Ocean Primary Productivity

PAR dependent time and depth resolved primary productivity model

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ABSTRACT:

A water column distribution of photosynthetically available radiation (PAR) was modeled based on the chlorophyll-a concentration in the surface layer with an empirical equation to support a depth and time resolved primary productivity model. A vertical distribution of PAR exhibited a variation for certain chlorophyll-a concentration, where a variation of diffused attenuation coefficient is expected. An empirical equation was proposed to model an optimum vertical distribution of PAR with chlorophyll-a concentration in the surface layer. This optically optimized PAR dependent depth and time resolved primary productivity model was validated with the in-situ measurements on the Equatorial Pacific, the East China Sea, and the Northwestern Pacific. The result indicated a good correlation between the model estimated primary productivity and the in-situ measurements, where the model showed a significant improvement from the previous one.

1. INTRODUCTION

A contribution of biota to a global warming in a long time scale is a strong interest of human beings as a storage of carbon dioxide. Also, it is expected that biota exhibits its variation of standing stock relative to a climate change. Bengtsson et al. (1999) studied perceived inconsistencies between global temperature observations over the last two decades and results from climate simulations with some hypothesis for the slower global warming. The biosphere may have a certain contribution to the global warming. The terrestrial biosphere has been essentially in balance with implying compensating growth of the biosphere (Houghton et al. (1997)). But oceanic biota has not been studied well. Langenfelds et al.(1999) pointed a variation of oceanic biota to the carbon flux with the atmosphere shows a temporal variability. Christian et al. (1997) estimated the net flux of carbon across particular depth and pointed the biological pump being a sink for atmospheric CO2 in the North Pacific Subtropical Gyre.

Now, we have a continuous observation of ocean color sensors since 1996. A discontinuity of ocean color measurements between the Ocean Color Temperature Scanner (OCTS) (Shimada et al. 1999) and the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) (McClain et al. 1992) was only two months. Although there are some overlaps of satellite programs, it has a possibility of data sets to study a contribution of phytoplankton to a climatological change for these 10 years. The OCTS and the SeaWiFS provide a similar specification with bands, FWHM, maximum radiance and SNR, which are based on the experience from the Coastal Zone Color Scanner (CZCS). In contrast, the Moderate Resolution Imaging Spectrometer (MODIS) and the Global Imager (GLI) have a narrow band width with 36 bands, to establish multi-purpose missions on ocean, land, atmosphere, and cryosphere.

Primary productivity of the glove estimated from the ocean color measurement by satellite is an approach to discuss a contribution of the oceanic biota to the global warming in a positive or negative contribution. Behrenfeld et al. (1997) and Falkowskie et al. (1998) proposed a light-dependent, depth-resolved model for carbon fixation based on the satellite data. Arrigo et al. (1998) implied a possibility of the primary production model in Southern Ocean waters.

In partly, those models worked in some extent. But less consistency on a primary productivity of the globe was observed. We proposed a photosynthetically available radiation (PAR) dependent time and depth resolved primary productivity model (Asanuma et al. (2000)). A vertical distribution of PAR is defined as an empirical equation of the chlorophyll *a* concentration in the surface, which is observed by an ocean color sensor. A carbon fixation rate is defined as a function of PAR and temperature. Primary productivity over the globe was computed and studied. Through the validation process of our primary productivity model, we realized that our model exhibited over estimates relative to in-situ measurements on the case II and similar waters.

2. PRIMARY PRODUCTIVITY MODEL

2.1 Depth and time resolved primary productivity model

We proposed a time and depth resolved primary productivity model to estimate a primary productivity from a satellite measurement (Asanuma et al. (2001a); Asanuma et al. (2001b)). This model provides vertical estimates of photosynthetically available radiation, chlorophyll *a* concentration, and primary productivity, which were not resolved by single layer models. A concept of our model is given as follows;

$$PP_{eu}=\int_t\int_z C(z)P_b\{z,PAR(z,day),T\}PAR(0,t)/PAR(0,day)\ dz\ dt \quad .....(1)$$

,where PP_{eu} is the primary productivity (mgC.m^{-2}. day^{-1}), P_b is the carbon fixation rate (mgC.mgChl-a^{-1}. m^{-3}.day^{-1}), $PAR(0,t)$ is the photosynthetically available radiation for each hour (Ein.m^{-2}. hour^{-1}), $PAR(z,day)$ is the photosynthetically available radiation for a day (Ein.m^{-2}. day^{-1}) , C is chlorophyll *a* concentration (mg.m^{-3}), T is the water temperature (deg-C), z is the depth in m and t is the time from 0 to 24 hours. We proposed the carbon fixation rate, P_b, as a function of PAR, temperature and depth from the in-situ measurement along the Equator and the middle latitude in the Pacific. The carbon fixation rate is given as follows;

$$P_b(z,PAR(z,day),T)=24\ [1-\exp\{-0.006\ a\ PAR\%(z)\}]\ \exp\{-0.005\ b\ PAR\%(z)\} \quad .....(2)$$

,and

$$a=0.1\ s\ PAR(0,\ day)+i$$
$$s=-0.00012T^3+0.0039T^2-0.0007T+0.2557$$
$$i=0.00023T^3-0.0108T^2+0.0868T-0.1042$$
$$b=0.00048T^3-0.0196T^2+0.1134T+3.1214$$

We empirically defined a vertical distribution of photosynthetically available radiation along the depth in percentage, $PAR\%(z,C_0)$, as a function of chlorophyll *a* concentration in the surface as follows;

$$Log(PAR\%(z,C_0))=(aC_0+b)Z+2 \quad ...(3)$$

,where C_0 is chlorophyll *a* concentration in the surface, which could be replaced by a satellite observation, Z is the depth, and a (-0.025) and b (-0.017) is empirical constants.

A vertical distribution of chlorophyll *a* concentration is proposed by the following function as a function of a vertical distribution of PAR and chlorophyll *a* concentration in the surface.

$$C(z)=[0.1-a\ C_0\ \exp\{-b\ PAR\%(z,C_0)\}]\exp\{-b\ PAR\%(z,C_0)\}+C_0 \quad .....(4)$$

,where a (0.7) and b (0.8) are empirical constants. In contrast, some empirical equations to estimate the vertical distribution of chlorophyll *a* were proposed using the Gausian function. In this study, chlorophyll *a* distribution is expressed empirically based on the vertical distribution of PAR, which determines the light field in the water and phytoplankton accommodates in the light field.

2-2. Photosynthetically available radiation

A determination of the PAR on the surface is another key issue to estimate the primary productivity. Frouin (2000) proposed a research product for the PAR from SeaWiFS measurement. The PAR at the surface for the day is computed with a remote sensing reflectance from SeaWiFS measurement. This method needs raw data of the globe for daily basis and it is difficult to conduct computation at the end user. In this study, a simple code is proposed to compute PAR with combining a model result and a probability function of cloud from satellite observation. ***PAR(t)*** at the sea surface is computed by MODTRAN-4.3 for the ideal atmospheric condition as a function of the time, ***t***, on the day of the year and the latitude. In this computation, the aerosol model is selected to the maritime extinction with 23 km visibility under the model for the mid-latitude summer atmosphere. Then, a probability function of cloud distribution is estimated from the SeaWiFS chlorophyll *a* distribution data set, where missing data is considered as the presence of cloud. Weekly composite data is selected to estimate a cloud probability function. Although there remains a possibility of the sun glint region in the missing data as discussed by Frouin (2000), an assumption was made that a weekly composite may have smaller possibility of the sun glint region than a daily composite. The averaged ***PAR(t)*** for the hour and for one month was computed by MODTRAN-4.3. Then, the PAR is given empirically with a probability function of cloud as follows:

$$PAR(t) = (0.9 - 0.05\, \Sigma Cloud)\, PAR(t) \quad .....(5)$$

,where ***Cloud*** is defined as 1.0 for the missing chlorophyll *a* data from a weekly composite chlorophyll *a* data. This research and GSFC showed a different PAR in higher latitude. Frouin (2000) estimated the PAR on the surface from the PAR on the top of the atmosphere with a transmission through the atmosphere. The maximum difference between two PARs is around 25 % at the higher latitude and the negligible difference in the lower latitude. The probability function of clouds from missing data has a possibility of the difference between two algorithms. Unfortunately, we are missing in-situ measurements of PAR over the higher latitude and it will be an important issue for the in-situ measurements in future.

2-3. Validation of primary productivity model

We computed a monthly primary productivity over the globe based on chlorophyll *a* distribution from the OCTS and the SeaWiFS, and the sea surface temperature distribution from the MCSST data sets generated by JPL from NOAA/AVHRR observation. The results of the primary productivity are verified with the in-situ measurements along the equatorial Pacific, the northwestern Pacific, and the East China Sea. In-situ measurements of the primary productivity were obtained

by the in-situ and the on-deck simulated in-situ incubation using ^{13}C solvent as the tracer. The incubation hours were set to 12 hours or 24 hours for the measurements. Figure 1 shows a scatter diagram between the primary productivity estimated by our model and in-situ measurements. Data along the equatorial Pacific and the Northwestern Pacific indicated a good agreement. Some data on the East China Sea indicated over estimates for in-situ measurements over 500 $mgC.m^{-2}.day^{-1}$. This over estimate suggests (i) a possibility of measurements over the different water mass between the model and in-situ data, where satellite data is spatially and temporally averaged for 9 km and one month each, (ii) a possibility of over estimates of primary productivity depending on the PAR vertical distribution, and (iii) a possibility of over estimates of carbon fixation rate depending on the PAR at the depth.

3. OPTICALLY OPTIMIZED PAR

3-1. Diffused attenuation coefficient and PAR

Fig.1 suggested the over estimate on the turbid waters or on the case II waters. Our estimate of vertical distribution of PAR is based on chlorophyll *a* concentration in the surface by the equation (3). In contrast, a general light attenuation through the water column is expressed by the following equation;

$$PAR(z) = PAR(0) \exp(-K_d\, z) \quad .....(6)$$

,where ***Kd*** is the down-welling diffused attenuation coefficient (m^{-1}), which depends on the wavelength, and 490 nm is used practically to indicate the property of the water.

Figure 2 shows vertical distributions of PAR estimated by our current model using the equation (3) and estimated by the equation (6). Vertical distributions of PAR for three typical sets of chlorophyll *a* concentration are plotted for the equation (3), including 0.05 (◆), 0.5 (▲) and 5.0 (■) $mg.m^{-3}$ with three block lines. For these three sets of chlorophyll *a* concentration, two sets of diffused attenuation coefficient for 490 nm are selected for each chlorophyll *a* concentration from the SeaWiFS monthly product over the East China Sea and the western Pacific Ocean in July of 2001. ***Kd***(490)s for chlorophyll *a* concentration of 0.05 $mg.m^{-3}$ are 0.028 and 0.033 (◇) m^{-1}, 0.5 $mg.m^{-3}$ are 0.065 and 0.085 (△) m^{-1}, and 5.0 $mg.m^{-3}$ are 0.2 and 0.35 (□) m^{-1}. The vertical distributions of PAR for these ***Kd***(490) are plotted by dotted lines. The vertical distribution of PAR for chlorophyll *a* concentration of 0.05 $mg.m^{-3}$ is between the vertical distributions of PAR for ***Kd***(490) of 0.028 and 0.033 m^{-1}. The vertical distribution of PAR for chlorophyll *a* concentration of 0.5 $mg.m^{-3}$ is deeper than that of PAR for ***Kd***(490) of 0.065 and 0.085 m^{-1}. The vertical distribution of PAR for chlorophyll *a* concentration of 5 $mg.m^{-3}$ is shallower than that of PAR for ***Kd***(490) of 0.2 and 0.35 m^{-1}. The difference of the vertical distribution of PAR for chlorophyll *a* (5 $mg.m^{-3}$) and ***Kd*** (0.2 and 0.35 m^{-1}) indicates that our model estimates the light field doesn't penetrate the water column, where more photosynthesis is expected in the deep layer of the surface water. The difference of PAR for chlorophyll *a* (0.5 $mg.m^{-3}$) and ***Kd*** (0.065 and 0.085 m^{-1}) indicates that our model estimates the light field penetrates more than expected by ***Kd***(490), where less photosynthesis is expected along the water column.

Currently, chlorophyll *a* concentration and diffuse attenuation coefficient are studied independently, and the empirical equations from two parameters are proposed independently. O'Reilly et al. (2000) proposed 4 bands ratio for three range of chlorophyll *a* concentration and applied to SeaWiFS products, where ratio of 510 to 555 nm, 490 to 555 nm, and 443 to 555 nm are used from low to high chlorophyll *a* concentration, but there remains uncertainty of the algorithm for a high chlorophyll *a* concentration. Mueller (2000) proposed 2 bands ratio of 490 to 555 nm to estimate a diffused attenuation coefficient, and also reported the uncertainty of the algorithm of diffused attenuation coefficient bigger than $0.25m^{-1}$. Chlorophyll *a* concentration and diffused attenuation coefficient are used to be independent parameters especially on the turbid water, where the difficulty of algorithm remains.

3-2. Variation of diffused attenuation coefficient

Figure 3 indicates a distribution of observation points as a function of chlorophyll *a* concentration and diffused attenuation coefficient for a monthly composite data of SeaWiFS in July 2001. Figure 3 shows a diffused attenuation coefficient exhibits a wide variation at a certain and higher chlorophyll *a* concentration. Figure 3 shows that optical properties of the water may not be given as a single function of diffused attenuation coefficient neither chlorophyll *a* concentration, especially on the case II water, which is a group of water with higher chlorophyll *a* and suspended matters.

We have tried to express the relationship between chlorophyll *a* concentration and diffused attenuation coefficient by a regression line. The equation (7) shows the regression line of the diffused attenuation coefficient as a function of chlorophyll *a* concentration.

$$Kd = -\exp(0.052\, C_0 - 0.06) + 1.1 \quad \ldots\ldots (7),$$

where ***Chl*** is chlorophyll *a* concentration given from the ocean color measurements. The regression line is plotted on Figure 3 with a block line and hatched triangles. Then a deviation of the diffused attenuation coefficient from the regression line (ΔKd) is computed by the next equation.

$$\Delta Kd = Kd - \exp(0.052\, C_0 - 0.06) + 1.1 \quad \ldots\ldots (8),$$

where, ***Kd*** is the diffused attenuation coefficient, given from the satellite observation. This deviation of the diffused attenuation coefficient (ΔKd) will be estimated from chlorophyll *a* measurement.

3-3. Optimization of PAR

In this step, we modify the vertical distribution of PAR given by the equation (3) to satisfy the PAR vertical distributions estimated from chlorophyll *a* concentration to be between the vertical distributions of PAR estimated by ranges of diffused attenuation coefficients. The next empirical equation determines PAR distribution as a function of chlorophyll *a* concentration.

$$Log(PAR\%(z,C_0))=(-0.0018\,C_0^3 + 0.022\,C_0^2 - 0.11\,C_0 - 0.024)Z + 2 \ldots\ldots (9).$$

Figure 4 shows the modified vertical distributions of PAR as a function of chlorophyll *a* concentration in the surface being located just between the vertical distributions of PAR estimated from diffused attenuation coefficient corresponding to each chlorophyll *a* concentration.

Vertical distributions of PAR estimated from chlorophyll *a* concentration in Figure 2 are drastically improved at high chlorophyll *a* concentration and high diffused attenuation coefficient. But Equation (9) is not sufficient to explain a variation of diffused attenuation coefficient at given chlorophyll *a* concentration.

Here, we combine two Equations (8) and (9) to explain a variation of vertical distribution of PAR as function of chlorophyll *a* concentration and diffused attenuation coefficient.

$$PAR(z) = PAR(0)\exp\{(-0.0018\,C_0^3 + 0.022\,C_0^2 - 0.11\,C_0 - 0.024 + \Delta Kd)\,Z\} \ldots\ldots (10)$$

The PAR at the depth Z m, ***PAR(Z)***, is estimated from the PAR at the surface, ***PAR(0)*** with chlorophyll *a* concentration and diffused attenuation coefficient at the surface.

3-4. Model run with an optically optimized PAR

We conducted a model run with the optically optimized PAR dependent depth and time resolved primary productivity model. Equation (3) was replaced with Equation (10) to explain a various light fields as a function of chlorophyll *a* concentration and diffused attenuation coefficient. Following to this replacement, it is possible to have a significant change in the carbon fixation rate (Equation (2)) and a vertical distribution of chlorophyll a concentration (Equation (4)).

We grouped in-situ primary productivity data into an equatorial Pacific, a sub-tropic region including the East China Sea and the Kuroshio water off Kyushu Island to Choshi peninsula, and a sub-arctic region including a mixing region among the Kuroshio originated warm cores and the Oyashio water, as we could obtain more in-situ observations since the previous model run.

Figure 5 shows the result of comparison between the new model and in-situ data. The correlation coefficient for the revised model was 0.77, where the correlation coefficient of the previous model was 0.31. The revised model indicates a significant improvement in the correlation between model and in-situ primary productivity.

4. SUMMARY

We have proposed the time and depth resolved primary productivity model using chlorophyll *a* concentration and sea surface temperature. Through the validation process of our model based on the in-situ measurements on the equatorial Pacific, the northwestern Pacific, and the East China Sea, our model exhibited an over estimation in some waters. It was suggested that the optical properties in the water is the major reason for the over estimate.

We studied the optical property of the water around Japan as a function of chlorophyll *a* concentration and diffused attenuation coefficient based on SeaWiFS data. The water with a higher chlorophyll *a* concentration exhibited a wide range diffused attenuation coefficient for a certain chlorophyll *a* concentration. This variation suggested the error in estimating a vertical distribution of PAR and chlorophyll *a* concentration as a function of chlorophyll *a* concentration in the surface water. Figure 2 shows deviations of the vertical distribution of PAR from the optical field estimated from diffused attenuation coefficient. Our previous empirical equation for the vertical distribution of PAR is modified to fit the variation of diffused attenuation coefficient at given chlorophyll *a* concentration as indicated by Equation (9). Then, the variation of diffused attenuation coefficient at certain chlorophyll *a* concentration is estimated as the difference of satellite observed diffused attenuation coefficient and the empirical equation, which represents the diffused attenuation coefficient for given chlorophyll *a* concentration (Equation (10)). By combining the modified empirical equation for PAR with chlorophyll *a* concentration and the variation of diffused attenuation coefficient, it is realized to express the vertical distribution of PAR.

As a result, the optically optimized PAR dependent depth and time resolved primary productivity indicated a good correlation between the model estimates and in-situ primary productivity measurements.

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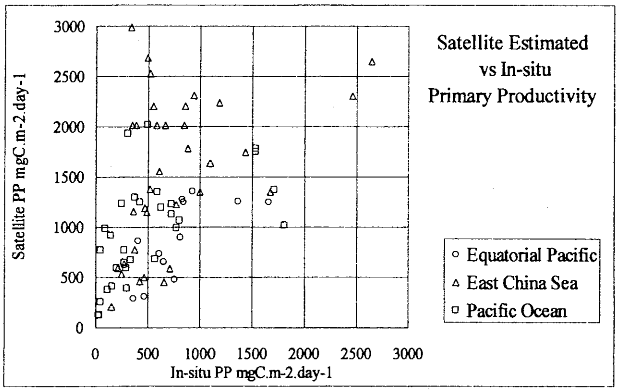

Figure 1. Primary productivity estimated by our model and in-situ primary productivity.

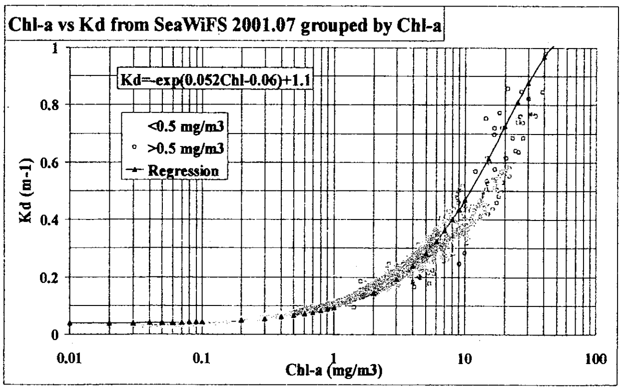

Figure 3. Distribution of water masses as a function of chlorophyll *a* concentration and diffused attenuation coefficient at 490 nm in July 2001, observed by SeaWiFS.

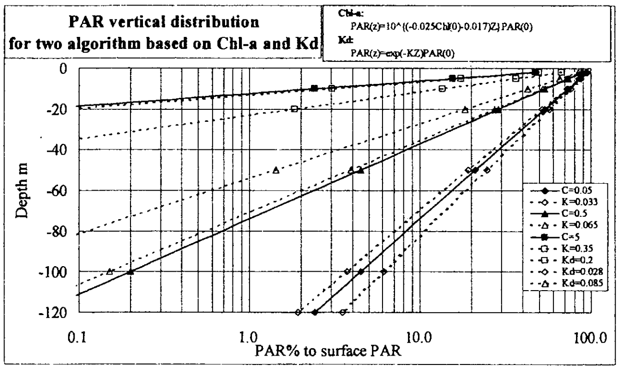

Figure 2. Vertical distributions of PAR for two algorithms based on chlorophyll *a* concentration (equation (3)) and diffused attenuation coefficient at 490 nm (eqution (6)).

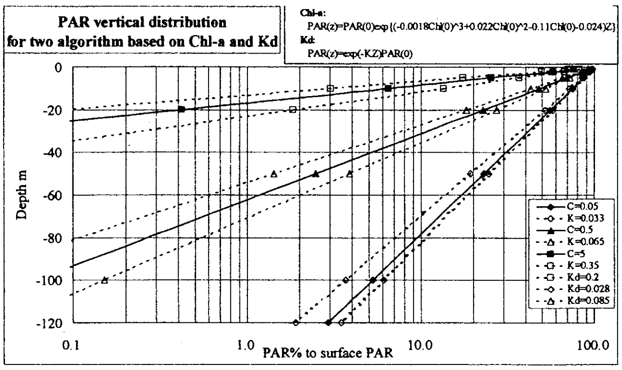

Figure 4. Vertical distributions of PAR for two algorithms based on chlorophyll *a* concentration (Equation (9)) and diffused attenuation coefficient at 490 nm (Equation (6))

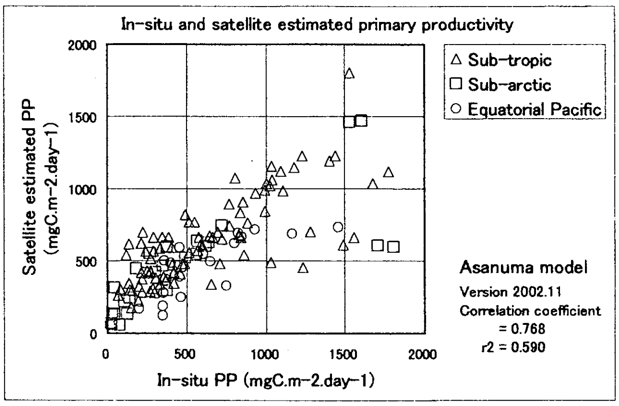

Figure 5. Primary productivity estimated by the optically optimized PAR dependent depth and time resolved primary productivity and in-situ primary productivity measurements.