Chlorophyll-a Evaluation using Terra/Aster Data

- Algorithm Theoretical Analysis, Ver.1-

○K. Iwashita※, J. C Dozier※※

ABSTRACT

The high-resolution satellite data has been utilized to monitoring water environments. However, without appropriate digital transformation for individual satellite band data, visualization of the polluted scene and assessment of relative differences in its concentration have been arduous.

Several digital transformation methods and numerical digital processing were applied to the multi-spectral satellite original set to minimize atmospheric effects ("the window") and unwanted sensor scan noise, which prevents the accurate extraction of oil at the water region. As results, detection of surface Chl-a and determination of its relative concentration were documented in laboratory/field experiments and successfully visualized by transformed Terra/ASTER and Landsat TM image analysis.

1.Introduction

The algorithm to correct the original set of high resolution satellite data, which has been analyzed and developed through lab/filed experiments, is based on a semi-analytical, bio-optical model of remote-sensing reflectance, $R_{rs}(\lambda)$, where $R_{rs}(\lambda)$ is defined as the water-leaving radiance, $L_w(\lambda)$, divided by the downwelling irradiance just above the sea surface, $Ed(\lambda,0^+)$. The $R_{rs}(\lambda)$ model has two free variables, the absorption coefficient due to phytoplankton at 675 nm, $a_\phi(675)$, and the absorption coefficient due to *Colored Dissolved Organic Matter* (CDOM) or gelbstoff at 400 nm, $a_g(400)$. The R_{rs} model has several parameters that are fixed or can be specified based on the region and season of the MODIS scene. These control the spectral shapes of the optical constituents of the model. $R_{rs}(\lambda_i)$ values from the MODIS data processing system are placed into the model, the model is inverted, and $a_\phi(675)$, $a_g(400)$, and chlorophyll a are computed.

The algorithm also outputs both the total absorption coefficients, $a(\lambda_i)$, and permits calculation of the phytoplankton absorption coefficients, $a_\phi(\lambda i)$, based on $a_\phi(675)$ retrievals. These are used in the calculation of the absorbed radiation by phytoplankton for use in the calculation of chlorophyll fluorescence efficiencies. Model is also dependent upon the instantaneous photosynthetically available radiation.

Further, Algorithm development is initially focused on tropical, subtropical, and summer temperate environments, and the model is parameterized .

2. Algorithm Basic Concepts

Morel and Gordon [1980] describe three approaches to interpret ocean color data in terms of the in situ optical constituents: empirical, semi-empirical, and analytical. In the analytical approach, radiative transfer theory provides a relationship between upwelling irradiance or radiance and the in situ inherent optical properties backscattering and absorption [e.g., Sathyendranath and Platt, 1997]. Then, constituent concentrations are derived from irradiance or radiance values measured at several wavelengths by inversion of the resultant system of equations. The algorithm for this project uses this approach, with the term "semi-analytical" invoked because bio-optical pieces of the radiative model are expressed by empirical relationships.

2-1. Considerable Physical Problems

After light enters the ocean, some of it eventually scatters back up through the surface. This light is called the water-leaving radiance $L_w(\lambda)$, and it can be deduced from space after removal of atmospheric effects. The magnitude, spectral variation, and angular distribution of this radiance depend on the following factors: the absorption and backscattering coefficients of the seawater, $a(\lambda)$ and $b_b(\lambda)$, respectively (known as the inherent optical properties); the downwelling irradiance incident on the sea surface $Ed(\lambda,0^+)$; and the angular distribution of the light within the ocean. To make things easier, we divide seawater into three components, each one having distinct optical properties of its own. These

※College of Industrial Technology , Nihon University
※※University of California, Santa Barbara

components are the seawater itself (water and salts), the particle fraction, and the dissolved fraction. Fortunately, $a(\lambda)$ is simply equal to the sum of the absorption coefficients for each component, and $b_b(\lambda)$ is equal to the sum of the backscattering coefficients. If we can accurately describe or model each spectrally distinct component of the absorption and backscattering coefficients, then we can determine the magnitude of each one from measurements of $L_w(\lambda)$ and $Ed(0^+, \lambda)$, given some assumptions about the angular distribution of light in the water. The key here is to accurately model the spectral behavior of $a(\lambda)$ for each component. The spectral behavior of $b_b(\lambda)$ is not as dynamic.

3. Mathematical of Algorithm

3.1 R_{rs} Model

The Rrs model is given by the following general equation, which is adapted from previous methods:

$$R_{rs}(\lambda)=ft2/Q(\lambda)\times b_b(\lambda)/[a(\lambda)+b_b(\lambda)] \quad \ldots\ldots (1)$$

where f is an empirical factor averaging about 0.32-0.33 [Gordon et al., 1975; Morel and Prieur, 1977; Jerome et al., 1988; Kirk, 1991], t is the transmittance of the air-sea interface, $Q(\lambda)$ is the upwelling irradiance-to-radiance ratio $Eu(\lambda)/Lu(\lambda)$, and n is the real part of the index of refraction of seawater. By making three approximations, (1) can be greatly simplified.

1) In general, f is a function of the solar zenith angle, $\theta 0$ [Kirk, 1984; Jerome et al., 1988; Morel and Gentili, 1991]. However, Morel and Gentili [1993] have shown that the ratio f/Q is relatively independent of $\theta 0$ for sun and satellite viewing angles expected for the MODIS orbit. They estimate that f/Q = 0.0936, 0.0944, 0.0929, and 0.0881, (standard deviation " 0.005), for λ = 440, 500, 565, and 665 nm, respectively. Also, Gordon et al., [1988] estimates that f/Q = 0.0949, at least for $\theta_0 > 20^\circ$. Thus, we assume that f/Q is independent of λ and θ_0 for all Terra/ASTER wavebands of interest, except perhaps for the band centered at 667 nm, which we don=t use.
2) t^2/n^2 is approximately equal to 0.54, and although it can change with sea-state (Austin, 1974), it is relatively independent of wavelength.
3) Many studies have confirmed that $b_b(\lambda)$ is usually much smaller than $a(\lambda)$ and can thus be safely removed from the denominator of following (2) [Morel and Prieur, 1977; references cited in Gordon and Morel, 1983], except for highly turbid waters.

These three approximations lead to a simplified version of (1),

$$R_{rs}(\lambda) \approx constant\ b_b(\lambda)/a(\lambda) \quad \ldots\ldots (2)$$

where the "constant" is unchanging with respect to λ and θ_0. The value of the constant is not relevant to the algorithm since the algorithm uses spectral ratios of $R_{rs}(\lambda)$ and the constant term factors out.

In the following sections, both $b_b(\lambda)$ and $a(\lambda)$ will be divided into several separate terms. Each term will be described empirically. The equations are written in a general fashion-i.e., the empirically derived parameters that describe each term are written as variables C and the actual values of the parameters that are used in the algorithm are shown in Tables 1a and 1b.

Table 1a Wavelength-Dependent Parameters for the semi-analytical Chlorophyll Algorithm for lake

λ	412(nm)	443(nm)	488(nm)	551(nm)
a0	2.22	3.59	2.27	0.42
a1	0.74	0.8	0.59	-0.22
a2	-0.5	-0.5	-0.49	-0.5
a3	0.0013	0.0111	0.0112	0.0111
bbw(m-1)	0.003339	0.002459	0.001561	0.000929
aw(m-1)	0.00478	0.00744	0.01633	0.0591

Table 1b Wavelength-Independent Parameters for the semi-analytical Chlorophyll Algorithm for lake

wavelength independent parameter					
X_0	-0.00182	S	0.0225	c_0	0.2818
X_1	2.058	p_0	51.9	c_1	-2.783
Y_0	-1.13	p_1	1	c_2	1.863
Y_1	2.57			c_3	-2.387

3.2 Back Scattering Term

The total backscattering coefficient, $b_b(\lambda)$ can be expanded as

$$b_b(\lambda)= b_{bw}(\lambda)+ b_{bp}(\lambda) \ldots\ldots (3)$$

where the subscripts "w" and "p" refer to water and particles, respectively. $b_{bw}(\lambda)$ is constant and well known [Smith and Baker, 1981]. $b_{bp}(\lambda)$ is modeled as

$$b_{bp}(\lambda)=X[551/\lambda]^Y \ldots\ldots (4)$$

The magnitude of particle backscattering is indicated by X, which is equal to b_{bp}(551nm), while Y describes the spectral shape of the particle backscattering.

Lee et al., [1994] empirically determined X and Y values by model inversion using a formula similar to (4). The X and Y values were compared to the $R_{rs}(\lambda)$ values measured at each station with the purpose of

finding empirical relationships for both X and Y as a function of $R_{rs}(\lambda)$ at one or more of the Terra/AQUA wavelengths. Once this was done, X and Y could be estimated from satellite data using following formula.

Expression for X;

$$X=Xo+X_1*R_{rs}(551)\text{…….(5)}$$

where X0 and X1 are empirically derived constants. Linear regression performed on the derived values of X vs. Rrs(551nm) taken from six observation of the Lake Inbanuma & experimental pond at Nihon University resulted in X0 and X1 values of B0.00182 and 2.058 (n = 53, r2 = 0.96). Figure 1 shows the regression graphically. If X is determined to be negative from 式 5 it is set to zero.

Expression for Y;

Y was found to covary in a rather general way with the ratio $R_{rs}(443nm)/R_{rs}(488nm)$. Variations in numerator and denominator values of this ratio are largely determined by absorption due to phytoplankton and CDOM. Absorption due to water is about the same and low at both wavelengths. Thus, to the extent that phytoplankton and CDOM absorption covary, the spectral ratio of the absorption coefficients, a(443nm)/a(488nm), will be only weakly dependent on pigment concentration, and the spectral ratio of backscattering coefficients should have a significant effect on the spectral ratio of Rrs. Y is thus

represented as

$$Y=Y_0+Y_1*R_{rs}(443)/R_{rs}(488)\text{…….(6)}$$

a linear function of Rrs(443nm)/Rrs(488nm) where Y_0 and Y_1 are empirically derived constants.

These empirical relationships are shown in Fig.1(a) & (b).

3.3 Absorption Term

The total absorption coefficient can be expanded as

$$a(\lambda)= a_w(\lambda) +a_\phi(\lambda)+ a_d(\lambda)+a_g(\lambda) \text{ …….(7)}$$

where the subscripts "w", "ϕ," "d," and "g" refer to water, phytoplankton, detritus, and CDOM ("g" stands for gelbstoff). Here $a_w(\lambda)$ is taken from Pope and Fry, [1997]. Expressions for $a_\phi(\lambda)$, $a_d(\lambda)$, and $a_g(\lambda)$ are omitted for limited space.

3.4 Weighted Chl-a Pigment Algorithm

Another consideration is that there should be a smooth transition in [chl a] values when the algorithm switches from the semi-analytical to the empirical method. This is achieved by using a weighted average of the [chl a] values returned by the two algorithms when near the transition border. When the semi-analytical algorithm returns an $a_\phi(675nm)$ value between 0.015 and 0.03 m^{-1}, [chl a] is calculated as

$$[chl\ a]=w\ [chl\ a]_{sa}+(1-w)\ [chl\ a]_{emp}\text{…….(8)}$$

where $[chl\ a]_{sa}$ is the semi-analytically-derived value and $[chl\ a]_{emp}$ is the empirically derived value, and the weighting factor is ;

$$w = [0.03-a_\phi(675)]/0.015.$$

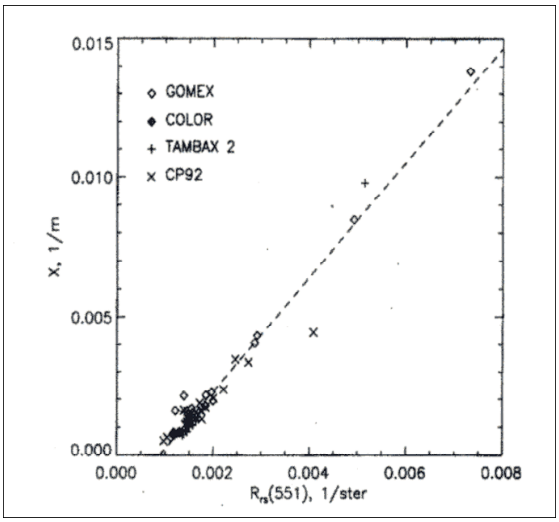

Fig. 1a X versus Rrs(551nm; visible green), where X is the magnitude of particle backscattering and Rrs is the Terra/Aster L1b data reflectance at 551 nm. The line is the linear regression quatioin;

$X=-0.00182+2.058\ Rrs(551nm)$ (n=53, r^2=0.96)

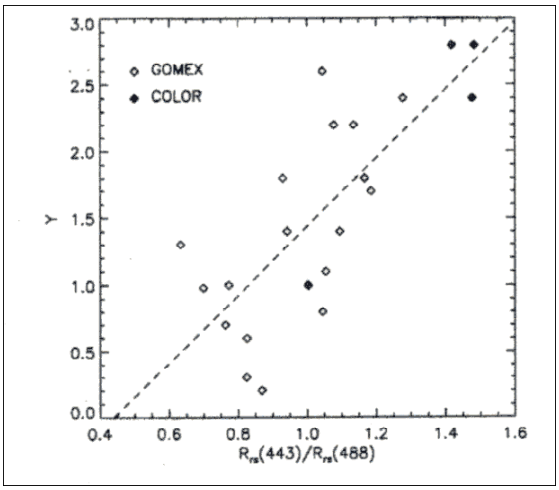

Fig. 1b Spectral shape of particle backscattering Y versus Rrs(443nm)/Rrs(488nm). The line is the linear regression ;

$Y=-1.13+2.57 Rrs(443nm)/Rrs(488nm)$ (n=22, r^2=0.59)

4. Algorithm Evaluation with Satellite Data Set

Several data sets within the low resolution coverage wide area evaluation set were numerically diagnosed as coming from waters where the pigments were much more packaged than those from the warm,

tropical and subtropical data sets evaluated earlier. The new packaged parameters are used to define a slightly different, packaged algorithm for upwelling and winter-spring temperate regions.

There are 326 points in an ensemble of multiyear, multiseason data sets from the California Current which we label as packaged. These consist of historical CalCOFI (n=303) and recent Cal9704 (n=23) data which we recently collected with G. Mitchell. The CalCOFI Rrs data were subsurface measurements, while the Cal9704 data were above-surface collections. Three hundred and three points (93%) from this packaged data set passed the semi-analytical portion of the new algorithm, yielding RMS1 and RMS2 errors for $[\text{chl a}]_{\text{retrieval}}$ of 0.111 and 0.268, respectively. The type II RMA slope was 0.999, the bias was -0.006, and the r^2 value was 0.917. The scatter plot overlays the one-to-one line, and the quantile plot is linear and overlies the one-to-one line but has a slight discontinuity near a chlorophyll value of 3. This indicates that some parameter modifications for the packaged algorithm are needed in this transition region.

Using the blended algorithm on 326 data points, the r^2 increased to 0.951 while the other statistics remained about the same. The RMS2 error of about 28% for the packaged algorithm also is better than our accuracy goal of 35% or less.

ACKNOWLEDGMENTS

The authors wish to acknowledge the State of California, Current Control and the US Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, Nevada for data support for this project.

References

1) Aiken, J., G.F. Moore, C.C. Trees, S.B. Hooker, and D.K. Clark, The SeaWiFS CZCS-type pigment algorithm, in SeaWiFS Technical Report Series, vol. 29, edited by S.B. Hooker and E.R. Firestone, Goddard Space Flight Center, Greenbelt, MD, 1995.
2) Arrigo, K.R., D.H. Robinson, D.L. Worthen, B. Schieber, and M.P. Lizotte, Bio-optical properties of the southwestern Ross Sea, J. Geophys. Res., 103: 21,683-21,695, 1998.
3) Austin, H.M., The Florida Middle Ground, Mar. Pollution Bull., 2, 171-172, 1970.
4) Austin, R.W., Inherent spectral radiance signatures of the ocean surface, in Ocean Color Analysis, pp. 2.1-2.20, Scripps Institute of Oceanography, San Diego, CA, 1974. Baker, K.S. and R.C. Smith, Bio-optical classification and model of natural waters, Limnol. Oceanogr., 27, 500-509, 1982.
4) Barnes, R.A., W.L. Barnes, W.E. Esaias, and C.R. McClain, Prelaunch acceptance report for the SeaWiFS radiometer, in SeaWiFS Technical Report Series, vol. 22, edited by S.B. Hooker, E.R. Firestone, and J. G. Acker, Goddard Space Flight Center, Greenbelt, MD, 1994.
5) Behrenfeld, M.J. and P.G. Falkowski, Photosynthetic rates derived from satellite-based chlorophyll concentration, Limnol. Oceanogr., 42, 1-20, 1997.
6) Bissett, W.P., J.S. Patch, K.L. Carder, and Z.P. Lee, Pigment packaging and chlorophyll a specific absorption in high-light oceanic waters, Proc. SPIE Int. Soc. Opt. Eng., 2963, 358-374, 1997.
7) Bricaud, A., A. Morel, and L. Prieur, Absorption by dissolved organic matter in the sea (yellow substance) in the UV and visible domains, Limnol. Oceanogr., 26, 43 53, 1981.
8) Bricaud, A., M. Babin, A. Morel, and H. Claustre, Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: Analysis and parameterization, J. Geophys. Res. 100: 13,321-13,332, 1995.
9) Brody, E., B.G. Mitchell, O. Holm-Hansen, and M. Vernet, Species-dependent variations of the absorption coefficient in the Gerlache Strait, Antarctic Journal, 27, 160-162, 1992.
10) Carder, K.L., R.G. Steward, J.H. Paul, and G.A. Vargo, Relationships between chlorophyll and ocean color constituents as they affect remote sensing reflectance, Limnol. Oceanogr., 31, 403-413, 1986.
11) Carder, K.L., R.G. Steward, G.R. Harvey, and P.B. Ortner, Marine humic and fulvic acids: Their effects on remote sensing of ocean chlorophyll, Limnol. Oceanogr., 34, 68 ≒ 81, 1989.
12) Carder, K.L., S.K. Hawes, K.A. Baker, R.C. Smith, G. Steward, and B.G. Mitchell, Reflectance model for quantifying chlorophyll a in the presence of productivity degradation products, J. Geophys. Res., 96, 20,599~20,611, 1991.
13) Carder, K.L., F.R. Chen, Z.P. Lee, and S.K. Hawes, Semianalytic Moderate-Resolution Imaging Spectrometer algorithms for chlorophyll a and absorption with bio-optical domains based on nitrate-depletion temperatures, J. Geophys. Res., 104, c3, 5403-5421, 1999.
14) Carder, K.L., F.R. Chen, J.P. Cannizzaro, J.W. Campbell, and B.G. Mitchell, Performance of MODIS semi-analytic ocean color algorithm for chlorophyll-a, Advances in Space Research, in press, 2003.