



Evaluation of chlorophyll retrievals from Geostationary Ocean Color Imager (GOCI) for the North-East Asian region



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ABSTRACT

Estimation of chlorophyll concentration in the marine biosphere has been the central topic of ocean color remote sensing since its advent. While various algorithms were proposed in the literature so far and tested for oceanic waters of diverse constituent composition, an independent algorithm evaluation is needed for local ocean waters that have dynamic variation in optically active water constituents such as colored dissolved organic matters (CDOM) and suspended particulate matter (SPM). This paper evaluates the performance of chlorophyll algorithms for Geostationary Ocean Color Imager (GOCI) radiometric data, using *in situ* measurements collected at 491 stations around Korea Peninsula during 2010–2014 from which there were 130 match-ups with GOCI data. For the evaluation in areas with high variation in SPM, water samples were first classified into three levels of SPM, and then the coefficients of candidate algorithms were newly derived for the turbidity cases using the *in situ* and GOCI remote sensing reflectance (R_{rs}) data. Functional forms of traditional band ratio algorithms (e.g. OC algorithms (O'Reilly et al., 1998) and Tassan's algorithm (Tassan, 1994)), fluorescence line height algorithm, and near-infrared-to-red band ratio approach were tested. The evaluation results for the coincident *in situ* pairs of R_{rs} and chlorophyll measurements showed that the mean uncertainty was <35% with the correlation around 0.8 by using the OC3 with turbidity consideration (OCT) and Tassan's algorithm with turbidity dependent coefficients (Tassan-TD). For the GOCI match-ups, the mean uncertainty for all turbidity levels was around 35% with correlation around 0.65, when OCT and Tassan-TD were used.

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1. Introduction

Estimation of chlorophyll pigment concentrations plays a critical role in understanding several key biological and geochemical processes in the ocean (Antoine et al., 1996; Guildford and Hecky, 2000; Stumpf et al., 2003; Wang et al., 2008). Its long-term and synoptic monitoring capability over large areas has made ocean color remote sensing an indispensable tool for understanding spatio-temporal dynamics of chlorophyll concentrations in the global ocean ((Goes et al., 2000; Yoder, 2003; Yamada et al., 2004; Gregg et al., 2005; Carr et al., 2006; Henson et al., 2010).

The estimation of chlorophyll concentrations (CHL), however, has been challenging for areas with optically complex waters. In such cases, CHL algorithms may be prone to large errors when they are applied to waters with optical properties that are not compatible with the assumptions in the algorithms ((Ruddick et al., 2001; Darecki and Stramski, 2004; Dall'Olmo et al., 2005; Gitelson et al., 2007; Moore et al., 2009; Spyarakos et al., 2011). For example, the OCx algorithms (O'Reilly et al., 1998) are not suitable for Case-2 waters in which the

absorption and scattering of other constituents such as colored dissolved organic matter (CDOM) and suspended particulate matter (SPM) do not co-vary with CHL (Darecki and Stramski, 2004; Lyon et al., 2004). A study (Darecki and Stramski, 2004) showed that the standard OC4 algorithm overestimates CHL by 150 to 200% for Moderate-Resolution Imaging Spectroradiometer (MODIS) and Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), and a regional tuning of the algorithm coefficients for the Case-2 Baltic Sea waters still produced mean normalized bias of 30%.

Recent studies have shown that CHL algorithms that do not consider the influence of SPM also create large errors in productive, turbid waters. Band ratio algorithms that utilize the blue-to-green wavelength range can overestimate CHL from 5- to 20-fold for a low CHL range (<0.05 mg/m³) when the mineral concentration is 1 g/m³ (Woźniak and Stramski, 2004). McKee et al. (2007) also showed that increasing SPM can reduce chlorophyll fluorescence signals per unit chlorophyll >50% for the SPM range of 0–10 g/m³.

Geostationary Ocean Color Imaging (GOCI) satellite was launched in June 2010, and has provided near real-time ocean color data over the areas around Korea, Japan, and East China for >5 years. Oceanic waters in the GOCI target area have diverse optical properties, ranging from relatively clear waters in the East/Japan Sea and East China Sea to

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extremely turbid waters (maximum SPM > 100 g/m³) in the coastal regions of Korea. In particular, the Yellow Sea and the west coast of the Korea Peninsula are highly turbid due to the tidal current in shallow waters and re-suspension of sediments, whereby the influence of suspended sediments is a dominant factor in characterizing optical properties of oceanic waters in the region. The first validation of GOCI CHL product was performed in 2012 (Moon et al., 2012), where three chlorophyll algorithms (OC2, OC3, and Tassan's algorithm) were tested with GOCI data of GOCI Data Processing System (GDPS) version 1.2, using a limited amount of *in situ* match-up data collected from coastal areas around the Korea Peninsula. The validation showed that the correlation between the algorithm and *in situ* CHL was generally poor ($R^2 \approx 0.25$ and RMSE ≈ 1.0) with the algorithms, exhibiting difficulty in coping with the diverse bio-optical properties around the area.

Whereas most of the field data in the previous evaluation were concentrated on turbid coastal areas around Korea preventing the reliable evaluation for clear waters in this study, we also used field measurements from the Nagoya data set in open ocean waters, to extend the validation range of these algorithms. The objective of this study is to assess the performance of widely used chlorophyll algorithms for waters of diverse optical properties in the GOCI target area, so that GOCI users understand the capability and uncertainty of each algorithm with respect to specific water types. In particular, this evaluation focused on the large variation of SPM concentrations that is characteristic in the data set which would cause large errors in traditional chlorophyll algorithms. The baseline algorithm performance was first evaluated with *in situ* remote sensing reflectance (R_{rs}) measurements that were resampled to GOCI spectral bands, and performance for GOCI data were assessed by using GOCI R_{rs} data processed by GDPS 1.3.2.

2. Data and methodology

2.1. In-situ measurements

The *in situ* measurements used in this study were obtained from several field campaigns conducted during 2010–2014 by two institutes – Korea Ocean Satellite Center (KOSC), Korea Institute of Ocean Sciences and Technology (KIOST) and Nagoya University, Japan. Radiometric data and water constituents such as CHL, absorption by CDOM (a_{CDOM}), and SPM were collected from coastal areas around the Korean Peninsula and East China Sea (KOSC data set), and the Tsushima Strait and East China Sea (Nagoya data set). The sampling locations of the *in situ* data are presented in Fig. 2, and the number of *in situ* measurements and coincident pairs between remote sensing reflectance and chlorophyll measurements are listed in Table 1. SPM data were not available for the Nagoya data, because the campaigns in these clear waters focused on analyzing phytoplankton pigments.

For CHL measurements, 1.5 – 3 L of surface ocean water within 1 m depth was collected in Niskin bottles and filtered through a 47 mm GF/F filter. Filtered pigments were sealed in cryogenic vials and preserved at -80°C , and CHL was computed in the laboratory analysis through the spectrophotometric technique (for the KOSC dataset), fluorometer, and high pressure liquid chromatography (HPLC) (for the Nagoya data

set). According to the result of inter-laboratory comparison experiment in (Moon et al., 2014), uncertainty of the CHL measurements via HPLC, fluorometer and spectrophotometer is approximately 20% when compared to the standard sample. For SPM, 500 mL water samples were filtered through 47 mm nuclepore polycarbonate filters (pore size 0.4 μm). The weight of the filter was measured before filtering and after drying the filter at 60°C for 4 h, and the filtered suspended particles were preserved at -20°C . Filtering for CDOM absorption was conducted using 25 mm syringe filters (pore size 0.45 μm) for the KOSC data set, and 25 mm GF/F filter of 0.7 μm for the Nagoya dataset. The filtration with the 0.45 and 0.7 μm pore sizes could result in higher CDOM concentration in the CDOM filtrate than with the 0.2 μm pore size which is normally used for coastal waters.

Two hyperspectral radiometers, ASD FieldSpec and TriOS-RAMSES, were used for above-water radiometric measurements. The ASD FieldSpec covers the spectral range of 350 – 1050 nm with a spectral resolution of 3 nm. A dual spectrometer unit with two fiber optic cables was used for simultaneous measurement of downward irradiance and upward radiance from ocean water. The TriOS-RAMSES hyperspectral radiometer system consists of one irradiance sensor and two radiance sensors (one for sky radiance and the other for upwelling radiance). The spectral range of the sensors is 350 – 950 nm, with a spectral resolution of 10 nm. For both radiometers, the radiance sensor was pointed toward the sea with a zenith angle of 30° from the nadir direction and an azimuth angle difference of 90° from the sun direction. Sky radiance was measured to the direction of 30° zenith angle from the zenith and with the same azimuth angle as sky radiance (Zibordi et al., 2009). The inter-comparison experiments performed by Toole et al. (2000) and Fougnie et al. (1999) reported that the uncertainty of *in situ* R_{rs} measurements by above-water instruments is 20–40% in turbid coastal waters, with the measurements protocols suggested in Mueller et al. (2003). For the sky glint removal in turbid waters that have non-zero near infrared (NIR) band R_{rs} , an additional sky glint removal technique Ruddick et al. (2006) was implemented in our data processing, where the sky glint signal was separated from the total upwelling radiance knowing that the R_{rs} spectrum in turbid waters is inversely proportional to the water absorption coefficient in the NIR region. An automated independent quality control process was employed to screen out invalid water samples having unrealistic R_{rs} spectrum compared to a generic bio-optical model (Moon et al., 2012).

2.2. Candidate chlorophyll algorithms

Functional forms of 4 chlorophyll algorithms were tested in this study.

2.2.1. OC3 algorithm

The functional form of the OCx algorithms (O'Reilly et al., 1998) which are popular for Case-1 like waters are given as

$$\log_{10}[\text{CHL}] = c_0 + c_1 \log_{10}X + c_2 \log_{10}^2X + c_3 \log_{10}^3X + c_4 \log_{10}^4X \quad (1)$$

where for OC3

$$X_{\text{OC3}} = \max(R_{rs}(443), R_{rs}(490))/R_{rs}(555). \quad (2)$$

2.2.2. Tassan's algorithm

In Tassan's approach (Tassan, 1994), the effects of CDOM and suspended particles on the blue-to-green band ratio ($R_{rs}(443)/R_{rs}(555)$) is compensated by using another band ratio, ($R_{rs}(412)/R_{rs}(490)$), as in

$$\log_{10}[\text{CHL}] = c_0 + c_1 \log_{10}X + c_2 \log_{10}^2X \quad (3)$$

Table 1

Number of *in situ* measurements (R_{rs} , CHL, SPM, $a_{CDOM}(440)$) and coincident data pairs between remote sensing reflectance (R_{rs}) and chlorophyll (CHL) measurements.

	Total	KOSC	Nagoya
<i>In situ</i> measurements	491	415	76
R_{rs}	370	325	45
CHL	477	402	75
SPM	413	413	0
$a_{CDOM}(440)$	467	413	54
Coincident pairs			
<i>In situ</i> R_{rs} - CHL	369	325	44
GOCI R_{rs} - CHL	130	107	23

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