STUDY OF OCEAN PRIMARY PRODUCTIVITY USING OCEAN COLOR DATA AROUND JAPAN

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Abstract

Ocean primary production is an important factor for determining the ocean's role in global carbon cycle. In recent years, much more chlorophyll-a concentration data in the euphotic layer were derived from the satellite ocean color sensors. The primary productivity algorithms have been proposed based on satellite chlorophyll measurements (Piatt, 1988; Morel, 1991) and other environmental parameters such as sea surface temperature or mixed layer depth (Behrenfeld and Falkowski, 1997; Esaias, 1996; Asanuma, 2002). In order to estimate integrated primary productivity in the whole water column, the vertical distribution of chlorophyll concentration below the sea surface should be reconstructed based on satellite data. In this paper, the vertical profile data of chlorophyll-a (Chl-a) measured around Japan Islands from 1974 to 1994 were reanalyzed based on the shifted-Gaussian shape proposed by Piatt *et al* (1988). Using this statistical model (neural network) and the photosynthesis irradiance parameters from Asanuma (2002), the distribution of primary productivity and its seasonal variation around Japan islands were estimated from SeaWiFS data, and the results were compared with in situ data and the other two models estimated from VGPM and mixed layer depth model.

Keywords: ocean color, primary productivity, chlorophyll profile, artificial neural network

I. Introduction

Ocean primary productivity is one of the important parameters in studying the ocean's role in global biogeochemical cycle. The absolute magnitude of carbon fixation attributed to marine photosynthetic organisms accounts for approximately 40 of the global total (Falkowski, 1998), and it seems that photo ynthetic processes fixed 40-50 G tons carbon every year (Longhurst, 1998). Photosynthesis process is the only mechanism to fix inorganic carbon in the ocean. The interest in climate change research needs us to study the primary productivity variation in order to understand phytoplankton on how it affects the air-sea carbon flux. Primary productivity is also the basis of marine food chain, therefore it is important variable in study the biomass estimation and fishery resources assessment.

Although the C method has been introduced to measure photosynthetic rate in field observation of primary productivity since 1950s, and a large amount of primary productivity data has been measured in different kinds of waters, it is difficult to describe the spatial and temporal distributions using field data only, due to data limitation. The ocean color sensors, such as CZCS, OCTS, SeaWiFS, MODIS etc. loaded on different satellites since 1978, have changed this situation greatly with the measurements of near surface Chl-a concentration from space.

Many different primary productivity models for the ocean color data from satellite

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remote sensing were proposed based on statistical analysis and photosynthetic model. Eppley *et al* (1985) provided an empirical relation between surface chlorophyll concentration and depth-integrated primary productivity in South California, Bright and several researchers modified this empirical model which both Chl-a concentration and sea surface temperature were used.

The empirical model is still valid in determining annual primary productivity as suggested by Esaias (1996). Another model is analytic model which is based on models of photosynthetic response of the algal biomass as the environmental variables such as light, temperature, nutrient concentration and the like. Behrenfeld and Falkowski (1997) presented a summary for analytic model and classified the primary productivity models into 4 different kinds, based on implicit levels of integrations, which include wavelength resolved models (WRM), wavelength integrated model (WIM), time integrated model (TIM) and depth integrated model (DIM). Behrenfeld and Falkowski (1997) proposed the vertically generalized productivity model (VGPM) and used seven-order polynomial function of sea surface temperature to describe the maximum chlorophyll-specific carbon fixation rate within water column.

Kameda *et al.* (2000) found that Japan and the maximum carbon fixation rate is modified using surface Chl-a concentration. Asanuma *et al*, (2002a) also noted that the VGPM gives an underestimated value in low chlorophyll concentration especially in tropical region, and they proposed a depth resolved primary productivity model with empirical relation between the carbon fixation and the environmental variables including PAR and sea surface temperature (SST). Howard (1995) proposed an algorithm for MODIS data by assuming that the surface observations of temperature and chlorophyll are uniform within mixed layer (Esaias, 1996). On the other hand, the vertical profile of Chl-a concentration obtained from diverse regions and environments shows a subsurface maximum. A shifted-Gauss distribution proposed by Lewis (1983) represents a rational description in most of the oceans. Matsumura and Shiomoto (1993) modified the shifted-Gauss distribution with the vertical gradient of the chlorophyll concentration and this relationship was verified in Sanriku area around Japan. However, the results show the difficulty to obtain the simple relationship between the Gauss function parameters and the surface chlorophyll concentration.

In this study, the depth resolved integral model will be used to estimate the ocean primary productivity around Japan Islands based on the ocean color data from OCTS and SeaWiFS sensors, and sea surface temperature from NOAA/AVHRR data. The photosynthetic rate proposed by Asanuma *et ah,* (2002b) is used in this study and the shifted- Gaussian profile of Chl-a concentration is reconstructed based on artificial neural network analysis using chlorophyll and temperature profiles provided by Japan Oceanographic Data Center (JODC) from 1974 to 1994. The results are then compared with *in situ* data in May 1997 and other models.

II. Primary Productivity Model

The daily water-column primary productivity is defined by the integral over depth and time as follows (Platt *et al.*, 1990).

$$PPeu = \int_0^D \int_0^\infty B(z) \int_{PAR} Pb(z,\lambda,t)\, d\lambda\, dt\, dz \quad (1)$$

where $B(z)$ is the biomass in vertical direction, Pb, is the rate of photosynthesis as a function of depth z, wavelength λ, and time /; *d* is the day length in hours; If the wavelength is integrated as suggested in Brehenfeld and Falkowski (1997), the wavelength integrated model (WIM) could be rewritten as:

$$PPeu = \int_0^{\infty} B(z) \int_{PAR} Pb(z,t)dtdz \qquad (2)$$

Asanuna *et al.* (2000) further proposed that the carbon fixation rate *Pb* is the function of photosynthetic available radiation (PAR), sea surface temperature (SST) and PAR variation along depth which is mainly related with Chl-a concentrations in case I waters, and the model, here equation (2), could be rewritten as:

$$PPeu = \int^{\infty} B(z) \int Pb(z, PAR(z,t), T)dtdz \qquad (3)$$

where *T* is sea surface temperature and the carbon fixation rate is given as follows,

P6=16[l-exp(-0.5a*A4«%(z)*0.01)exp(-0.3b*P^/?%(z).0.01) (4)
where *a*, *b* are coefficients; and *a* is related with PAR at the sea surface and sea surface temperature, and *b* is temperature function only (Asanuma, 2002a). *PAR{z)* is PAR in depth *z* in percent.

The vertical profile of Chl-a concentration, *B(z)*, is another important parameter as shown in equation 1-3. Lewis *et al* (1983) firstly used a Gaussian profile to describe this profile, and later Piatt *et al.* (1988) introduced a shifted-Gaussian function to provide a more versatile profile. It has been found that the shifted-Gaussian function provides a suitable description in most of the ocean (Kameda *et al*, 1998). *B(z)* and can be expressed as:

$$B(z) = B_0 + \frac{h}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(z-zm)}{2\sigma^2}\right) \qquad (5)$$

where *Bo* is the background biomass superimposed with a Gaussian function with depth *zm*, the depth of the chlorophyll maximum; ***a*** is the thickness of the peak and *h* is corresponding to the total biomass. In this study, we used more than 20 years field data sets collected by the JODC to train a three-layer artificial neural network to obtain 4 parameters in shifted-Gaussian from sea surface temperature, Chl-a concentration, mixed layer depth, Julian day and the locations (Osawa *et al*, 2002). The vertical distribution of photosynthetic available radiation along the depth is defined as

$$PAR(z) = PAR(0)\exp(-K_{dpar} Z) \qquad (6)$$

where K,i_{par} is the attenuation coefficient, which depends on the contents of the water column. The statistical results in Morel (1988) show that the attenuation coefficient for the whole spectrum in the euphotic zone can be expressed as,

$$Kdpar = 0.121 Chl^{0.429} \qquad (7)$$

where Chi is the mean value in euphotic zone, while the euphotic depth can be determined by *exp(-kdpar* < 0.01).

On other the hand, the solar irradiation also changes with time in one day. Ishikuma (1967) equation was used to describe tile variation of PAR in one day,

$$PAR(t) = PAR(0)Sin^3(\pi t / DL) \qquad (8)$$

where DL is day length in hours; t is time from 0 to DL, and noon time is at $DL/2$.

III. Data Sets And Processing

3.1 Satellite Data

From Equation (3) - (8), we can see that several environmental parameters are needed to estimate the ocean primary productivity. The SeaWiFS chlorophyll and photosynthetic available radiation

(PAR) data arc provided from GSFC7NASA. The SeaWiFS monthly-bin data are used to obtain the distribution of chlorophyll around Japan. The spatial resolution is 9 km. The data coverage is global and the time range is from January to December 2000. The ADEOS/OCTS data in May 1997 are also used in comparison with *in situ* primary productivity. The ADEOS/ OCTS data are Chl-a (Ver. 4) and provided by EORC/NASDA. The Sea surface temperature from NOAA/AVHRR of PODAAC/JPL is mainly used for photosynthetic rate calculation.

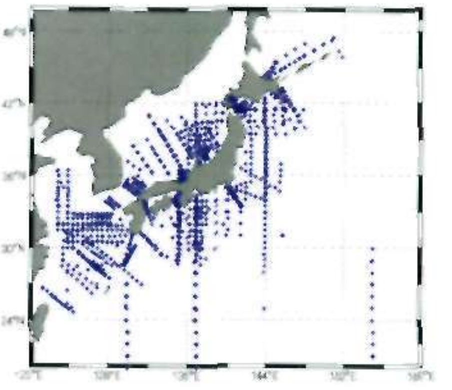
3.2 In situ data

In situ data of Chl-a and temperature profiles are obtained from The Japan Oceanographic Data Center (JODC). The data coverage is from 20-48°N, 120-160"E, while the time coverage is from 1974 to 1994 including both temperature and chlorophyll profiles. The total data are 8694 profiles. Temperature profile is used to determine the mixed layer depth assuming the temperature difference from the sea surface 0.5°C. Chl-a profile is used to derive the shifted-Gaussian profile as defined in Equation (5).

Figure 1 shows the data spatial distribution used in determining the shifted-Gaussian function of Chl-a profile. The mixed layer depth data from Levitus (1994) was also used in determining the Chl-a profile from satellite data using the trained neural network.

3.3 Data processing

In order to determine the 4 parameters of the shifted-Gaussian profile of chlorophyll concentration, all in situ chlorophyll profiles were fitted to the shifted- Gaussian function mentioned in the Equation (8). The data sets from satellite sensors could be used to determine the chlorophyll profile including sea surface temperature, Chl-a concentration



data could be found from Levitus' data sets. Table 1 shows the correlation coefficient of 4 parameters in the shifted-Gaussian and the three parameters, SST, Chl-a and MLD. It seems to be difficult to obtain an explicit expression among these parameters. Kameda *et al* (1998) used more than 7 groups of equations to describe the chlorophyll-a vertical profile using SST and Chl-a concentration in the surface. Here 3 layers neural network were constructed and trained by Stuttgart Neural Network Simulator (SNNS). The results show the simulation is reasonable after it is compared with the *in situ* profiles (details see Osawa, 2002).

Table I. Correlation coefficient among the 4 parameters in the shifted-Gaussian profile and SST, Chl-a and MLD.

	Bo	h	Sigma	Zm
SST	-0.26	-0.4 1	-0.20	0.48
Chi- a	0.28	0.68	-0.01	-0.35
MLD	0.05	0.04	0.54	0.19

The primary productivity estimation is based on Equation (3) - (8) and the euphotic-depth is calculated using iterate procedures until the irradiance decreased to 1 level. Finally, the daily primary productivity in water column is integrated in day length with irradiance variations in Ishikuma(1967).

IV. Results And Discussions

Figure 2 shows the comparison of the primary productivity distribution in May 1997 derived from Behrenfeld and Falkowski (1997) model (hereafter BF) and our method, which combines the shifted-Gaussian function of Chl-a vertical profile using neural network method and photosynthetic rate of equation (4) from Asanuma (2002a) (hereafter NN). Both Chl-a concentration and sea surface temperature data are from the ADEOS/OCTS sensors. Both images show the high primary productivity in Japan Sea and north from 35°N, which is also the mixing area of Kuroshio Current. BF model seems to give much large value compared with our results especially in the middle of Japan Sea and the coastal area. Along Japan coast, our result gave a little large value compared with BF, which is considered as the integral effect in NN model. In both images, we can also rind the minimum areas around 18°N in both images but our result owns a little larger value. This tendency is reasonable due to that BF model overestimates in the high latitude and underestimates in the tropical area (Asanuma, 2002b; Kameda 2002). In order to confirm the above explanation, Figure 2 shows the comparison of both models from 0-40°N along 144°E. We can see BF model gives much larger value beyond 33°N, and a little larger value from 0-8"N. Figure 3 shows the comparison between our result and Held data, which are from Kasai *et al* (1998), Shiomoto *et al* (1978) and Furuya (1978). We can see the model result gives rather high correlation 0.77 but the value seems to 2 times of Held data. One of the reasons may be due to that *PAR* data set used in our model is for May 2000.

Figure 4 shows the seasonal variation of primary productivity around Japan. Plankton bloom could be found in both April and July, 2000. The maximum of primary productivity area is also moving from 30-40°N in April to 40-50"N in July in 2000.

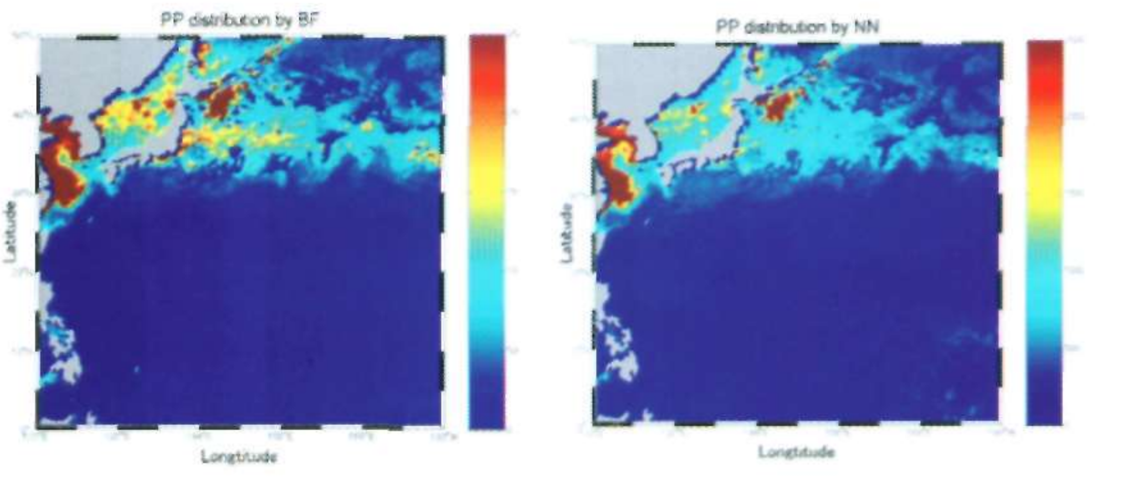


Figure 2. Comparison of primary productivity distribution (mgCm-2day-1) in May 1997 from the BF model (left) and the NN model (right)

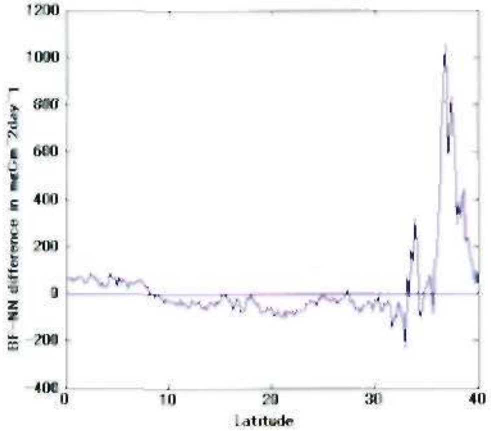


Figure 3. The difference between B&F and NN from 0-40N along 144E

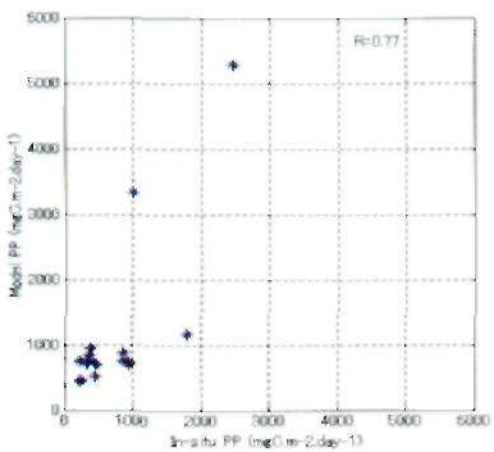


Figure 4. Comparison between NN results and in-situ data around Sanriku in May 1997

Figure 5 is the variation of primary productivity in area (30-40"N, 144-156°E) in 2000 and the comparison among different models, the area average value is calculated. Here the mixed layer model (Esaias, 19%) shown in Yodcr+MLD in Figure 5) and Kamcda model (Kameda *et al*, 2000, shown in Ishizaka) are also included in this figure. Our result shown in NN+ASA in the figure gives larger value in July and August (summer time), and rather low value from November to January compared with other models. A small plankton bloom is also found in October and November in both BF and MLD models, but not in Ishizaka and our NN result. The reason is not clear and much more Held data in 2000 arc needed to validate the NN result.

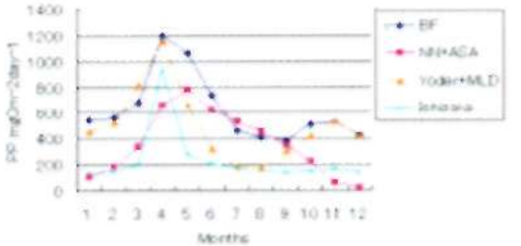


Figure 5. Variation of primary production in 2000 in area 30°-40°N 114°-156°E

V. Conclusions

In this study, the depth and time integrated models are used to estimate ocean primary productivity around Japan after combining the construction of the shifted- Gaussian profile of Chl-a concentration with the neural network, and the rate of photosynthesis from Asanuma (2002a). The model results have been compared with *in situ* data in May 1997 and other models. Our results show lower value around Japan Islands and larger value in tropical area. This result seems to be reasonable compared with BF model. Since there was no *in situ* data was found in 2000, we estimated the primary productivity in May 1997 using the ADEOS/OCTS data. Our result gives a rather good distribution compared with field data but with a much-larger value. One of the reasons is due to the isolation data in May 2000 used here. As Chl-a concentration obtained from satellite data is not just for surface value, actually it is an average effect in light penetrating zone as pointed out by Ballestero (1999) and other scientists before. How to Cv.«jtruct the vertical profile of Chl-a with considering the light penetrating in the ocean is another important problem. Much more Held experiments are needed to be carried out for validating our results in the future.

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