Development and Verification of SGLI/GCOM-C1 Ocean Algorithms

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Abstract

Several ocean algorithms have been developed for the Second-Generation Global Imager (SGLI) on the Global Climate Observation Mission – Climate (GCOM-C) satellite (planned launch, 2016). Here we present verification of the ocean algorithms designed to retrieve the inherent optical properties, phytoplankton functional types and primary productivity. The satellite algorithm verification is defined here to evaluate accuracy of target variables using input parameter(s) obtained from in situ measurements rather than from satellite measurements. The verification of inherent optical properties (IOP) algorithms showed RMSE of 0.12, 0.22, and 0.05 for the absorption coefficient of phytoplankton, detrital materials plus colored dissolved organic materials, and the backscattering coefficient of suspended particles, respectively. Verification of the primary production algorithm indicated that it almost satisfied the values measured in situ by a factor of 2. Other algorithms such as phytoplankton functional types (PFTs) and size classes (PSCs) algorithms, which can be derived from the optical properties of phytoplankton rather than from chlorophyll a concentration, showed RMSE of 1.1–1.6% in a relative abundance of PFTs/PSCs. Towards validation of the ocean algorithms, a radiometer called the Compact-Optical Profiling System (C-OPS), as well as another compact radiometer system specifically designed for turbid waters, were configured for in situ observation. The latter was found to reduce shelf-shading error to within 10%. Furthermore, Ultra-High Performance Liquid Chromatography systems (UHPLC) have been developed for rapid measurements (7 min) of phytoplankton pigments in a water sample (conventional HPLC takes 30 min). This new system significantly increases spatio-temporal coverage of in situ data required for algorithm validation.

Keywords : Ocean, SGLI, GCOM-C, algorithm

1. Introduction

The Global Climate Observation Mission (GCOM) is one of the Earth Observation research mission by Japan Aerospace Exploration Agency (JAXA). Currently a successive launch of three satellites are planned over the coming 13 years (i.e. the 2016–2029 period) in seek of establishment and demonstration of a global, long-term satellite observation system for understanding global climate change and water cycle in the Earth. Especially, a series of satellites designed for global climate change research (GCOM-C) will carry the optical instrument, Second-generation Global Imager (SGLI), which consists of the Visible and Near-infrared Radiometer (VNR) and the Infrared Scanner (IRS). The SGLI is expected to enable satellite observation of 13 ocean variables relevant to global carbon cycles and ecosystem functions, the latter of which can be defined in context of both marine ecology and fisheries.

The satellite products of the first phase of GCOM-C (GCOM-C1 hereafter) are generally classified into 2 groups, (a) Standard Products and (b) Research Products. The Standard Products are defined as satellite products that are (I) required to achieve mission goals and (II) suitable for operational data distribution. On the other hand, Research Products are defined as products in a research phase of its development and application, or not necessarily ready for operational data distribution. These are summarized in Table 1.

In the past years (2009–2012), a significant effort has been
made for development of ocean algorithms (as well as the land and atmosphere algorithms) to enable satellite observation of the above-mentioned ocean variables. Among these variables, the inherent optical properties of seawater constituents, phytoplankton functional types (PFTs), and red tide are products especially unique in the GCOM-C1/SGLI mission. Furthermore, primary production algorithms challenge significant improvement by a new approach. This short paper reports the milestone achievements and current community effort in Japan for the development of the GCOM-C1/SGLI1 ocean algorithms for these variables.

2. Outline of Data Processing For Ocean Algorithms

The ocean algorithms for the GCOM-C1 were developed by principal investigators of the GCOM-C mission, and submitted to JAXA by September 2011. The operation of JAXA is to implement and evaluate these algorithms. Each algorithm code was checked and confirmed working well on computation environment in JAXA. The data processing from Level 1 to Level 3 of ocean standard products using the algorithms were checked by using satellite data simulated based on GLI data obtained from previous JAXA mission12. The ocean standard products are composed of three groups (Fig. 1), namely, O1: Sea Surface Temperature (SST), O2: atmospheric aerosol, the normalized water leaving radiance (nLw) and Photosynthetically Available Radiation (PAR), and O3: chlorophyll-a (chl a), suspended solid and Coloured Dissolved Organic Materials (CDOM). O1 and O2 products are output from Level 1B scene data, which has the spatial resolution of 1 km and 250 m, and O3 products are derived from the normalized water leaving radiance in the O2 group. The algorithm codes use Hierarchical Data Format (HDF5) for input/output. The maximum memory size

<table>
<thead>
<tr>
<th>Standard Products</th>
<th>Research Products</th>
</tr>
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<tbody>
<tr>
<td>Normalized Water Leaving Radiance [µW cm⁻² sr⁻¹]</td>
<td>Inherent Optical Properties of seawater constituents</td>
</tr>
<tr>
<td>Atmospheric correction parameters [-]</td>
<td>(The absorption coefficient of phytoplankton [m⁻¹],</td>
</tr>
<tr>
<td>Photosynthetically Available Radiation (PAR) [mol photons m⁻² day⁻¹]</td>
<td>The absorption coefficient of detritus+CDOM [m⁻¹],</td>
</tr>
<tr>
<td>Chlorophyll-a pigment concentration of phytoplankton [mg m⁻³]</td>
<td>The backscattering coefficient of suspended particles [m⁻³]</td>
</tr>
<tr>
<td>optical absorption coefficient of Coloured</td>
<td>Net primary productivity [mgC m⁻³ day⁻¹]</td>
</tr>
<tr>
<td>dissolved organic materials (CDOM) [m⁻³]</td>
<td>Phytoplankton Functional Types (PFTs)¹ [%]</td>
</tr>
<tr>
<td>Suspended solid concentration [g m⁻³]</td>
<td>Phytoplankton Size Classes (PSCs)² [%]</td>
</tr>
<tr>
<td>Sea Surface Temperature (SST) [°C]</td>
<td>Euphotic depth [m]</td>
</tr>
<tr>
<td>Multi-sensor merged ocean colour [various]</td>
<td>Multi-sensor merged SST [°C]</td>
</tr>
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</table>

*¹ PFTs include diatoms, haptophytes and cyanobacteria
*² PSCs include micro-, nano- and picophytoplankton

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Fig. 1 GCOM-C1 operation flow of ocean algorithms
and processing time required to run each standard algorithm were checked for the processing of simulation data on the JAXA processing system. The fourth research announcement started in 2013, and each principal investigator will re-submit the improved algorithm(s) by the end of September in 2014, to replace the previous version of the algorithms. These algorithms will be validated through practical data production and distribution in the web site, JAXA Satellite Monitoring for Environmental Studies (JASMES).

3. Ocean Inherent Optical Properties (IOPs)

Inherent Optical Properties (IOPs) are the optical proxies (i.e. the absorption coefficient or the backscattering coefficient) of biological/geochemical variables such as phytoplankton, detrital particles and CDOM. Optical remote sensing is a detection and quantification of optical signal of these targets, rather than their concentration per se. In addition, some of these biological/geochemical variables can alter the water-leaving radiance signal even under a same concentration (e.g. phytoplankton, suspended particles), due to optical phenomena. Therefore it is desirable, in remote sensing point of view, to retrieve their optical properties for better understanding of variability of biological/geochemical signal carried in the water-leaving radiance measured. The optical properties can still be converted to biological/biogeochemical units such as the concentration via bio-optical algorithms, when necessary for oceanographers. There is also an oceanographic variable, concentration of which cannot readily be determined analytically (e.g. CDOM). In such a case, its optical property can be served as an index of its concentration.

The GCOM-C IOP algorithm is based on a semi-analytic inversion algorithm that simultaneously derives the absorption coefficients of phytoplankton, detrital materials and the CDOM as well as the backscattering coefficient of suspended particles. The mathematical concept of the GCOM-C/SGLI algorithm was examined and compared to other algorithms available around the world during IOP round robin exercise organized by NASA. The GCOM-C1/SGLI algorithm first solves a system of equations for a relationship between the observed radiance and IOPs, in order to obtain the absorption and backscattering coefficients of the bulk seawater, and then derive these coefficients of individual water constituents. In this type of approach, however, multiple solutions (rather than a real solution that makes sense in physical point of view) are usually found mathematically. Compared to other algorithms, the SGLI/GCOM-C algorithm is unique in that an initial guess of some parameters required for the inversion (that accounts for a combined effect of multiple scattering and solar and satellite geometries) is made to ease the multiple-solution problem. It iteratively updates the parameters during the inversion rather than employs a fixed value of the parameters throughout the inversion (i.e. dynamic parameterization, see Fig.2a) in order to find a physical solution that also satisfies physical solution. The iteration is repeated until the derived absorption and backscattering coefficients converges, and then it is stopped to output the coefficients as a final solution. When they do not converge, it is defined as a failure of the inversion. The algorithm was tested against in situ measurements of the IOPs and the water-leaving radiance using NASA

![Fig. 2](image-url)
NOMAD dataset\(^5\) (Fig. 2b-d). The Root-Mean Square Error (RMSE) in log10 space (variation in chl \(a\) in real world shows a wide dynamic range, and the logarithmic transformation is usually taken in analysis to obtain the normality in data distribution for statistical treatment) ranges from 0.08 to 0.48 (the absorption coefficient of phytoplankton), 0.09 to 0.34 (the absorption coefficient of detritus + CDOM), 0.04 to 0.05 (the backscattering coefficient of suspended particles), depending on wavelengths in consideration (412 to 555 nm here). Separation of the absorption coefficient between detritus and CDOM has been attempted empirically, which is however found to require more sensitivity tests.

4. Phytoplankton Functional Type (PFT)/Phytoplankton Size Class (PSC)

Phytoplankton functional types are classification of phytoplankton groups that contribute to a specific function(s) in biogeochemical cycles or ecosystem dynamics. For example, diatom fixes silicate, having a specific role, or function, in silicate cycles. Similarly, some of haptophytes (such as coccolithophore) fix calcium, contributing to calcite flux. Both functions are even related to carbon cycles; diatom is said to largely contribute to the biological pump whereas some haptophytes to the carbonate counter pump. On the other hand, a relatively large phytoplankton, or microplankton such as diatom, are grazed by relatively large zooplankton due to its grazing preference, characterizing a path of energy transfer in complex food web. Similarly a relatively small phytoplankton is grazed by relatively small zooplankton and tends to contribute to a formation of a relatively long food chain in the ecosystem. Thus, size-based classification, or phytoplankton size class (PSCs), is also a meaningful classification in transfer of biomass (or carbon) from primary producers to predators in higher trophic levels, hence in ecological functioning. In addition, some small cell-sized phytoplankton groups that contribute to a specific function(s) in biodiversity, are grazed by relatively large zooplankton due to its grazing preference, characterizing a path of energy transfer in complex food web.

For a field sample of phytoplankton, an existence of specific PFT and PSC can operationally be determined by using High-Performance Liquid Chromatography (HPLC) as well as by microscopy and other methodology such as flow-cytometry. The basic principle of HPLC determination is that those PFTs and PSC contains carotenoid pigments that are said to be specific to each PFT or PSC (bio-marker pigments). Although such determination of PFTs and PSC has an anomaly due to co-existence of the pigments over different PFTs and PSCs, it is frequently used as a useful approximation. It was found from a global dataset of HPLC pigments that relative abundances of some PFTs (i.e. % of diatoms, haptophytes, chlorophytes, cyanobacteria, prochlorococcus, other pico-eukaryotes) and PSCs (% of micro-, nano- and picoplankton) are closely linked to chlorophyll \(a\) (chl \(a\) [mg m\(^{-3}\)]) of the total phytoplankton population\(^6\). The relationship can be quantified by the least square method using in situ data so that the relative abundance is estimated from chl \(a\) (Fig. 3). Since chl \(a\) can be derived from the satellite measurement of the normalized water leaving radiance (GCOM-C standard product), PFTs/PSCs can also be derived from the satellite eventually. In that way, algorithms for estimating PFTs/PSCs were developed and tuned with an even larger dataset (13,503 data points) than the previous dataset\(^6\) (5,870 data points). Recently, the algorithms were further revised in such a way that a relationship between chl \(a\) and the absorption coefficient of phytoplankton at 443 nm (aph \(443\) [m\(^{-1}\)]), which is determined from the in situ observation as \(\log_{10}(\text{chl } a) = 1.3977 \log_{10}(\text{aph}(443)) + 1.7927 \) \((r^2 = 0.82, p < 0.01)\), is used so that the PFTs/PSCs can be estimated from a\(_{ph}\) \(443\) derived from the IOP algorithm described in the previous section of this article. A verification of the algorithms using in situ measurements of chl \(a\) as input shows that RMSEs are 11.6, 11.1 and 10.1 [%] for micro-, nano- and picoplankton, and 11.1, 5.1, 8.2 [%] for diatom, haptophytes and cyanobacteria, respectively (Fig. 3), under the assumption that the SGLI-derived chl \(a\) has no error.

5. Ocean Primary Production Algorithm

Estimation of column integrated daily net primary production \((PP_{\text{col}})\), which is carbon assimilation by photosynthesis of phytoplankton in the ocean, is essential for the mission objective of GCOM-C/SGLI (i.e. carbon cycles theme). Most of the primary production algorithms developed in the past used chl \(a\) concentration. Such approaches have been revealing a significant insight of photosynthetic activities in the oceans\(^7\).\(^8\) On the other hand, estimation of chl \(a\) concentration from the water-leaving radiance measured by satellite has uncertainty due to (1) the effects of pigment packaging that can lead to underestimation and (2) the interference of colored dissolved organic matter (CDOM) that can lead to overestimation. Another uncertainty is derivation of photosynthetic rate of phytoplankton used in the primary production algorithm. Although the vertically generalized productivity model (VGPM)\(^9\) which is one of the frequently used algorithms expresses the maximal photosynthetic rate \((P^0_{\text{opt}})\) as a function of sea surface temperature (SST), the SST derived \(P^0_{\text{opt}}\) had large errors, particularly underestimation more than two folds in the polar waters\(^10\). Furthermore, discussion on the effect of global warming to primary productivity in the ocean
using satellite data is facilitated, if the photosynthetic rate is treated independent of the SST.

To solve these issues, we have developed phytoplankton absorption-based production model and improved it for SGLI/GCOM-C1: $P_{\text{opt}}^b \times \text{chl} \ a$ in the VGPM, which means productivity at a depth with the maximal photosynthetic rate within a water column, was expressed by photosynthetic available radiation (PAR) absorbed in phytoplankton. In situ primary production and optical data to develop the algorithm were measured in the North Pacific, Japan Sea, East China Sea, Southern Ocean, Chukchi Sea (Arctic Ocean), and Bering Sea. Additional datasets of the Bermuda Atlantic Time-series Study (BATS), Hawaii Ocean Time-series (HOT) and The California Cooperative Oceanic Fisheries Investigations (CalCOFI) were also obtained for the development and validation of the algorithm. Accuracy in the estimation of $P_{\text{opt}}^b \times \text{chl} \ a$ and $P_{\text{eu}}^{\text{opt}}$ were fairly well and estimated values of $P_{\text{opt}}^b \times \text{chl} \ a$ and $P_{\text{eu}}^{\text{opt}}$ using the new algorithm almost satisfied a factor of 2 of the values measured in situ (log-transformed RMSE = 0.34 and 0.33, respectively) even though the validation dataset includes data from the polar regions.

6. Redtide Detection

The red tide algorithm is based on Siswanto et al. (2013) developed based for *Kaielina mikimotoi* red tide in the western part of Seto Island Sea in Japan with MODIS data. This algorithm contains following steps; (1) If the normalized water leaving radiance at the wavelength of 547 nm ($nLw547$) is not the peak, it is clear water, (2) If ($nLw443-nLw412)/31 > (nLw488-nLw443)/45$ and ($nLw488-nLw443)/45 > (nLw547-nLw488)/69$, then it is total suspended matter or colored dissolved organic matter dominated waters, (3) If the normalized water leaving radiance at the wavelength of 547 nm ($nLw547$) is not the peak, it is clear water, (4) If $nLw547 > 0.8$, it is diatom red tide, (5) If ($nLw547-nLw488)/135 > 0.0003 \ (\text{ln(CHL)}^2 + 0.0024 \ \text{ln(CHL)}) - 0.0005$) where CHL represents chl a, it is mixed water of red tide and non-phytoplankton material, (4) If $nLw547 > 0.8$, it is diatom red tide, (5) If those conditions are all negative it is dinoflagellate bloom. Fig. 4 shows an example of optically-detected red tide due to diatom. Since wavelengths of SGLI are different from MODIS, slight modification may be still necessary. The detection can be verified with eye observation data from airplane and ship by fisheries agency and local fisheries institutes.

7. Sea Surface Temperature (SST)

The finer spatial resolution is a distinct feature of the SST derived from GCOM-C1/SGLI (SGLI-SST). The SST imagery with a 250~500 m spatial resolution will be available in the ocean near the continents by the SGLI-SST algorithm.

The SGLI-SST will be produced through the cloud removing and atmospheric correction processes. The algorithm for these processes has been developed on the basis of the existent, widely-used SST retrieval algorithm. The main algorithm for removing cloud, which is required to define cloud-free pixel within a satellite scene, is developed via several “threshold tests”. The atmospheric correction will be performed by the calculation of the Non-Linear SST (NLSST) or Multi-Channel SST (MCSST) equations. The parameters (equation coefficients, threshold values, etc.) used in the SGLI/GCOM-C SST algorithm will be adjusted after the GCOM-C launch to achieve the accuracy of less than 0.8℃ in the RMSE compared to the in-situ observation.

8. Towards Verification and Validation of SGLI/GCOM-C Ocean Algorithms

The acquisition and standardization of in situ optical measurements must be essential for the calibration and validation exercises of SGLI. Recently, Dr. Stanford B. Hooker (NASA), a Co-Investigator of the JAXA project “Highly frequent and accurate observations of marine phytoplankton pigments and light regimes using state-of-the-art technologies (Principal Investigator: Dr. Koji Suzuki, Hokkaido University)”, has developed a state-of-the-art instrument for acquiring observations of the AOPs (apparent optical properties) of seawater data from 320~875 nm, which is the Compact-Optical Profiling System (C-OPS) based on new microradiometers. These state-of-the-art technologies will be used for high-frequent and high-quality measurements satisfying the accuracy requirements for the verification of GCOM-C1/SGLI ocean algorithms.

To measure the water-leaving radiance in highly turbid coastal waters, a radiative observation buoy system is being developed. Radiometer’s diameter has to be small because self-shading error by the radiometer body becomes large in turbid waters especially in absorptive waters. Results of Tokyo bay ship observation indicate that the diameter of 10 mm $\Phi$ could reduce the self-shading error smaller than 10% in infrared wavelength region, in which water absorbs strongly. To avoid reflection and shading by a boat and foams generated by the boat, a buoy system is adopted. Two radiometers (ASD Inc., HandHeld2) are used for the water-leaving radiance and the downward irradiance just above the surface. Each radiometer connects with a micro personal computer, respectively, and is controlled on-board via wireless local area network.

Because ocean color remote sensing requires particularly high calibration accuracy, a number of high quality in situ observation data for products (e.g. PFTs) are also required. Pigment analysis using High-Performance Liquid Chromatography (HPLC) has
become a routine measurement for estimating the biomass and composition of phytoplankton since 1990’s. Such HPLC pigment data can be used to estimate the distribution of PFTs in the world ocean from space. However, the run-time of most of the HPLC methods is generally ca. 30 min or more, which is still time consuming to obtain a datum and also provides an unnecessary constraint on accuracy. Recently, we have developed a novel method for phytoplankton pigment analysis using Ultra-High Performance Liquid Chromatography (UHPLC), which enables us to complete the separations of algal chlorophylls and carotenoids within 7 min with similar or higher resolutions as conventional HPLC methods (Suzuki and Kamimura, in prep.).

9. Summary and Conclusion

Current state of several SGLI/GCOM-C ocean algorithms that have been developed during 2009–2012 is reported. The algorithms are expected to meet a target accuracy defined for each variable, and the verification and validation may take two step processes: the first to determine accuracy of variables derived from inputs obtained from in situ measurements (verification), the second from inputs actually obtained from the
satellite observation (validation). While the validation can only be done after a launch of GCOM-C1/SGLI which is currently planned in 2016, verification of IOPs algorithms showed RMSE of 0.12, 0.22 and 0.05 for the absorption coefficient of phytoplankton, the absorption coefficient of CDOM plus detritus and the backscattering coefficient of suspended particles, at the wavelength of 443 nm, respectively (Fig. 2), provided that input to the algorithm is error-free. Similarly, verification of primary production algorithm indicated the error factor of about 2. Other algorithms such as PFTs/PSCs were further revised so that they could be derived from the optical properties of phytoplankton rather than chl a concentration. The revised algorithm showed RMSE of 8.2–11.6% in the relative abundance, depending on phytoplankton type considered. In addition, the red tide and SST algorithms have also been developed and ready for verification where collection of a significant number of in situ measurements is essential. Towards the verification, C-OPS and a compact radiometer system specifically designed for turbid waters, would be used, the latter of which reduced the shelf-shading error within 10%. Furthermore, UHPLC systems have also been developed. Thus, we conclude that GCOM-C1/SGLI ocean algorithms have been successfully developed in due course, providing an opportunity of operationalization and/or release of the GCOM-C1/SGLI ocean products.

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References

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