SGLI/GCOM-C1

Algorithm Theoretical Basic Document

Ocean net primary productivity (ONPP)

Version 3.3
31 March 2016

PI: Toru Hirawake[1*]
Co-I: Amane Fujiwara[2], Tomonori Isada[3] and Sei-ichi Saitoh[1, 4]

[1] Faculty of Fisheries Sciences, Hokkaido University
[2] JAMSTEC
[3] Field Science Center, Hokkaido University
[4] Arctic Research Center, Hokkaido University

*e-mail: hirawake@salmon.fish.hokudai.ac.jp

Contributors
Ryosuke Futsuki[1], Katsuhito Shinmyo[2], Shintaro Takao[3], Koji Suzuki[3], Yuichi Nosaka[4], and Yutaka W. Watanabe[3]

[1] PASCO Corporation, [2] NTT Data MSE Co., Ltd,
[3] Faculty of Environmental Earth Sciences, Hokkaido University,
[4] Ishinomaki Senshu University

This ATBD is based on Hirawake et al. "Light absorption-based primary productivity model for ocean color remote sensing" preparing to submit to Remote Sens. Environ.

1. Algorithm outline

1.1 Algorithm Code

ONPP_V3.3.f95

1.2 Product Code

ONPP (Ocean net primary productivity, research level product)

1.3 PI

Toru Hirawake (GCOM-C1 2nd RA 133, 4th RA 304)

1.4 Overview of algorithm

This algorithm estimate column integrated daily net primary productivity as a carbon assimilation by photosynthesis of phytoplankton in the ocean.

Most of the algorithms developed in the past used chlorophyll *a* (chl *a*) concentration [*Behrenfeld and Falkowski*, 1997a]. However, estimation of chl *a* concentration from satellite data has uncertainty due to the effect of pigment packaging which leads to underestimation [*Hirawake et al.*, 2000; *Mitchell and Holm-Hansen*, 1991] and of colored dissolved organic matter (CDOM) which leads to overestimation [*Matsuoka et al.*, 2007]. Another uncertainty is derivation of photosynthetic rate of phytoplankton. Although the vertically generalized productivity model (VGPM) [*Behrenfeld and Falkowski*, 1997b] which is one of the frequently used algorithms expressed the maximal photosynthetic rate (P^{B}_{opt}) as a function of sea surface temperature (SST), the SST derived P^{B}_{opt} had large error [*Kameda and Ishizaka*, 2005], particularly in the polar waters [*Hirawake et al.*, 2011]. Furthermore, the photosynthetic rate should be an independent parameter on the SST to discuss the effect of global warming to primary productivity in the ocean.

To reduce these issues, absorption-based primary productivity model [*Hirawake et al.*, 2011] was developed. The model was based on the result of Marra et al. [2007] who demonstrated that primary productivity normalized to absorption coefficient of phytoplankton is relatively invariant in the world ocean, and applying the relationship between primary productivity and absorption coefficient to the VGPM. Reduction in the effects of SST and chl *a* estimation in the Southern Ocean [*Hirawake et al.*, 2011], and of CDOM in the Bering and Chukchi Seas [*Hirawake et al.*, 2012] has been confirmed. In this project, additional dataset in the temperate waters were obtained and the absorption-based model was expanded.

Dataset to develop the algorithm includes the primary productivity and absorption coefficient data from the Southern Ocean, Chukchi Sea (Arctic Ocean), Bering Sea, North Pacific and Bermuda (n = 232) but does not include highly turbid coastal area currently (Figure 1). The details of sampling and analysis for primary productivity, absorption coefficients, pigments (HPLC and fluorometry), spectral radiation were described elsewhere [*Hirawake et al.*, 2012; *Hirawake et al.*, 2011].

Data from the waters around Kuril Islands (cruise of R/V Multanovski in 2014, n=12) and time-series of primary productivity from Station ALOHA of the HOT project are used for validations with in-situ and satellite (MODIS/aqua SMI, monthly) absorption data, respectively.

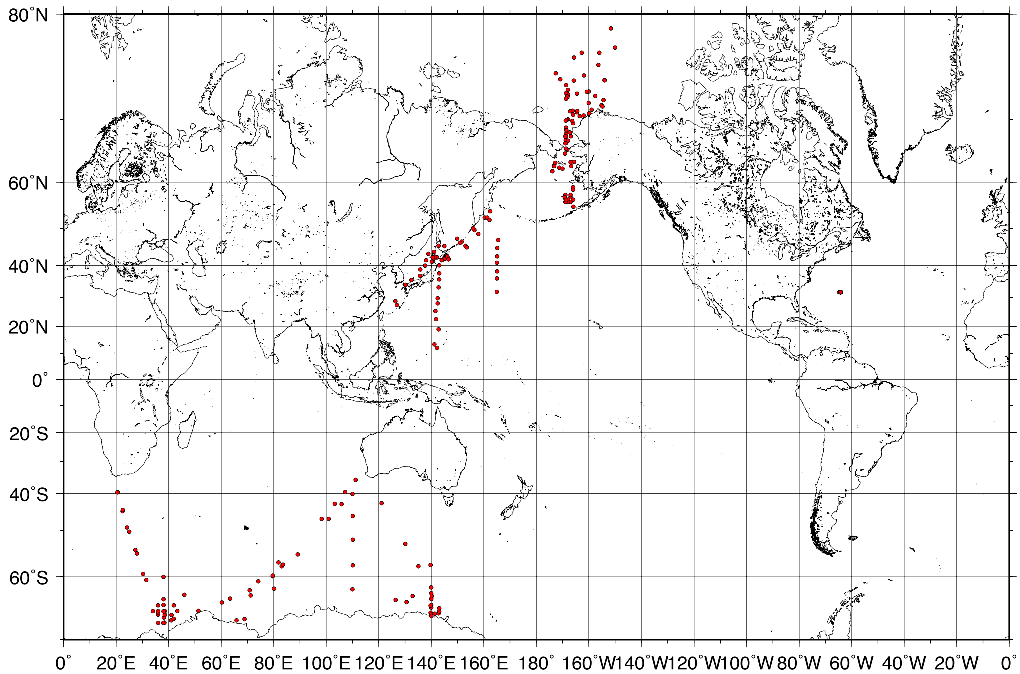

Figure 1. Map showing the location of sampling stations (red cicles).

2. Theoretical Description

2.1 Mathematical Description of Algorithm

Basic algorithm for the absorption-based model is the vertical generalized productivity model (VGPM) which is a function of satellite derived chl *a* and SST

(Behrenfeld and Falkowski, 1997):

$$PP_{\mathrm{eu}} = P^{\mathrm{B}}_{\mathrm{opt}} \times \frac{0.66125 \times E_0}{E_0 + 4.1} \times Z_{\mathrm{eu}} \times C_{\mathrm{surf}} \times D_{\mathrm{irr}}\,, \qquad (1)$$

where PP_{eu}, E_0, Z_{eu}, C_{surf} and D_{irr} is column integrated daily ocean net primary productivity (ONPP, mg C m^{-2} d^{-1}), daily incident irradiance in quantum unit (same as photosynthetic available radiation, PAR, mol photons m^{-2} d^{-1}), euphotic zone depth determined as the depth at which PAR is 1% of the sea surface (m), sea surface chl *a* concentration (mg chl *a* m^{-3}) and day length (h), respectively. $P^{\mathrm{B}}_{\mathrm{opt}}$ is chl *a* normalized optimal photosynthetic rate in the water column (mg C (mg chl $a)^{-1}$ h^{-1}). The seventh-order polynomial function of SST was used to derive $P^{\mathrm{B}}_{\mathrm{opt}}$ as in Behrenfeld and Falkowski [1997b]. In this study, $P^{\mathrm{B}}_{\mathrm{opt}} \times C_{\mathrm{surf}}$ (mg C m^{-3} h^{-1}) was replaced by an empirical function of spectrally averaged absorption coefficient of phytoplankton at the sea surface $\bar{a}_{\mathrm{ph}}(0\text{-})$ (m^{-1}) expressed by following equation:

$$\bar{a}_{\mathrm{ph}}(0-) = \frac{\int_{400}^{700} a_{\mathrm{ph}}(\lambda, 0-)\,\mathrm{d}\lambda}{700 - 400}\,, \qquad (2)$$

where $\bar{a}_{\mathrm{ph}}(\lambda, 0\text{-})$ is absorption coefficient of phytoplankton at each wavelength, λ, and a flat spectrum (constant over the visible region) of surface irradiance in quantum unit is assumed [*Hirawake et al.*, 2011]. Note that homogeneous distribution of vertical chl *a* concentration is assumed and its concentration is same as the C_{surf} when applying this model.

For the SGLI/GCOM-C1, E_0, Z_{eu} and $a_{\mathrm{ph}}(\lambda, 0\text{-})$ are given as products 'PAR', 'EZD' and a part of 'IOP'. D_{irr} is calculated from latitude and date [*Brock*, 1981]. If the EZD (m) is deeper than sea bottom depth, the bottom depth is used instead of EZD. C_{surf} is not necessary to input here. Although Hirawake et al. (2011, 2012) used simple relationship between $P^{\mathrm{B}}_{\mathrm{opt}} \times C_{\mathrm{surf}}$ (P_{opt}) and $\bar{a}_{\mathrm{ph}}(0\text{-})$ or $a_{\mathrm{ph}}(443, 0\text{-})$, algorithm in this project applied absorbed radiation by algae (Morel et al. 1991) per day length (ARA, Futsuki et al. in preparation) instead of absorption coefficients to derive P_{opt} :

$$ARA = \bar{a}_{\mathrm{ph}} \times E_0 \times DL^{-1}. \qquad (3)$$

Relationship between P_{opt} and *ARA* has dependency on PAR due to difference in quantum yield under different light intensities and saturation of photosynthesis under high radiation. Therefore, we separated the relationship to three ranges of E_0:

$$P_{opt} = 10^{(2.89497 + 1.39751 \times \log_{10} ARA)}$$
$$\text{when } 0 < E_0 < 20 \text{ mol photons m}^{-2} \text{ d}^{-1}, \quad (4)$$

$$P_{opt} = 10^{(1.74729 + 0.96122 \times \log_{10} ARA)}$$
$$20 \leq E_0 < 40 \text{ mol photons m}^{-2} \text{ d}^{-1} \quad (5)$$

$$P_{opt} = 10^{(1.3221 + 0.79609 \times \log_{10} ARA)}$$
$$E_0 \geq 40 \text{ mol photons m}^{-2} \text{ d}^{-1}. \quad (6)$$

Coefficient of determination (r^2) of the three functions had 0.88 (n=74), 0.70 (n=105) and 0.68 (n = 53), respectively (Figure 2a-c).

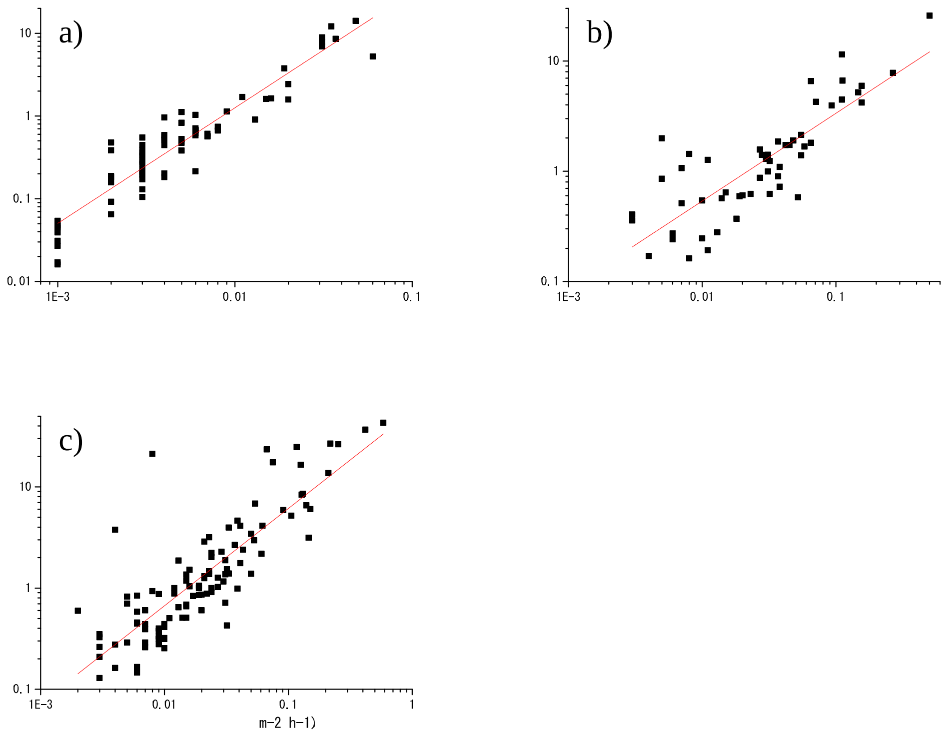

Figure 2. Relationship between P_{opt} and *ARA*. (a) $0 < E_0 < 20$, (b) $20 \leq E_0 < 40$, (c) $E_0 \geq 40$ mol photons m^{-2} d^{-1}.

As shown in Eq. (2), absorption coefficients over whole visible region are required to retrieve $\bar{a}_{ph}(0-)$. However, number of wavelength of the SGLI is quite limited and estimation error in absorption coefficients at longer wavelengths more than 500 nm is large. Therefore, $\bar{a}_{ph}(0-)$ was estimated empirically from $a_{ph}(443, 0-)$to reduce missing pixels (Figure 3):

$$\bar{a}_{ph}(0-) \quad = 0.59472 \times a_{ph}(443, 0-)^{1.09856}, \qquad (r^2 = 0.987, n = 246). \qquad (7)$$

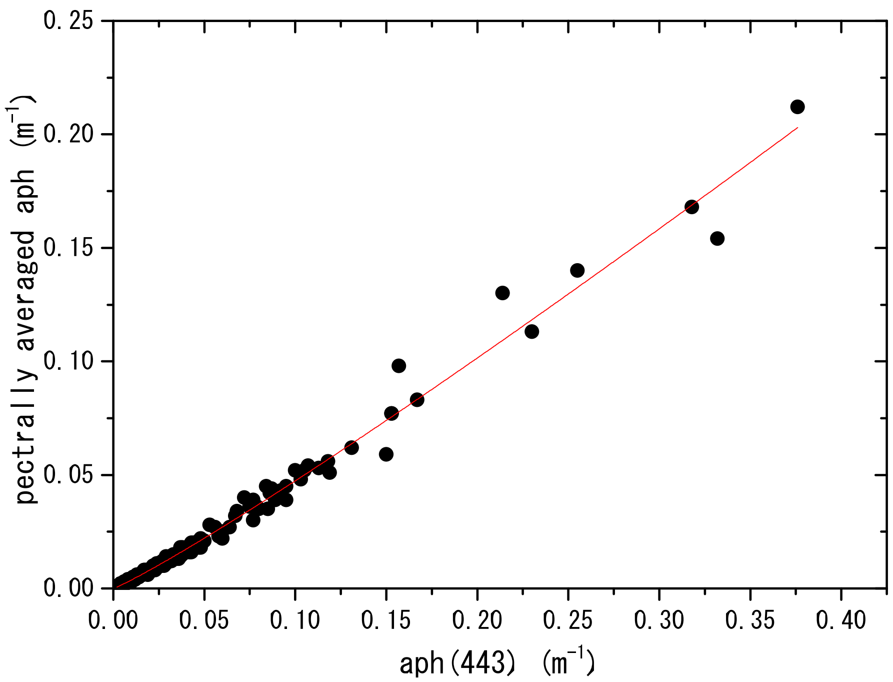

Figure 3. Retrieval of $\bar{a}_{ph}(0-)$ from $a_{ph}(443, 0-)$.

2.2 Validation

Reproducibility of the ONPP algorithm was confirmed using same dataset as that for the algorithm development (Figure 4). Although the dataset includes data from various optical conditions such as the polar seas and coastal region, the algorithm accounted for 78% and 64% of the observed variability in P_{opt} and PP_{eu}, respectively.

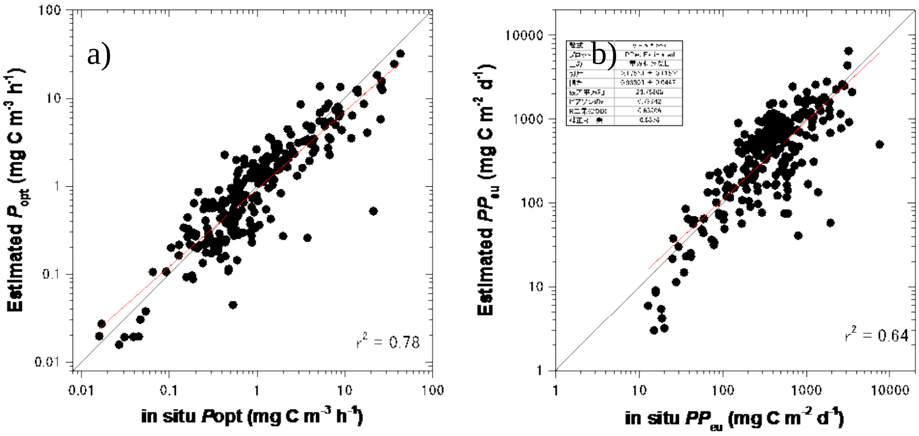

Figure 4. Relationship between estimated and observed values of (a) P_{opt} and (b) PP_{eu}. Black line shows 1:1 relationship.

The ONPP algorithm was validated using the in situ data from the waters around Kuril Islands (n = 12). As shown in Figure 5, estimated values from both algorithms satisfied a factor of 2 of measured values (RMSE = 0.230 and 0.287).

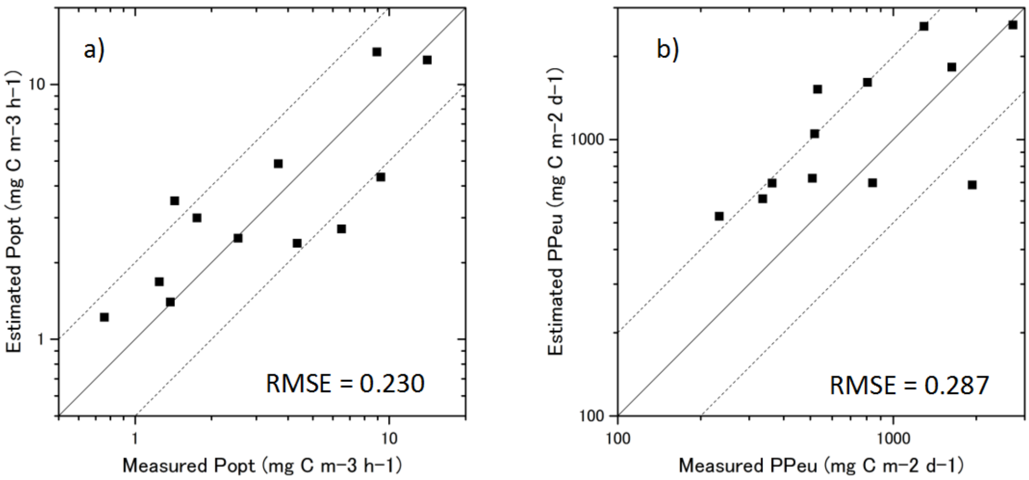

Figure 5. Comparison between in situ and estimated values of (a) P_{opt} and (b) PP_{eu}.

PP_{eu} estimated using MODIS satellite data was also validated (Figure 6). Retrieved PP_{eu} using MODIS data coincided with in situ one until 2008. However, underestimation of PP_{eu} was remarkable after 2008. We used previous release of MODIS data (R2013) and degradation of satellite sensor had affected on the trends of the MODIS product. Underestimation is probably attributed to this phenomenon. NASA has already released new version of the MODIS data (R2014.0) recently. Therefore, we should validate using the new one, particularly for the data since 2008.

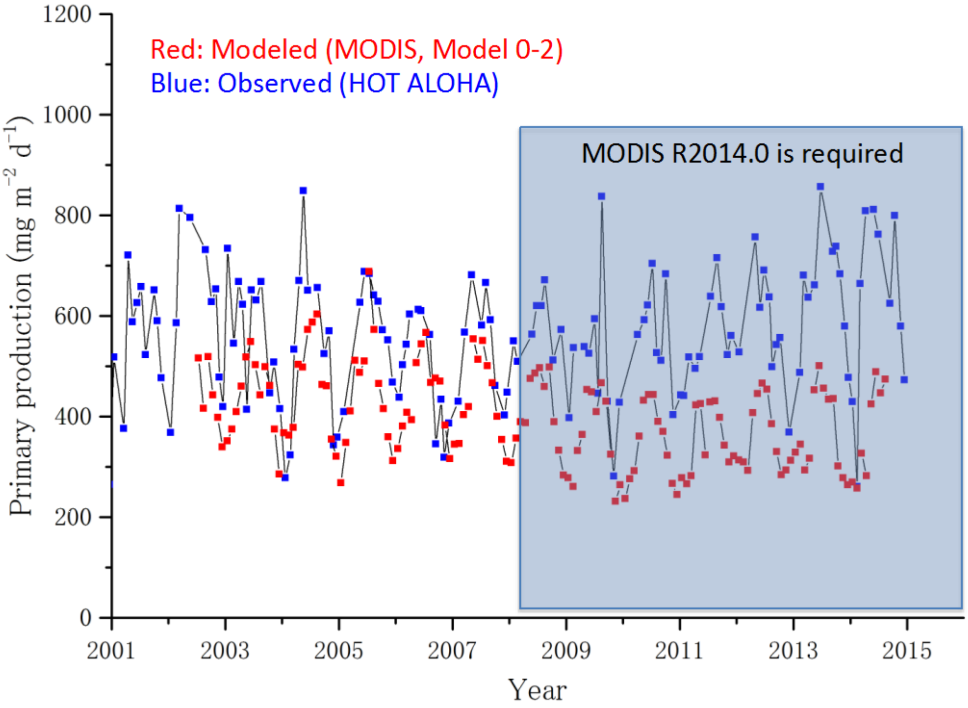

Figure 6. Comparison between observed and estimated primary production at Station ALOHA.

3. References

Behrenfeld, M. J., and P. G. Falkowski (1997a), A consumer's guide to phytoplankton primary productivity models, *Limnol. Oceanogr.*, *42*, 1479-1491.

Behrenfeld, M. J., and P. G. Falkowski (1997b), Photosynthetic rates derived from satellite-based chlorophyll concentration, *Limnol. Oceanogr.*, *42*, 1-20.

Brock, T. D. (1981), Calculating solar radiation for ecological studies, *Ecological Modelling*, *14*(1-2), 1-19.

Hirawake, T., K. Shinmyo, A. Fujiwara, and S. i. Saitoh (2012), Satellite remote sensing of primary productivity in the Bering and Chukchi Seas using an absorption-based approach, *ICES Journal of Marine Science*, *69*(7), 1194-1204.

Hirawake, T., H. Satoh, T. Ishimaru, Y. Yamaguchi, and M. Kishino (2000), Bio-optical relationship of Case I waters: The difference between the low- and mid-latitude waters and the Southern Ocean, *Journal of Oceanography*, *56*, 245-260.

Hirawake, T., S. Takao, N. Horimoto, T. Ishimaru, Y. Yamaguchi, and M. Fukuchi (2011), A phytoplankton absorption-based primary productivity model for remote sensing in the Southern Ocean, *Polar Biology*, *34*(2), 291-302.

Kameda, T., and J. Ishizaka (2005), Size-fractionated primary production estimation by a two-phytoplankton community model applicable to ocean color remote sensing, *Journal of Oceanography*, *61*, 663-672.

Marra, J., C. C. Trees, and J. E. O'Reilly (2007), Phytoplankton pigment absorption: A strong predictor of primary productivity in the surface ocean, *Deep-Sea Research I*, *54*, 155-163.

Matsuoka, A., Y. Huot, K. Shimada, S. I. Saitoh, and M. Babin (2007), Bio-optical characteristics of the western Arctic Ocean: implications for ocean color algorithms, *Can J Remote Sens*, *33*(6), 503-518.

Mitchell, B. G., and O. Holm-Hansen (1991), Bio-optical properties of Antarctic Peninsula waters: differentiation from temperate ocean models, *Deep-Sea Research*, *38*, 1009-1028.