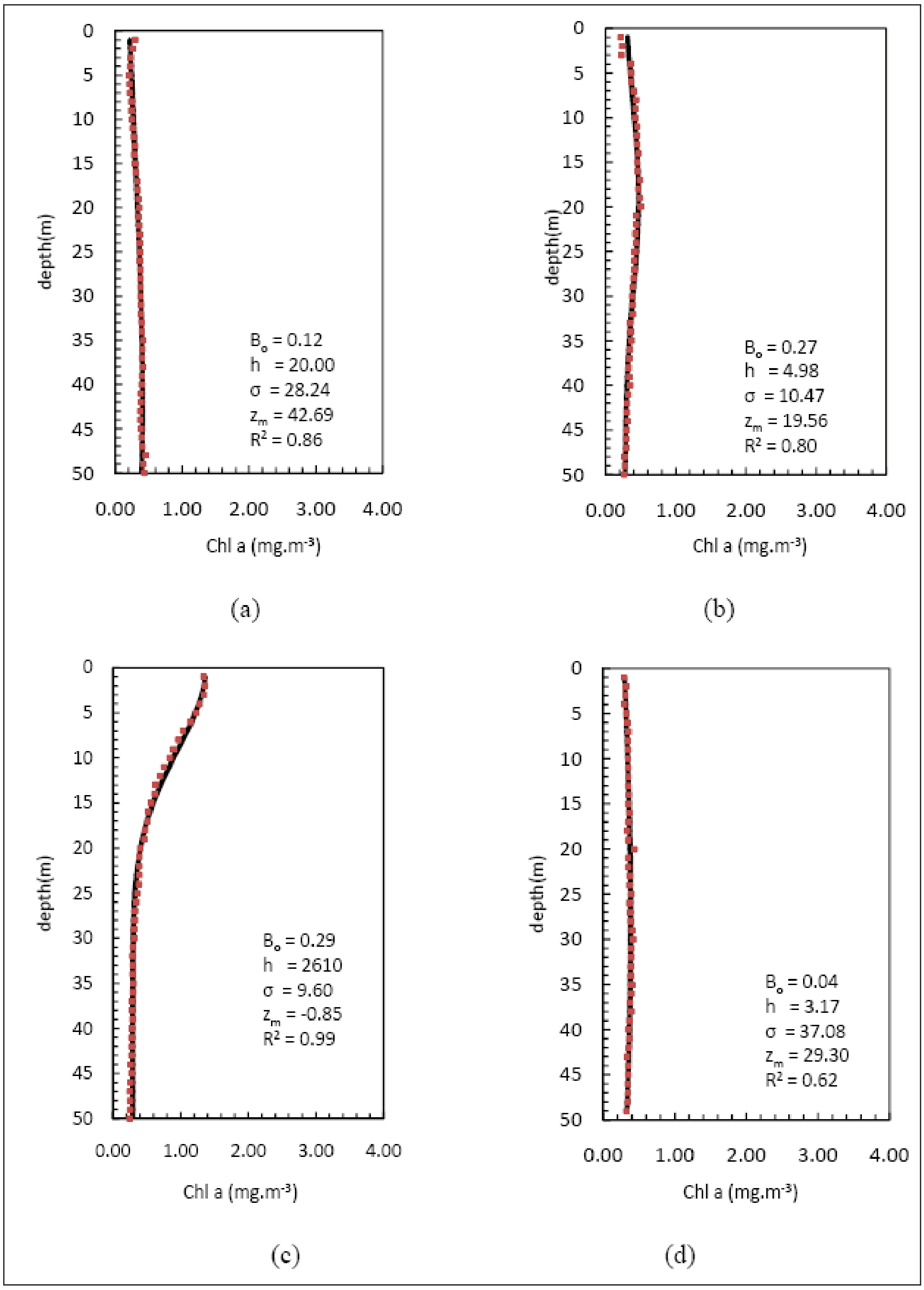

Figure 6. Vertical distribution of chlorophyll-a concentration (mg/m3) at station 15: Northwest monsoon (a), Transition II (b), Southeast monsoon (c), Transition I (d) (▬ model, ■ observation data).

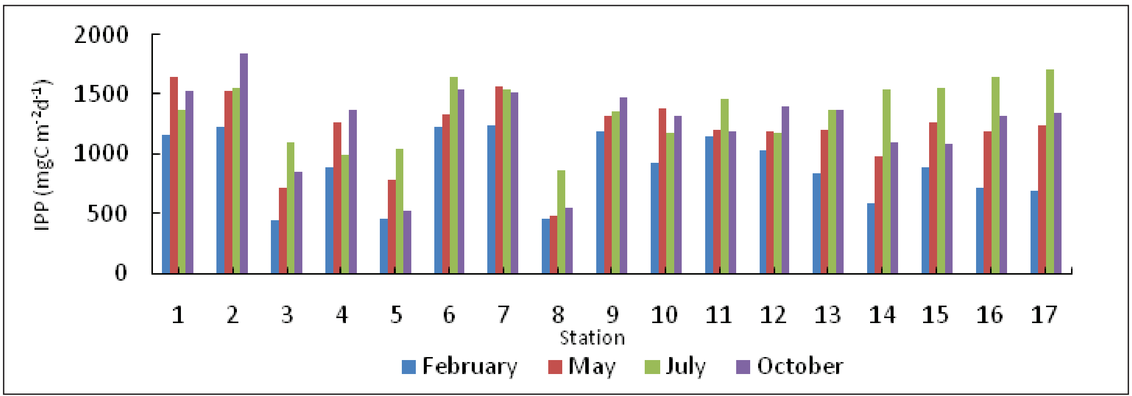

Figure 7. Total integrated primary productivity (IPP) at 17 stations in Ambon Bay.

Similar to the chlorophyll-a profile trend, the IPP (up to the euphotic depth or maximum measured depth) during the southeast monsoon was generally higher than that of during the northwest monsoon. In the inner bay, the IPP varied between 400 mgC $m^{-2}d^{-1}$ and 1850 mgC $m^{-2}d^{-1}$ while the IPP in the outer bay ranged between 600 mgC $m^{-2}d^{-1}$ and 1700 mgC $m^{-2}d^{-1}$ (Fig. 7).

The comparison of IPP (up to the depth of 10 meters) between the inner bay and the outer bay was conducted. Similarly, highest and lowest IPP was in the southeast monsoon (July) at between 764 and 1277 mgC $m^{-2}d^{-1}$ and in the northwest monsoon (February) at between 197 and 595 mgC $m^{-2}d^{-1}$.The results also showed that IPP in the inner bay was higher than that in the outer bay (Fig. 8). In the southeast monsoon, the average of IPP in the inner and outer bays was at about 1117 and 979 mgC $m^{-2}d^{-1}$, respectively. Similarly, in the northwest monsoon the average of IPP in the inner and outer bays was at 455 and 345 mgC $m^{-2}d^{-1}$, respectively. In the transition season I and II, the different of IPP between in the inner and outer bays was between 250 and 350 mgC $m^{-2}d^{-1}$, respectively these differences were mainly caused by the existence of sill located between the IAB and OAB that reduced the process of water mixing and waters between IAB and OAB were different. In the inner bay, terrestrial discharge tended to give more impacts to the water condition due to more rivers in this area. Meanwhile, Banda Sea water was more influencing to the OAB due to its location directly facing the Banda Sea.

DISCUSSION

The estimated IPP in this study showed similar variation with the results of Kemili and Putri (2012) who estimated IPP around Banda Sea using satellite data. They found that the variation of IPP around this water was about 500 (northwest monsoon) and 1700mgC $m^{-2}d^{-1}$ (southeast monsoon). These results indicated that the model of Pbopt and Emax applied in the model of IPP estimation could be applied in this study area. They also stated that this variation was related to the downwelling and upwelling processes around the observation areas. Similarly, in this study it was found that in some stations IPP in the southeast monsoon was higher than the one in the other seasons (Fig. 6). In other stations, IPP in the southeast monsoon was relatively lower than the one in the transition I and II seasons (Fig. 6). It is suggested that this condition was due to its relatively close location of the stations to the estuary which may contain large amount of nutrients during the southeast monsoon. During this season, the precipitation was high; therefore a large amount of nutrients may be discharged from river into the estuary. As a consequence, there was a strong intensification of chl-a on the surface during this season inhibiting light penetration and thus lessening the productivity below the surfaces. Therefore, there was a strong stratification of chl-a concentration between the water surface and below the surface (Fig. 4). These conditions lead to the relatively lower IPP in the southeast monsoon compared to those of in the transition I and II even though the peaks of chl-a in the southeast monsoon at these stations were relatively higher.

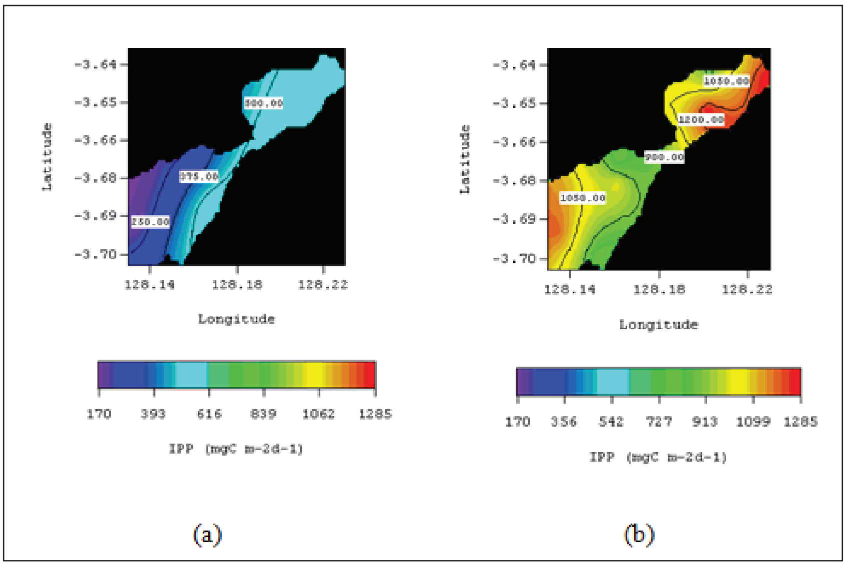

Figure 8. Spatial distribution of IPP in Ambon Bay: during the northwest season (a) and during the southeast season (b).

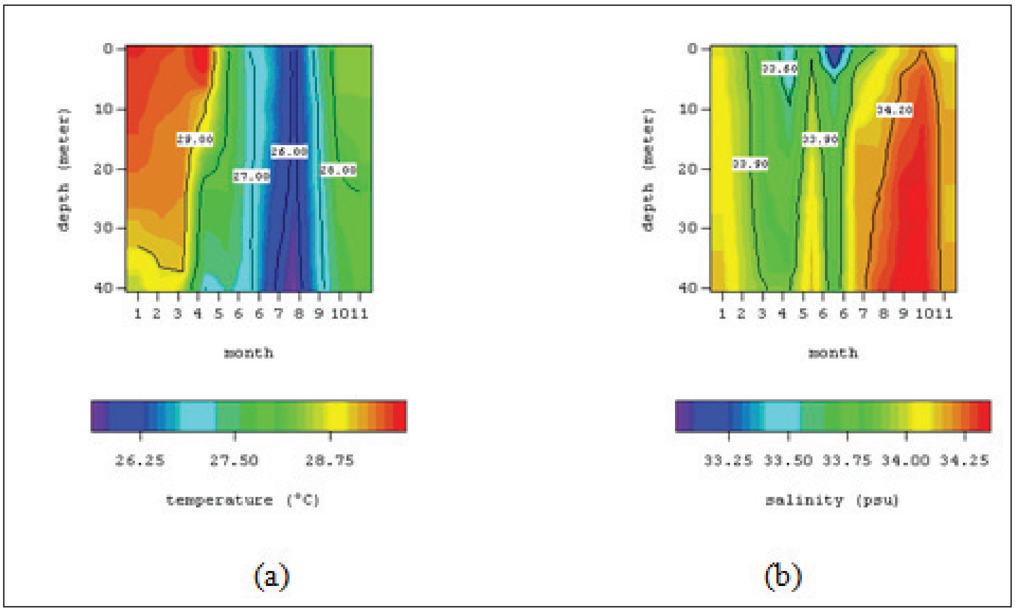

Figure 9. Vertical profile of temperature (a) and salinity (b) at station 15 in the Outer Ambon Bay.

The intensified IPP followed by the shallower chlorophyll-a peak (z_m) and the increase of the total chlorophyll-a within the peak in the southeast monsoon indicated the increase of nutrients in this area from either upwelled waters or river run-off. Upwelling process in Banda Sea has been observed during the southeast monsoon while downwelling took place in this area during the northwest monsoon (Wyrtki, 1961; Gordon and Susanto, 2001; Suciaty et al., 2008; Kemili and Putri, 2012). Likely, upwelling was also observed in this research region as represented by vertical profile of temperature and salinity in station 15 in which the decrease of temperature and the increase of salinity occurred between May and September (Fig. 9). This result was not surprising because this station was located on OAB facing directly to Banda Sea, so that the condition of waters in OAB could be influenced more by Banda Sea than by river discharge. Meanwhile, downwelling was indicated by the increase of temperature and the decrease of salinity at the resting period. The role of terrestrial discharge was likely to influence the elevating IPP during the southeast monsoon during which the precipitation was about 45%, higher than that during the northwest monsoon.

CONCLUSION

It can be concluded that in the Inner and Outer Ambon Bay, the level of chlorophyll-a concentration and IPP in July was higher than those of in other seasons due to upwelling and relatively high precipitation during the southeast monsoon. In contrast, downwelling and relatively low precipitation during the northwest monsoon (February) caused the relatively low level of chlorophyll-a concentration and IPP.

In addition, the results revealed that the magnitude of IPP in Inner Ambon Bay was more influenced by the river run-off while IPP in the Outer Ambon Bay was more influenced by physical process in Banda Sea waters. Then, the existence of narrow channel between inner and outer sides of the bay caused inhibition of the mixing processes of waters so that IPP in the inner bay was higher than that of in the outer bay.

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