Validation of the semi-analytical algorithm for estimating vertical underwater visibility using MODIS data in the waters around Korea

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Abstract : As a standard water clarity variable, the vertical underwater visibility, called Secchi depth, is estimated with ocean color satellite data. In the present study, Moderate Resolution Imaging Spectroradiometer (MODIS) data are used to measure the Secchi depth which is a useful indicator of ocean transparency for estimating the water quality and productivity. To estimate the Secchi depth Z_v , the empirical regression model is developed based on the satellite optical data and *in-situ* data. In the previous study, a semi-analytical algorithm for estimating Z_v was developed and validated for Case 1 and 2 waters in both coastal and oceanic waters using extensive sets of satellite and *in-situ* data. The algorithm uses the vertical diffuse attenuation coefficient, K_d (m^{-1}) and the beam attenuation coefficient, c (m^{-1}) obtained from satellite ocean color data to estimate Z_v . In this study, the semi-analytical algorithm is validated using temporal MODIS data and *in-situ* data over the Yellow, Southern and East Seas including Case 1 and 2 waters. Using total 156 matching data, MODIS Z_v data showed about 3.6m RMSE value and 1.7m bias value. The Z_v values of the East Sea and Southern Sea showed higher RMSE than the Yellow Sea. Although the semi-analytical algorithm used the fixed coupling constant (= 6.0) transformed from Inherent Optical Properties (IOP) and Apparent Optical Properties (AOP) to Secchi depth, various coupling constants are needed for different sea types and water depth for the optimum estimation of Z_v .

Key Words : vertical underwater visibility, MODIS, Secchi depth, vertical diffuse attenuation coefficient, beam attenuation coefficient

1. Introduction

As a measure of the clarity of seawater, the vertical underwater visibility is important for the environmental

underwater monitoring, commercial, and military operations (Zaneveld and Pegau, 2003; Change *et al.*, 2010; Weeks *et al.*, 2012). The vertical underwater visibility is defined as the penetration depth of solar

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VIS radiation. Long-term monitoring of vertical underwater visibility based on Secchi depth has been conducted since nineteenth century for monitoring the light availability related to marine organism (Lorenzen, 1970, 1972; Morel, 1988; Morel and Berthon, 1989; Falkowski and Wilson, 1992; Park *et al.*, 1998; Doron *et al.*, 2011; Weeks *et al.*, 2012). With *in-situ* Secchi depth data, various satellite ocean color data have been used to estimate vertical and horizontal vertical underwater visibility on a global scale (Doron *et al.*, 2011; Weeks *et al.*, 2012; Barnes *et al.*, 2013). The vertical underwater visibility is affected by the optics of the detector, the Inherent Optical Properties (IOPs) and Apparent Optical Properties (AOPs) of seawater (Zaneveld and Pegau, 2003). Among several optical properties, the vertical diffuse attenuation coefficient, K_d (m^{-1}) and the beam attenuation coefficient, c (m^{-1}) are related directly with the vertical and horizontal vertical underwater visibility (Doron *et al.*, 2007, 2011; Zaneveld and Pegau, 2003). Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Medium-spectral Resolution Imaging Spectrometer (MERIS) and Moderate Resolution Imaging Spectroradiometer (MODIS) have provided the optical properties related to vertical underwater visibility (Doron *et al.*, 2011, Barnes *et al.*, 2013). The Geostationary Ocean Color Imager (GOCI) is able to provide hourly various optical property products such as remote sensing reflectance (R_{rs}) and diffuse attenuation coefficient (K_d). The estimation of vertical underwater visibility is conducted by two algorithms in the present study. The first is the empirical algorithm based on the relationship between simultaneous *in-situ* measurements of Secchi depths and water-leaving reflectance (or chlorophyll or K_d of satellite data) (Prasad *et al.*, 1998; Kratzer *et al.*, 2003; Kloiber *et al.*, 2002). Although the empirical model is easy to be developed and applied with large Secchi depth historical databases, this model is developed based on Case-1 waters (Morel *et al.*, 2007; Min *et al.*, 2007; Doron *et al.*, 2007, 2011). As the other method,

the semi-analytical algorithm, is proposed by Doron *et al.* (2007) and this algorithm uses the approximations of the radiation transfer related to IOPs, and AOPs. To estimate the vertical underwater visibility, the semi-analytical algorithm estimates and uses K_d and the beam attenuation coefficient (c) for both Case 1 and 2 water types (Doron *et al.*, 2007). The algorithm is comprehensively validated with more than 400 matchups of a large database containing *in-situ* Secchi depth data of various water types and MERIS, MODIS and SeaWiFS data (Doron *et al.*, 2011). In the preview, the validation result shows only the correlation coefficient between satellite-based and *in-situ* Z_v , but the quantitative accuracy such as RMSE or bias is not provided. This study aims to validate quantitatively the semi-analytical algorithm using temporal MODIS and *in-situ* Z_v data in the coastal and open ocean waters. The advantages and limitations of this semi-analytical algorithm are also suggested.

2. Materials and methods

1) Materials and study area

To generate the temporal Z_v data, Terra/Aqua MODIS data during 2000~2012 are used. MODIS data obtained at each 11:30 and 13:30 local time every day. The 490 nm and 555 nm remote sensing reflectance data (R_{rs}) of MODIS Level 2 Local Area Coverage (LAC) Ocean Color Product are used. Additionally, MODIS Geolocation product (MOD03/MYD03) is used to provide the solar zenith angle.

To validate MODIS Z_v data, the *in-situ* Secchi depth data during 2000~2012 are used. Korea Oceanographic Data Center (KODC) provides *in-situ* Secchi depth data by using Secchi disk on ships over the Yellow, Southern, East Seas, and East China Sea from 1960. For quality control, Secchi depth data is taken the range test obtained from time-series Secchi depth data. Fig.

Table 1. Dataset used in this study

Type	Sensor	Specifics	Source
R_{rs}	Terra/Aqua MODIS Level 2 LAC ocean color product (2000 ~ 2012)	1km spatial resolution 23 products (AOT, R_{rs} , Chl-a, etc.) *.L2_LAC_OC Float SR ⁻¹	NASA Ocean color web
Solar zenith angle	Terra/Aqua MODIS Geolocation product (MOD/MYD03) (2000 ~ 2012)	1km spatial resolution Swath product 8 products (Height, Solar zenith, land/sea mask etc.) *.HDF Integer	NASA LAAD web
<i>in-situ</i> Secchi depth	Secchi disk (2000 ~ 2012)	1960~now regular line observation Total lines, total points	Korea Oceanographic Data Center (KODC)

Fig. 1. Study area (left) and the positions of *in-situ* data acquisition (right).

1 (left) shows the study area and Fig. 1 (right) shows the sites of *in-situ* data acquisition. Total 156 matching points were obtained from *in-situ* Secchi depth data and MODIS data. Water around the Korean Peninsula shows various ocean optical properties. The field data from 1998 to 2009 indicates that the East Sea and Yellow Sea are classified into Case-1 and Case-2 waters, while the East China Sea shows optical properties of both Case-1 and Case-2 waters (Moon *et al.*

et al., 2010a). In the Southern Sea, the coastal waters belong to Case-2 and the offshore area is similar to the Case-1 water (Moon *et al.*, 2010a). Moon *et al.*, (2010b) shows that the beam absorption coefficient in the Yellow Sea is significantly influenced by suspended matters, and optical properties of the East Sea are determined by dissolved organic matters than others (Moon *et al.*, 2010b).

Table 2 shows the statistics of *in-situ* Secchi depths

Table 2. Summary of the *in-situ* Secchi depths used for estimating and validating the vertical underwater visibility

Geographic zone	Date	Numbers	Min-max(mean $\pm$ std.)
Yellow Sea	June, 2000~October, 2012	62	1.0 - 19.5 m(7.0 $\pm$ 4.3 m)
Southern Sea	April, 2000~ October, 2012	54	1.5 - 24.5 m(10.4 $\pm$ 4.9 m)
East Sea	April, 2000~ October, 2012	32	6.5 - 20 m(14.5 $\pm$ 3.6 m)
East China Sea	August, 2000~ August, 2010	8	2.5 - 16 m(8.0 $\pm$ 4.9 m)

during 2000~2012 and the data are used for matching and validating of MODIS data over the study area. The Secchi depths of Yellow Sea from 62 sampling datasets show lower Z_v values of less than 20 m compared with other sea data. The East Sea shows the highest Z_v mean value of approximately 15 m. The Southern Sea shows the broad Z_v range. The East China Sea data of total 8 dataset are also used in this study.

2) Preprocessing of satellite and *in-situ* data

In the computing process of MODIS Z_v , it is also important to include spatial and temporal matching process of *in-situ* and satellite data in the preprocessing stage. For each *in-situ* site, the average values of 3×3 pixels extracted from MODIS data are used. During the averaging process, the pixels of MODIS data under cloud are not excluded. For accurate validation, it is only used the *in-situ* data measured during ± 30 minutes of satellite acquisition time. MODIS R_{rs} and solar zenith angle are re-projected and re-sampled to Geographic coordinate system having WGS84 datum and 0.01 degree spatial resolution. MODIS solar zenith angle data are applied with the scale factor (≈ 0.01).

3) The semi-analytical algorithm for estimating vertical underwater visibility

(1) The retrieval of spectral irradiance reflectance below the surface R

The spectral irradiance reflectance just below the sea surface, R is estimated using in-water remotely sensed reflectance, r_{rs} (sr^{-1}) as :

$$R(\lambda) = r_{rs}(\lambda) \times Q \quad (1)$$

where r_{rs} is deduced from R_{rs} using the Equation 2:

$$r_{rs} = \frac{R_{rs}(\lambda)}{0.52 + 1.7R_{rs}(\lambda)} \quad (2)$$

Q is a bidirectionality factor that varies between approximately 3.5 and 4.2 depending mostly on the water type. Note that the value of Q is 4 in the work of Loisel and Morel (2001), which is estimated $R(490)$ and $R(560)$ of MODIS irradiance reflectance data.

(2) The conversion of R to the absorption coefficient (a) and backscattering coefficient (b_b)

R is related with a and b_b as:

$$R(\lambda) = \frac{E_u(\lambda)}{E_d(\lambda)} = f(\lambda) \frac{b_b(\lambda)}{a(\lambda)} \quad (3)$$

$f(\lambda)$ is a proportionality factor between R , a , and b_b , and varies between approximately 0.2 and 0.45. The values of $f(\lambda)$ at $\lambda = 490$ nm and 560 nm are taken as 0.335 based on Loisel and Morel (2001).

b_b is the sum of b_{bw} and b_{bp} which are the backscattering coefficients of the pure seawater and marine particles respectively:

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bp}(\lambda), \quad (4)$$

$b_{bw}(490)$ is taken equal to 0.00345 m^{-1} based on the measurement data (Morel, 1974). $b_{bp}(490)$ is calculated by using $R(490)$ and $R(560)$ as:

$$b_{bp}(490) = \frac{N}{D}, \quad (5)$$

where,

$$N = -B_{490-560} b_{bw}(560) + B_{490-560} \frac{a_w(560)}{f(560)} R(560) + \alpha_{490-560} B_{490-560} \frac{f(490) R(560)}{f(560) R(490)} b_{bw}(490) \quad (6)$$

$$- \alpha_{490-560} B_{490-560} \frac{R(560)}{f(560)} a_w(490),$$

$$D = 1 - \alpha_{490-560} B_{490-560} \frac{f(490) R(560)}{f(560) R(490)} \quad (7)$$

The spectral variations of the particles, which were observed by Babin *et al.* (2003) and Barnard *et al.* (1998), derives the backscattering ratio between two bands as follows:

$$B_{490-560} = \frac{b_{bp}(490)}{b_{bp}(560)} = 1.003 \quad (8)$$

$b_{bw}(490)$ and $b_{bw}(560)$ are taken as 0.00345 and 0.0009 respectively (Morel, 1974), and $a_w(560)$ is 0.0619 (Pope and Fry, 1997). $\alpha_{490-560}$, the ratio of $a_{res}(560)$ to $a_{res}(490)$ has the average value of 0.323 (Doron *et al.*, 2011).

The absorption coefficient $a(490)$ is estimated by using $b_b(490)$ as:

$$a(490) = \frac{f(490) b_b(490)}{R(490)} \quad (9)$$

(3) Algorithm to estimate $K_d(490)$ and $c(490)$

$K_d(490)$ is estimated using $a(490)$, $b_b(490)$ and the solar zenith angle (θ_s) based on Lee *et al.* (2005) as:

$$k_d(490) = (1 + 0.005\theta_s) a(490) + 4.18(1 - 0.52e^{-10.8a(490)}) b_b(490) \quad (10)$$

The value of c at $\lambda = 490\text{nm}$ can be expressed as:

$$c(490) = a(490) + b_p(490) + b_w(490), \quad (11)$$

where,

$$b_p(490) = \frac{b_{bp}(490)}{-0.0310 + 0.0503 \tanh \left(\frac{b_{bp}(490) + 0.00686}{0.00820} \right)} \quad (12)$$

(4) Algorithm to estimate vertical underwater visibility Z_v

According to Tyler (1968) and Preisendorfer (1986), the Secchi depth Z_v can be expressed as:

$$Z_v = \frac{\ln \left(\frac{C_0}{C_{min}} \right)}{K_d(490) + c(490)} = \alpha \times \gamma_0, \quad (13)$$

where,

$$\alpha = \frac{1}{K_d(490) + c(490)}, \quad (14)$$

$$\gamma_0 = \ln \frac{C_0}{C_{min}} = 6 \quad (15)$$

C_0 is the inherent contrast between the disk and background water, and C_{min} is the minimum apparent contrast perceivable by the human eye. Although the γ_0 is the coupling constant between 5 and 10 for varying conditions, Doron *et al.* (2007, 2011) suggests that γ_0 is taken as 6, showing a strong relationship between satellite based α and *in-situ* data of the ocean sites.

α is estimated as:

$$\alpha = \frac{1}{0.0989x^2 + 0.8879x - 0.0467} \quad (16)$$

where $x = K_d(490) + c(490)$.

The flow chart in Fig. 2 shows the detailed procedure to generate MODIS Z_v data based on the semi-analytical algorithm described in Section 2.

Fig. 2. The flow-chart of generating MODIS Z_v data.

3. Results

Fig. 3 shows the relationship between $1/(K_d+c)$ estimated from MODIS data and *in-situ* Z_v of all seas and water depths. The parameter $1/(K_d+c)$ consists of the optical beam absorption, backscattering, and solar zenith angle. As in Fig. 3 (left), $1/(K_d+c)$ shows the linear positive relationship and high correlation coefficient with *in-situ* Z_v for all seas and different water depths. The ratio of $1/(K_d+c)$ to Z_v is the coupling constant, γ_0 . In the semi-analytical algorithm, this coupling constant was taken as $\gamma_0 = 6$. In open water and deep water, the coupling constant is close to 6. This means that the semi-analytical algorithm is considered mainly in Case-1 waters. The present result in Fig. 3

Fig. 3. The relation between $1/(K_v + c)$ estimated from MODIS data and *in-situ* Z_v for all seas (left) and water depth (right).

Fig. 4. The scatter diagram of Terra/Aqua MODIS Z_v and *in-situ* Z_v .

shows lower coupling constants than 6 for all seas and depths. In the shallow waters along coasts, $\gamma_0 \leq 5$; while $\gamma_0 \geq 5$ in the deep and open waters. Thus, different coupling constants should be used, depending on the types of seas and water depths, for increased accuracy in estimating the Z_v value.

To validate the semi-analytical algorithm, the MODIS Z_v and *in-situ* Z_v values are compared on the all 156 matching points. Fig. 4 shows the scatter diagrams of MODIS-based and *in-situ* Z_v with the RMSE values for Terra and Aqua. It can be seen that, on average, the MODIS-based data overestimate the *in-situ* Z_v values. MODIS data aboard Terra and Aqua

satellite were obtained before and after noon. In Fig. 4, Terra MODIS data show smaller RMSE ($=3.86$ m) than Aqua MODIS data ($=5.13$ m), and some data points of Aqua MODIS Z_v show rather large difference from *in-situ* Z_v . This difference can not be associated with the number of data points between Terra and Aqua because they are roughly the same. It may well be caused by the difference in solar zenith angle, cloud coverage, or optical properties after noon. Further study using GOCI hourly data is required to explain the exact cause of this difference.

Fig. 5 is the scatter diagram between the *in-situ* Z_v and Z_v estimated from Terra/Aqua MODIS data for different seas and water depths. The smallest mean Z_v is in the East China Sea and is 8.2 m; while the largest mean Z_v is in the East Sea and is 16.5 m. The mean Z_v in the Yellow Sea East China Sea and Southern Sea is 8.8 m and 16.5 m respectively. As to the accuracy, the Southern Sea and East Sea have large RMSE of 4.0 m and 3.9 m respectively, and the smallest RMSE is 2 m in the East China Sea, but from only 8 samples, so that the statistical uncertainty is large.

In terms of different water depths shown in the right of Fig. 5, the general trend is that Z_v increases with increasing depth although Z_v is not, in the strict sense, linearly proportional to the water depth. The RMSE values tend to increase as the water depth increases, but the small RMSE of 2.45 m in the shallowest waters

Fig. 5. The scatter diagrams of MODIS-based Z_v and *in-situ* Z_v for the 4 seas (left) and different water depths (right).

Fig. 6. Bias (= MODIS Z_v - *in-situ* Z_v) value of Z_v for different satellites (a), water depths (b), and seas (c).

may be due to the small Z_v mean and/or statistical uncertainty associated with small sample numbers.

As mentioned with reference to Fig. 4, MODIS overestimates the *in-situ* Z_v data. The difference

between the MODIS-based and *in-situ* Z_v is larger by Aqua than Terra, and the average amount of overestimation is approximately 1.7 m as shown in Fig. 6 (a). There is no definite relation among different water

depths as in Fig. 6 (b) with the largest difference for the water depth greater than 100 m. As to the dependence on the seas shown in Fig. 6 (c), the differences between the MODIS-based and *in-situ* Z_v are similar for the three seas except the East China Sea in which there is statistical uncertainty due to small number of sampling points.

4. Conclusion

During 2000~2012, the vertical underwater visibility data based on the semi-analytical algorithm is validated by using MODIS and *in-situ* data acquired at the Yellow, Southern, East Sea, and East China Seas. The parameter $1/(K_d + c)$, which comprises the MODIS optical properties, showed high correlation and a linear relationship with *in-situ* Z_v . However, the coupling constant of MODIS data was found to be smaller than the fixed coupling constant of 0.6 used in the previous semi-analytical algorithm. Thus, it is recommended to apply adaptive coupling constants for different seas and water depths for improved measurement accuracy. The Yellow Sea and East China Sea show lower Z_v range under 9 m and the East Sea shows high Z_v value over 16m. The Southern Sea shows the largest Z_v range from 3 to 25 m among sea area and the lowest accuracy (= 4.0 m RMSE) of MODIS Z_v . MODIS Z_v data applied by the semi-analytical algorithm is about 3.6 m RMSE and 1.7 m bias value. MODIS Z_v of Aqua satellite, the Southern Sea, and water depth over 100 m shows lower accuracy than other dataset. In further study, it will be attempt the improvement of semi-analytical algorithm by considering the optical properties of the sea area and water depth.

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