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GOCI Yonsei Aerosol Retrieval (YAER) algorithm and validation during DRAGON-NE Asia 2012 campaign

M. Choi¹, J. Kim¹, J. Lee^{2,3}, M. Kim¹, Y. Je Park⁴, U. Jeong¹, W. Kim¹, B. Holben³, T. F. Eck^{3,5}, J. H. Lim⁶, and C. K. Song⁶

¹Department of Atmospheric Sciences, Yonsei University, Seoul, South Korea ²Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA

³NASA Goddard Space Flight Center, Greenbelt, MD, USA

⁴Korea Ocean Satellite Center, Korea Institute of Ocean Science and Technology, Ansan, South Korea

⁵Universities Space Research Association, Columbia, MD, USA

⁶National Institute of Environmental Research (NIER), Inchon, South Korea

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Correspondence to: J. Kim (jkim2@yonsei.ac.kr)

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Abstract

The Geostationary Ocean Color Imager (GOCI) onboard the Communication, Ocean, and Meteorology Satellites (COMS) is the first multi-channel ocean color imager in geostationary orbit. Hourly GOCI top-of-atmosphere radiance has been available for

- the retrieval of aerosol optical properties over East Asia since March 2011. This study presents improvements to the GOCI Yonsei Aerosol Retrieval (YAER) algorithm over ocean and land together with validation results during the DRAGON-NE Asia 2012 campaign. Optical properties of aerosol are retrieved from the GOCI YAER algorithm including aerosol optical depth (AOD) at 550 nm, fine-mode fraction (FMF) at 550 nm, singula protection of the GOCI and the together with the toge
- single scattering albedo (SSA) at 440 nm, Angstrom exponent (AE) between 440 and 860 nm, and aerosol type from selected aerosol models in calculating AOD. Assumed aerosol models are compiled from global Aerosol Robotic Networks (AERONET) inversion data, and categorized according to AOD, FMF, and SSA. Nonsphericity is considered, and unified aerosol models are used over land and ocean. Different assumptions
- for surface reflectance are applied over ocean and land. Surface reflectance over the ocean varies with geometry and wind speed, while surface reflectance over land is obtained from the 1–3% darkest pixels in a 6km × 6km area during 30 days. In the East China Sea and Yellow Sea, significant area is covered persistently by turbid waters, for which the land algorithm is used for aerosol retrieval. To detect turbid water pix-
- els, TOA reflectance difference at 660 nm is used. GOCI YAER products are validated using other aerosol products from AERONET and the MODIS Collection 6 aerosol data from "Dark Target (DT)" and "Deep Blue (DB)" algorithms during the DRAGON-NE Asia 2012 campaign from March to May 2012. Comparison of AOD from GOCI and AERONET gives a Pearson correlation coefficient of 0.885 and a linear regression
 equation with GOCI AOD = 1.086× AERONET AOD 0.041. GOCI and MODIS AODs
- are more highly correlated over ocean than land. Over land, especially, GOCI AOD shows better agreement with MODIS DB than MODIS DT because of the choice of



surface reflectance assumptions. Other GOCI YAER products show lower correlation with AERONET than AOD, but are still qualitatively useful.

1 Introduction

Aerosols have an important role in the Earth's climate system, influencing climate directly through scattering and absorbing radiation, and indirectly by acting as cloud condensation nuclei (IPCC, 2013). Both ground-based and satellite measurements show an increasing trend of aerosol optical depth (AOD) over East Asia (IPCC, 2013; Hsu et al., 2012; Yoon et al., 2014). In particular, the increasing AOD trend over Asia is strongest during the dry seasons from December to May. Furthermore, aerosol types
over East Asia are more complex than over other regions (J. Kim et al., 2007; Lee et al., 2010a). To quantify its impact on climate, accurate observation of aerosol over East Asia is required.

Aerosol can be detected by remote sensing from ground-based and satellite measurement. AERONET (Aerosol Robotic Networks) is the representative global network

- of ground-based sun photometer observations, with an absolute observation uncertainty for a single AOD measurement of 0.01 (Holben et al., 1998; Eck et al., 1999). Satellite observations from low earth orbit (LEO) and geostationary earth orbit (GEO) allow detection of aerosol over a wider area. Many aerosol retrieval algorithms have been developed and improved using multi-channel sensors in LEO such as the Moder-
- ate Resolution Imaging Spectroradiometer (MODIS), Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), Medium Resolution Imaging Spectrometer (MERIS), Ozone Monitoring Instrument (OMI), and Visible Infrared Imaging Radiometer Suite (VIIRS) (Higurashi and Nakajima, 1999; J. Kim et al., 2007; Hsu et al., 2006, 2013; Jackson et al., 2013; Kaufman et al., 1997a; Levy et al., 2007, 2013; Remer et al., 2005; Sayer et al., 2012; Tarrea et al., 1908, 2007, 2012; was Hauring and Hauring at al., 2014). Multi-
- et al., 2012; Torres et al., 1998, 2007, 2012; von Hoyningen-Huene et al., 2011). Multichannel observations from LEO give global coverage at high accuracy but with the disadvantage of low temporal resolution. The magnitude of the uncertainty of retrieved



AOD from MODIS is reported as 0.03 + 5% over ocean and 0.05 + 15% over land (Remer et al., 2008; Levy et al., 2010). Aerosol retrieval algorithms have been developed using data from GEO meteorological satellite series such as the Geostationary Operational Environmental Satellite (GOES), Geostationary Meteorological Satellite (GMS),

- and Multifunction Transport Satellite (MTSAT) (Kim et al., 2008; Knapp et al., 2002; Wang et al., 2003; Yoon et al., 2007; Urm and Sohn, 2005). These satellites provided high temporal resolution observation with several observations per day, but had disadvantages with the coarser spatial resolution due to the higher orbit altitude than LEO and lower accuracy due to a wider spectral response function and single visible chan-
- nel. The magnitude of the uncertainty of retrieved AOD using GOES has been reported as 0.13 (Knapp et al., 2005). Despite the extensive observations to date, the confidence level of satellite-based globally averaged AOD trends is still "low" (IPCC, 2013).

The Geostationary Ocean Color Imager (GOCI) onboard the Communication, Ocean, and Meteorological Satellites (COMS) is the first multi-channel visible- and

- ¹⁵ near infrared–wavelength sensor in GEO (Ahn et al., 2012; Choi et al., 2012; Kang et al., 2006). The center wavelengths of the eight channels are 412, 443, 490, 555, 660, 680, 745 and 865 nm, similar to other ocean color sensors such as the Coastal Zone Color Scanner (CZCS), SeaWiFS, MERIS, and MODIS, but GOCI has higher spatial resolution of 500 m × 500 m from GEO. It observes East Asia hourly during the
- ²⁰ daytime, a total of eight times per day. A prototype of the GOCI Yonsei AErosol Retrieval (YAER) algorithm was developed (Lee et al., 2010b) and is improved in this study to include dynamic and non-spherical aerosol models as in (Lee et al., 2012). Aerosol optical properties (AOPs) such as aerosol optical depth, size information, and absorptivity can be retrieved hourly from the GOCI YAER algorithm with spatial reso-
- ²⁵ Iution of 6 km × 6 km. The availability of hourly AOPs, not only AOD, for East Asia from GOCI is expected to help describe the diurnal changes of aerosol plume characteristics with high accuracy when long-range transport occurs. Retrieved AOPs from GOCI every hour can be used to improve the accuracy of air quality modeling (Park et al., 2014; Saide et al., 2014).



The Distributed Regional Aerosol Gridded Observation Networks – North East Asia 2012 campaign (DRAGON-NE Asia 2012 campaign) took place in Korea and Japan from 1 March to 31 May to observe aerosol and its variability using a dense mesoscale network of ground-based sun photometers. The campaign provides a dataset for validation of aerosol retrieval algorithms.

This study introduces the improvement of the GOCI YAER algorithm and validation results during the DRAGON-NE Asia 2012 campaign. Because MODIS data were used for the prototype algorithm before the launch of GOCI, this study is the first to use real GOCI data. The GOCI YAER products are validated with AERONET data from 38 sites during the DRAGON-NE Asia 2012 campaign. Inter-comparison of AOPs between GOCI and MODIS Collection 6 (C6) is also performed for the same period. This study uses data from the campaign to thoroughly validate the improved GOCI YAER

algorithm. In Sect. 2, the improvements of the GOCI YAER algorithm are summarized. In Sect. 3, some aerosol event cases are analyzed using products from the improved algorithm. In Sect. 4, retrieved GOCI YAER products are validated with AERONET and MODIS. In Sect. 5, an error analysis of GOCI YAER AOD against AERONET AOD is presented. Section 6 provides a summary and conclusions.

2 Improvements of the GOCI YAER algorithm

²⁰ Figure 1 shows the flowchart for the GOCI YAER algorithm. The improvements will be described according to the sequence shown in the flowchart.

Since the distribution of GOCI Level 1B (L1B) radiance data in March 2011, the GOCI YAER algorithm has been updated. The flowchart describes the contents of the overall algorithm step by step. Starting with the GOCI L1B radiance, the top-of-atmosphere reflectance (ρ_{TOA}) is calculated,

$$\rho_{\text{TOA}}(\lambda) = \frac{\pi \cdot L(\lambda)}{\mu_0 \cdot E_0(\lambda)},$$

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(1)

where λ is the wavelength of each GOCI channel (412, 443, 490, 555, 660, 680, 745, 865 nm), $L(\lambda)$ is observed radiance from GOCI, μ_0 is the cosine of the solar zenith angle (θ_0), and E_0 is the extraterrestrial solar flux.

2.1 Cloud masking and quality assurance

- ⁵ The three cloud masking tests are the absolute reflectance test, uniformity test, and dust callback test, and consist of
 - 1. $\rho_{\rm TOA}$ (490 nm) > 0.40 \rightarrow cloud over land or ocean
 - 2. Standard deviation of 3×3 pixels ρ_{TOA} (412 nm) > 0.0025 \rightarrow cloud over land Standard deviation of 3×3 pixels ρ_{TOA} (865 nm) > 0.0025 \rightarrow cloud over ocean
- 3. ρ_{TOA} (412 nm)/ ρ_{TOA} (660 nm) > 0.75 → Dust over ocean (not masked)

Note that ocean pixels with glint angle less than 40° are also masked out. After cloud masking, 12×12 pixel area, with each pixel of resolution $500 \text{ m} \times 500 \text{ m}$ are composited to give aerosol retrieval resolution of $6 \text{ km} \times 6 \text{ km}$. In this step, only pixels with values of ρ_{TOA} (490 nm) within the central 20–60% of the range for the 144 pixels are averaged for aerosol retrieval resolution. The darkest 20% and the brightest 40% of pixels are discarded to remove remaining cloud, cloud shadow, and surface contamination and retain the dark pixels that are suitable for aerosol retrieval (Remer et al., 2005; Levy et al., 2007). The number of pixels used for aerosol retrieval resolution and the retrieved AOD at 550 nm determine the quality assurance (QA) measure for each pixel, as listed

²⁰ in Table 1. The GOCI YAER algorithm allows a retrieved AOD range from -0.1 to 5.0, but QA is only greater than 1 when the value is in the range between -0.05 and 3.6.

2.2 Surface reflectance over land and ocean

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The lack of a 2.1 μ m channel in GOCI limits the capability to estimate surface reflectance in the visible from the 2.1 μ m TOA reflectance as in the MODIS DT algorithm (Levy et al., 2007; Kaufman et al., 1997b). Instead, the GOCI YAER algorithm



uses the minimum reflectivity technique to determine the surface reflectance (ρ_{SFC}) over land and turbid water (Herman and Celarier, 1997; Hsu et al., 2004; Koelemeijer et al., 2003). First, each scene's TOA reflectance is corrected to the Rayleigh-corrected reflectance (RCR) (Hsu et al., 2013). It is assumed that in a 30 day period, changes

- in surface reflectance are insignificant and there is at least one clear day (Lee et al., 2010b). To increase the number of samples to find clear pixels, it is also assumed that surface reflectance is homogeneous over in 12 × 12 pixels. Thus, the spatial resolution of surface reflectance is the same as the aerosol retrieval resolution of 6 km × 6 km. To allow for changes of surface reflectance with sun-satellite geometry, RCRs at a given
- ¹⁰ hour during the day are composited for each month. The maximum number of samples available to determine surface reflectance at a pixel is 144 pixels × 30 days, a total of 4320 samples. Samples are sorted in ascending order according to RCR at 412 nm and selected from the darkest 1–3%. At 412 nm, the variability of surface reflectance is lower and atmospheric signals such as Rayleigh scattering or aerosol reflectance
- are higher than at longer wavelengths. Thus, the RCR at 412 nm is used to find clear pixels during the 30 day window. Threshold of 1 % for lower bound is to avoid cloud shadow. The threshold of 3 % for the upper bound comes from the ratio of the first minimum during 30 days. The RCRs of selected pixels are averaged for each channel, giving a surface reflectance corresponding to the middle of each month (day 15).
 Finally, linear interpolation according to retrieval date is applied.

Figure 2 shows examples of surface reflectance at 443 and 660 nm; the difference between ocean and land is less at 443 nm, but noticeable at 660 nm. Turbid water areas with high reflectance at 660 nm are found near the coast of China in the Bohai Sea and in the northern East China Sea; this clearly shows a semi-permanent presence of turbid

²⁵ water pixels during the 30 days. From March to May, surface reflectances decrease over land because of melting snow and increasing vegetation. The land algorithm is applied to pixels where surface reflectances at 443, 490, 555, and 660 nm are less than 0.3.

On the other hand, it is assumed that ocean surface reflectance varies with geometry and wind speed (Cox and Munk, 1954); the wind speed at 10 m a.s.l. is taken account



of in the Look-up Table (LUT) calculation using a radiative transfer model. The nodal points of wind speed in the LUT calculation are 1, 3, 5, 7, 9, and 20 ms⁻¹. Using ECMWF wind speed data with 0.25° × 0.25° spatial resolution at every 6 h, the LUT is interpolated to each pixel's wind speed to calculate AOD over the ocean. Note that ocean retrieval is performed only when the sun glint angle is greater than 40° (Remer et al., 2005).

2.3 Turbid water detection

Aerosol retrieval over turbid water is a difficult problem for the GOCI YAER algorithm. Half of ocean in the GOCI field-of-regard (FOR) is the Yellow Sea with very high yearround turbidity. If the wind-speed dependent ocean surface reflectance is applied over turbid water, the surface reflectance can be underestimated, and thus AOD can be overestimated. The previous GOCI YAER algorithm (Lee et al., 2010b) used the surface reflectance ratio (SRR) for turbid water detection, which is the ratio of surface reflectance at 640 and 860 nm. If turbid water pixels are detected, the surface reflectance

from the second minimum RCR during the previous 30 day period is used for AOD retrieval. Persistent-turbid areas during the previous 30 days can be detected in this way, but it is hard to detect rapid temporal variations of turbidity. In this study, real-time turbid water detection is applied.

According to Li et al. (2003), ρ_{TOA} at 550, 660, and 865 nm showed higher val-²⁰ ues over turbid water than over clear water. They used the difference between ρ_{TOA} at 550 nm and the value interpolated to 550 nm from ρ_{TOA} at 470, 1240, 1640, and 2130 nm using a linear fit on a log-log scale. In this study, because GOCI does not have IR channels, $\Delta \rho_{660}$ is defined as the difference in reflectance at 660 nm between the observed ρ_{TOA} at 660 nm and linearly interpolated between ρ_{TOA} at 412 and 865– ²⁵ 660 nm. Increased ρ_{TOA} due to turbid water is stronger at 660 nm than at 412 and

865 nm so that $\Delta \rho_{660}$ shows a higher value over turbid water than over clear water.

To determine the threshold of $\Delta \rho_{660}$ for distinguishing turbid and clear water over the ocean, hourly data for the 1st and 15th day of each month for 3 years from March 2011



to February 2014 are analyzed. The analysis is implemented over two distinct areas: the Yellow Sea (115–126° E, 30–40° N) and an area of clear water (130–140° E, 25– 30° N), as in Lee et al. (2010b). A strict threshold for defining pixels as clear water is necessary to prevent misdetection of less turbid water as aerosol. Figure 3 shows the cumulative normal distribution of $\Delta \rho_{660}$, where ratios below –0.05 are 99.0 and 67.4 % for clear water and Yellow Sea pixels, respectively. Finally, pixels with $\Delta \rho_{660}$ below –0.05 are not considered as turbid water so that the ocean algorithm is applied. On the contrary, pixels where $\Delta \rho_{660}$ is above –0.05 are considered as turbid water so that the land algorithm is applied. Note that the surface reflectance of turbid water pixels is adjusted to the minimum turbidity during the 30 days so that surface reflectance can be underestimated when severely turbid water occurs within the 30 days. Values of the ratio below 0.02 comprise 99.6 % of the Yellow Sea pixels. Therefore, pixels where $\Delta \rho_{660}$ is above 0.02 are considered as severely turbid water, and excluded from the retrieval procedure.

¹⁵ To confirm whether $\Delta \rho_{660}$ effectively detects turbid water, two turbid water cases are selected in Fig. 4. One is a clean atmosphere case (26 April 2012), and another case involves dust over the northern part of the Yellow Sea (27 April 2012). To compare the sensitivity between pixels over turbid water and those with absorbing aerosol, the Deep blue Aerosol Index (DAI) is calculated using GOCI TOA reflectance at 412 and 443 nm (Hsu et al., 2004, 2006; Ciren and Kondragunta, 2014). Note that DAI and $\Delta \rho_{660}$ are plotted over no-cloud pixels. Only positive DAI pixels are presented to check for the existence of absorbing aerosol such as dust. The true color image for the clean case shows severe turbidity in the ocean along the coast lines of eastern China and the western Korean peninsula. The next day, there is heavy Asian dust over northern Yellow

²⁵ Sea, and turbid water is in the same position as the day before. $\Delta \rho_{660}$ shows a higher signal over turbid water (~ 0.02) than Asian dust (~ -0.01), while DAI shows a higher signal over Asian dust (~ 4.8) than turbid water (~ 1.6). Although heavy aerosol plumes can have $\Delta \rho_{660}$ above -0.05 because of the strict threshold for clear ocean, this does



not cause problems because the land algorithm is applied, and the area is not masked out.

An additional role of $\Delta \rho_{660}$ is to detect the remaining cloud-contaminated pixels after cloud masking. There are inhomogeneous cloud pixels over the right half of the scene

⁵ in Fig. 5. Most cloud pixels are effectively screened by the cloud-masking steps, but thin cloud pixels remain and show high $\Delta \rho_{660}$ above 0.05 (red color). This is a similar to the "Visible Reflectance Anomaly" of the VIIRS aerosol algorithm (Jackson et al., 2013). Because pixels with $\Delta \rho_{660}$ above 0.02 are considered as severe turbid water and screened, the remaining cloud pixels are also masked using this test.

10 2.4 Aerosol models

Assumed aerosol models play an important role in aerosol retrieval. To reflect global climatological properties, AERONET inversion data (Dubovik and King, 2000) are used for aerosol models. A classification method for AERONET inversion data using Fine-mode fraction (FMF) at 550 nm and Single scattering albedo (SSA) at 440 nm is adopted (J. Kim et al., 2007; Lee et al., 2010a, 2012), but there are some differences for the GOCI YAER algorithm.

Composited AERONET data are only used for the period up to February 2011, which is before GOCI's first observation, to avoid overlap between the period of climatology and retrieval. Global sites are selected where the number of individual AERONET re-

- trieval data is greater than 10 times giving a total of 747 sites. From those sites, the number of data that have all the AOPs in all channels is 66 712. They are classified into 26 aerosol models according to FMF at 550 nm and SSA at 440 nm (Table 2). Note that AOPs change as AOD increases because of the hygroscopic growth effect or aggregation (Reid et al., 1998; Eck et al., 2003). Therefore, each aerosol model is separated again into low moderate, and high AOD groups corresponding to the AOD ranges of
- again into low, moderate, and high AOD groups corresponding to the AOD ranges of 0.0–0.5, 0.5–0.8, and 0.8–3.6 respectively. Finally, the AOPs of each aerosol model are averaged and used as input for LUT calculation.



The AERONET inversion algorithm considers aerosol nonsphericity using a mixture of polydisperse, randomly-oriented homogeneous spheroids (Mishchenko et al., 1997; Dubovik et al., 2006). Phase functions of the inversion data applying nonsphericity are adopted directly into aerosol models.

5 2.5 LUT calculation and inversion procedure

Table 3 shows the LUT dimensions for calculation using libRadtran, a radiative transfer model (RTM) (Mayer and Kylling, 2005). The input options of this RTM to calculate ρ_{TOA} for different aerosol conditions include the spectral phase function and SSA so that the values of each model from AERONET inversion data can be used directly. Note that the input spectral AODs for LUT calculation are normalized to 550 nm using the climatology of each model's Angstrom exponent (AE) between 440 and 870 nm.

- In the inversion step, AOD is calculated from the comparison between observed and calculated reflectance according to the assumed aerosol model. The retrieved AOD at each channel is converted to the value at 550 nm using the AE of each aerosol model.
- If the observed aerosol properties are exactly the same as those of one of the aerosol 15 models and there are no other errors, the AODs from the GOCI channels converted to 550 nm should have the same values. Only four channels (443, 555, 660, and 680 nm) are used over land when surface reflectances in these channels are less than 0.3. Otherwise, all eight channels are used over ocean because the ocean surface is darker
- than the land. To find optimized aerosol models, the standard deviation (stddev) of the 20 converted AODs at 550 nm from spectral values is calculated for each model. The three models with lowest stddev are then selected for the final AOD, FMF, SSA, and AE. Note that the final products are the stddev-weighted averages from the selected aerosol models. The GOCI YAER algorithm classifies a total of six aerosol types using
- the retrieved final FMF and SSA (Table 4). 25



3 Case studies of GOCI YAER products during the DRAGON-NE Asia 2012 campaign

During the DRAGON-NE Asia 2012 campaign, there are several cases of high aerosol loading. Two representative cases are presented here; the heavy pollution haze case

- on 6 May, and the dust case on 27 April. On 6 May 2012, a white haze plume was detected over northeastern China and the Yellow Sea from the true color image as shown in Fig. 6a. GOCI YAER AOD, FMF, AE, SSA, and aerosol type are plotted in Fig. 6b–f. Note that all pixels regardless of QA values are included in the AOD plot, while only pixels with positive AOD are shown for other products. High AOD ranging from 1.2
- to 2.0 is found at the center of the haze plume, with retrieved FMF and AE of about 0.8 and 1.2, respectively. This means that the haze aerosol is a fine-mode dominated aerosol. The SSAs at those pixels are in the range 0.955–0.975, corresponding to non-absorbing aerosol. The detected aerosol type of the haze is therefore "Non-absorbing fine" aerosol, shown as blue in Fig. 6f.
- ¹⁵ The distribution of FMF, AE, and SSA over land is more inhomogeneous than over ocean, particularly, for pixels with low AOD, which may be due to the spatial variation of land surface reflectance and its uncertainty. Nevertheless, it is encouraging that there is less discrepancy between ocean and land, with products showing a continuous distribution across the coastline for both high (~ 1.0) and low AOD (~ 0.3) pixels.
- Another case is a severe dust case on 27 April 2012 as shown Fig. 7. Heavy yellow dust plumes are evident in the GOCI true color image. These developed in the Gobi Desert the previous day were transported to the northern part of the Korean peninsula across the Yellow Sea. The dust plume has a horizontal scale about 1000 km from inland China to the Yellow Sea, with AOD at its center above 2.0 (red color), and about
- 1.2 at the edge of the plume. The dust plume over the northern part of the Korean peninsula is mixed with cloud, but the plume in the southern part shows low AOD of about 0.3, with FMF and AE of 0.3 and 0.5, respectively, corresponding to coarse-mode dominated aerosol. SSA ranges from 0.90 to 0.92, corresponding to moderately



absorbing aerosol. From the FMF and SSA, the aerosol plume is classified as "Dust", shown as yellow in Fig. 7f.

4 Evaluation of GOCI YAER products during the DRAGON-NE Asia 2012 campaign

Generally, in spring, various aerosol events such as Yellow dust or anthropogenic aerosol occur frequently and intensively over East Asia (Redemann et al., 2003; Schmid et al., 2003; S. W. Kim et al., 2007). Although the campaign was limited to the spring, it has the advantage of abundant ground-based observations over Korea and Japan. During the campaign, a total of 40 sun photometers were deployed at ur ban sites and coastline sites. Over the urban areas of Seoul and Osaka, in particular, distances between AERONET sites are about 10 km, which makes validation of satel-

lite data possible at high spatial resolution.

MODIS onboard Aqua and Terra is a representative sensor for observing global aerosol, and its aerosol retrieval algorithms have been developed and improved con-

- tinuously (Remer et al., 2005; Levy et al., 2007; Hsu et al., 2006). Recently, an updated new version was released as C6 (Levy et al., 2013; Hsu et al., 2013). MODIS aerosol products consist of dark target (DT) over both ocean and land and deep blue (DB) products over land-only. Their validation against AERONET showed good agreement globally (Levy et al., 2013; Sayer et al., 2013). Because the validation of GOCI us ing AERONET is limited in spatial coverage, inter-comparison using the satellite-based
 - MODIS dataset is valuable for GOCI YAER evaluation over East Asia.

Therefore, GOCI YAER AOD at 550 nm, FMF at 550 nm, SSA at 440 nm, and AE between 440 and 870 nm are evaluated using both the ground-based AERONET and satellite-based MODIS datasets.



4.1 Validation conditions between ground-based AERONET and satellite-based GOCI and MODIS

For the validation, 38 of the campaign sites are selected, each at least 20 observed days. The current Level 2.0 version 2 direct-sun all points observation products, inversion products, and the spectral de-convolution algorithm (SDA) products are used in this study (Holben et al., 1998; O'Neill et al., 2003; Dubovik and King, 2000). From the direct sun measurement, AOD and Angstrom exponent are used. The validation for FMF is done using both inversion and SDA products, while the validation for SSA is done using inversion products. Note that the almucantar observation is only possible when the solar zenith angle is greater than 50° (Dubovik et al., 2000), so inversion data are unavailable near noon.

Aerosol data from GOCI and AERONET are collocated temporally and spatially for the comparison. The ground-based AERONET observes the sun/sky radiance at intervals of a few minutes at a fixed site, while GOCI observes aerosol over East Asia

- at hourly intervals. GOCI pixels within 25 km of an AERONET site are averaged, and AERONET data within 30 min from GOCI observation time are averaged. Colocation is carried out when at least one pixel of GOCI and one temporal value of AERONET exist. Note that AERONET does not observe AOD at 550 nm directly so that it is interpolated from other channels using a quadratic fit on a log-log scale (Eck et al., 1999).
- ²⁰ The colocation condition between AERONET and MODIS is the same as for GOCI. Note that validation of MODIS using AERONET is performed for AOD only.

4.2 Inter-comparison condition between MODIS and GOCI

The different characteristics of MODIS and GOCI as LEO and GEO sensors, respectively, need to be considered when inter-comparison is performed. Spatial colocation is based on the fixed grid scale in the GOCI FOR. The GOCI observation area is divided into 0.2° × 0.2° latitude–longitude resolution grid cells. Therefore, MODIS and GOCI data within the same fixed grid are separately averaged, and then matched spatially.



Temporal colocation is based on the MODIS observation time. MODIS level 2 aerosol data are provided as granules, and the maximum difference in scan time in one granule is about 5 min. The maximum difference in GOCI scan time for one scene is about 30 min, and GOCI scans the FOR every hour. Therefore, two GOCI scenes within 1 h centered on the MODIS overpass time are interpolated to the MODIS time, and are collocated with MODIS temporally.

4.3 Validation of AOD

The validation involves use of the linear regression equation, and validation metrics include the Pearson's linear correlation coefficient (*R*), root mean square error (RMSE), mean absolute error (MAE), mean bias error (MBE), and the ratio within expected error (% within EE). Note that MBE and MAE are the mean of differences and absolute differences of value between AERONET and GOCI, respectively. The range of expected error (EE) of AOD is adopted from MODIS DT over land.

AOD Figure 8 shows the spatially and temporally collocated of GOCI and MODIS at the AERONET VS. 38 DRAGON AERONET 15 "MODIS Corrected_Optical_Depth_Land" sites. at 550 nm and "MODIS_Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimate" from MODIS/Aqua are used as the AOD of MODIS DT and DB, respectively. A total of 9602 data points are matched with GOCI for all QA values, and 8652 for only QA = 3 data. There is good agreement between AERONET and GOCI with high 20 data counts (red color) gathered near the one-to-one line. Because GOCI pixels with QA = 3 are less cloud contaminated than those with all QA values, there are fewer overestimated pixels from the GOCI QA = 3 set. Thus, all validation criteria show better results for QA = 3 than for all QA except for the y intercept of the linear regression

²⁵ line. Most comparison points are concentrated within the EE and immediately below EE in AERONET AOD < 0.4, but widespread points above EE result in the increase of the *y* intercept for all QA. Such pixels seem to be contaminated by cloud so, in general, have QA less than 3. Therefore, when only QA = 3 pixels are compared



with AERONET, the *y* intercept has a more negative value of -0.041 than for all QA (-0.001). The correlation coefficient for AOD between AERONET and GOCI (QA = 3) is 0.885, which is higher than for MODIS DT (0.881) and DB (0.872). For RMSE, MAE, and % within EE, GOCI is better than MODIS DT. Munchak et al. (2013) described that MODIS DT Collection 6 AOD is biased high over urban surfaces.

Otherwise, the recent MODIS DB Collection 6 algorithm controls surface reflectance differently according to surface type, giving high accuracy regardless of surface type (Hsu et al., 2013). The ratio within EE of MODIS DB against AERONET is 69.7 % for all AERONET sites, which is greater than for GOCI (56.9 %).

- ¹⁰ Results of inter-comparison of AOD between GOCI and MODIS are shown in Fig. 9. Note that ocean pixels near most coastal sites are classified as turbid water and retrieved using the land algorithm. Thus, it is hard to validate the GOCI ocean algorithm using AERONET, but it is possible using MODIS DT ocean AOD. Inter-comparison of the ocean AOD of MODIS DT and GOCI shows good agreement (R = 0.912). The slope of the regression line is 0.983 and the γ intercept is 0.056. Both algorithms con-
- sider wind speed dependent surface reflectance. Because the ocean surface is darker than the land surface, it is easier to detect cloud pixels over ocean and so there are fewer overestimation points for GOCI.

The GOCI AOD over ocean is retrieved from the ocean algorithm over clear water and the land algorithm over turbid water (or heavy aerosol loading). The AOD over turbid water pixels is not retrieved in the MODIS DT ocean algorithm, so direct comparison over turbid water is impossible (Lee et al., 2010b)

A common feature of comparisons of GOCI products using MODIS DT and DB over land is that there are more scattered points above the one-to-one line than in ²⁵ comparisons between AERONET and GOCI. Because cloud is effectively cleared in AERONET Level 2 data, most collocated cases with AERONET are in fact cloud-free cases. MODIS DT and DB use the characteristics of cloud in visible and infrared (IR) wavelengths for cloud screening, but there are no IR channels in GOCI so that cloud screening is carried out using visible–near IR channels only. It is more difficult to dis-



tinguish the cloud signal clearly over land using only visible characteristics because of bright surface reflectance, especially for urban surfaces. If cloud is not removed correctly, its signal is considered as aerosol, and AOD is overestimated. This explains the greater number of pixels scattered above the one-to-one line in both comparisons over

- ⁵ land. GOCI YAER AOD over land is better correlated with MODIS DB (R = 0.856) than DT (R = 0.794), and the linear regression line over land between GOCI and MODIS DB is also closer to the one-to-one line than with MODIS DT. In MODIS DT, visiblewavelength surface reflectances over land are retrieved from TOA reflectances of IR channels (2.1 µm), while the minimum reflectance method is used for the surface reflectances in MODIS DP. That method is also applied for determining surface
- flectance database in MODIS DB. That method is also applied for determining surface reflectance for GOCI YAER; hence the tendency and accuracy of retrieved AOD from GOCI are closer to MODIS DB than DT.

4.4 Validation of Angstrom exponent, fine-mode fraction, and single scattering albedo

- ¹⁵ The GOCI YAER AE, FMF, and SSA are determined from the climatological values of the three selected aerosol models in the inversion procedure to calculate AOD. Therefore, the possible product retrieval ranges are limited by the aerosol models. AE, FMF, and SSA can be retrieved in the ranges of 0.0930–1.744, 0.156–0.956, and 0.871– 0.970, respectively.
- Figure 10a and b shows the comparison of AE between AERONET and GOCI. The correlation coefficient is 0.566 in Fig. 10a, which is significantly lower than for the AOD comparison (0.885). The difference in spectral aerosol signal does not vary much with aerosol model when AOD is low, so the error of AE can be large at low AOD. When AOD is less than 0.3, the value of AE are about 1.3 for AERONET, but about 0.7 for the GOCI
- retrieval; thus when these points are removed, the correlation coefficient increases to 0.664 in Fig. 10b. AE is underestimated from GOCI compared with AERONET (MBE = -0.255) for the whole range although highest density of points from AERONET and GOCI coincide.



Although the MODIS DT AE over land can be calculated using spectral AOD at 470 and 660 nm, inter-comparison of the AE between MODIS DT and GOCI is not done over land in this study. Levy et al. (2010) reported that AE is not available globally at sufficient quantitative accuracy so that it was removed from the main products of the

- ⁵ Collection 6 DT algorithm (Levy et al., 2013). Therefore, comparison is only performed over the ocean. The MODIS DT AOD over the ocean is retrieved at 550 and 860 nm, so the AE between these two channels is compared with the GOCI AE in Fig. 10c. Over the ocean both GOCI and MODIS DT assume Fresnel reflectance with wind speed dependence for the surface reflectance, and the surface reflectances is similar between
- GOCI and MODIS DT over, and the surface reflectance of ocean is lower than that of land. Therefore, high counts are well matched and the RMSE and MBE (0.386 and 0.021, respectively) are better than those of AERONET vs. GOCI (0.400 and -0.255, respectively) although the correlation coefficient is much lower at 0.386.

FMF is provided directly from SDA AERONET, or calculated using the almucantar
 retrievals of fine AOD and the total AOD at 675 nm from AERONET inversions. Both AERONET FMF products are compared with the GOCI YAER FMF in Fig. 11a and
 b. Note that both comparisons are for AERONET AOD > 0.3. The correlation coefficients are 0.685 and 0.748 for SDA and inversion AERONET, respectively. These are higher values than for AE validation, but less than for AOD validation. High counts of AERONET are grouped around 0.9–1.0, but those of GOCI are grouped at 0.8. GOCI

²⁰ FMF is underestimated compared with AERONET for the whole FMF range. The MBE values are -0.180 and -0.168, respectively.

The inter-comparison of FMF between MODIS DT and GOCI over the ocean is shown in Fig. 11c. The correlation is better (R = 0.418 and RMSE = 0.184) than for

of AE (R = 0.332 and RMSE = 0.386). The validation results for FMF are analogous to those of AE because both parameters are sensitive to the particle size in visible wavelengths.

Figure 12 shows the results of comparing SSA between AERONET inversion and GOCI. Only 617 points are collocated temporally and spatially because Level 2



AERONET SSA is only provided for AOD > 0.4 and almucantar observation is performed when the solar zenith angle is greater than 50° (Dubovik and King, 2000).

The correlation coefficient is 0.368, which is the lowest among the GOCI products. Nevertheless, the accuracy of GOCI SSA is comparable with that of OMI SSA over East

- Asia. According to Jethva et al. (2014), the correlation coefficient between AERONET and OMI SSA is 0.406. They also showed that 44.91 and 70.29% of OMI SSA data are within differences of ±0.03 and ±0.05 with respect to AERONET. GOCI SSA shows higher ratios than OMI, 71.0 and 86.3%, for the same criteria over North East Asia. A preliminary redundancy test (Lee et al., 2012), which showed that GOCI SSA may
- ¹⁰ be underestimated at high SSA (~ 0.95) and overestimated at low SSA (~ 0.85), is consistent with the results of GOCI SSA validation against AERONET. The difference between absorbing and non-absorbing aerosols is significant in the UV and shorter visible (blue) wavelengths, and weak at longer visible (green and red) wavelengths. GOCI YAER algorithm is optimized for AOD retrieval using aerosol model composition classified by FMF and SSA. In the next generation GOCI-2 mission to be launched in
- 2019, SSA can be retrieved more accurately utilizing UV channel.

In conclusion, GOCI AE, FMF, and SSA show lower accuracy than AOD. Nevertheless, these values can be useful for qualitative studies, although not for quantitative studies.

20 5 Error analysis of GOCI YAER AOD

Uncertainties in surface reflectance, assumed aerosol model, cloud masking, and geometry result in systematic errors of retrieved AOD. In this section, the difference in AOD between GOCI and AERONET is analyzed to quantify the respective error sources affecting the accuracy of GOCI AOD.

²⁵ The difference in AOD between GOCI and AERONET is shown in Fig. 13a as a function of AERONET AOD. The 16–84 % range for each bin widens as AOD increases, as with satellite products. GOCI AOD has a negative bias of –0.1 against AERONET for



AERONET AOD < 0.4, while there is no consistent bias but a skewed distribution toward the positive differences for AERONET AOD > 0.9. The minimum reflectivity technique can overestimate surface reflectance due to contamination by the remaining cloud or aerosol, resulting in negative bias at low AOD. On the other hand, the ac-

- ⁵ curacy at high AOD can be affected by the assumed aerosol model or cloud masking. An insignificant bias of the median points supports the validity of the assumed aerosol model, but a positive skewed distribution can be attributed to the remaining cloud contamination due to cloud masking using visible channels only. It is difficult to distinguish aerosol and cirrus cloud without information from IR wavelengths (Lee et al., 2013).
- ¹⁰ The next comparison is the difference in AOD between GOCI and AERONET plotted against scattering angle in Fig. 13b. There is a consistently negative bias over all scattering angles for low AOD (< 0.3), where it is difficult to find noticeable scattering angle dependency. For high AOD (> 0.3), GOCI AOD is underestimated at scattering angles near 115 and 140° and overestimated at 145° and above 160°.
- ¹⁵ The method for determining surface reflectance is applied equally to all pixels regardless of surface type. To test the accuracy as a function of surface type, the normalized difference vegetation index (NDVI) is adopted, defined as ($\rho_{TOA}(865 \text{ nm}) - \rho_{TOA}(660 \text{ nm})$)/($\rho_{TOA}(865 \text{ nm}) + \rho_{TOA}(660 \text{ nm})$). Generally, it is negative over ocean and positive over land. It is close to 1 when the surface is green because of vegetation
- ²⁰ growth, while it is close to zero over less green areas. Figure 13c shows the difference in AOD between GOCI and AERONET plotted against NDVI. Note that negative NDVI is possible when GOCI ocean pixels are collocated with AERONET at coastal sites. The difference is small (0–0.05) and the bias is for low NDVI (–0.4 to 0.1). However, the difference decreases linearly from 0.05 to –0.2 as NDVI increases from 0.1 to
- 0.6, due to the limitation in minimum reflectivity technique with search window of one month during the dynamic vegetation change in the spring season and its reference at 412 nm channel. AOD is significantly underestimated by GOCI with increasing vegetation cover, thus surface type must be considered to improve the algorithm as for the enhanced MODIS DB algorithm (Hsu et al., 2013). Additionally, this may be partially



due to the most densely vegetated surfaces in both Korea and Japan being forested mountains therefore some AOD may be below the elevated surface altitude as very few AERONET sites were located on mountains.

6 Conclusion

⁵ The prototype GOCI YAER algorithm over the ocean (Lee et al., 2010b) was further developed with employing a non-spherical aerosol model to improve aerosol retrieval algorithm over the ocean using MODIS data (Lee et al., 2012). From this heritage, the GOCI YAER algorithm is extended to land and improved over the ocean and land. GOCI has the advantages of high spatial (500 m × 500 m) and temporal (hourly) resolution using eight channels in visible wavelengths. Therefore, other properties such as FMF, AE, and SSA as well as AOD can be retrieved from the GOCI YAER algorithm at 6km × 6km resolution.

Different surface reflectance assumptions and channels are applied for the land and ocean. Turbid water is classified according to $\Delta \rho_{660}$, and the land algorithm is applied over turbid water. Nonsphericity and dynamical properties of aerosol are reflected in the aerosol models.

The DRAGON-NE Asia 2012 campaign in spring has enabled the evaluation of GOCI YAER products over 38 sites in Korea and Japan using AERONET data and MODIS over East Asia. AOD from the GOCI YAER shows good agreement with AERONET with

- ²⁰ a correlation coefficient of 0.885, which is better than for MODIS DT (R = 0.836) and DB (R = 0.872). The ratio within ±(0.05 + 0.15 × AERONET_AOD) of GOCI is 56.9 %, which is worse than MODIS DB (69.7 %) but better than MODIS DT (44.0 %). In the inter-comparison between GOCI and MODIS, GOCI and MODIS DT show good agreement over ocean with high correlation (R = 0.912). Over land, GOCI YAER shows bet-²⁵ ter agreement and less bias with MODIS DB (R = 0.856, RMSE = 0.212) than MODIS
- DT (\vec{R} = 0.794, RMSE = 0.278) likely due in part to similar surface reflectance assumptions used in both GOCI and MODIS DB. For size parameters such as AE and FMF,



GOCI agrees less well with AEORNET (R = 0.566-0.748) and tends to underestimate (MBE = -0.335 to -0.168). Over ocean, the comparison of size parameters between GOCI and MODIS DT shows significantly poorer agreement (R = 0.386-0.418), but data points with high frequency are well matched. For the SSA, GOCI shows low cor-

relation of 0.368 and 0.082 with AERONET and MODIS DB, respectively, but the range of SSA (0.90–0.95) is well matched each other. In conclusion, GOCI YAER AOD shows high accuracy against MODIS, and other aerosol parameter products can be used qualitatively although their accuracy is less than AOD.

From the error analysis, GOCI YAER AOD shows a negative bias of -0.1 for low AOD (< 0.4), and the negative bias increases as NDVI becomes higher. It is necessary to improve the accuracy of surface reflectance over vegetated areas for the next version, and possibly account for the elevation of forested mountains relative to the aerosol vertical profile.

The phase function of non-spherical properties from AERONET is included directly by using a scalar RTM, libRadtran; this RTM is less accurate for calculating Rayleigh scattering for the short visible wavelengths (~ 400 nm). A vector RTM might be helpful in improving the accuracy of the GOCI YAER algorithm in the near future. The current validation period is limited to Spring 2012, and thus the seasonal dependence of accuracy is not presented in this study. Nearly 4 years of GOCI data have been accumulated

²⁰ since March 2011, which will allow long-term validation and analysis to be carried out to investigate retrieval accuracies and uncertainties in the near future.

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²⁵ campaign used in this investigation. We also thank the MODIS science team for providing valuable data for this research. This research was supported by the GEMS program of the Ministry of Environment, Korea, and the Eco Innovation Program of KEITI (2012000160002).



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 Table 1. Conditions for determining pixel QA values from 0 to 3.

QA	Number of pixels (N) selected from possible 12 × 12 pixels	Range of retrieved AOD at 550 nm
0	$6 \le N \le 14$	$-0.10 \le AOD < 0.05$, or $3.6 < AOD \le 5.0$
1	15 <i>≤ N ≤</i> 21	$-0.05 \le AOD \le 3.6$
2	22 ≤ <i>N</i> ≤ 35	$-0.05 \le AOD \le 3.6$
3	$36 \le N \le 58$ (maximum)	$-0.05 \le AOD \le 3.6$

Discussion Pa	AM 8, 9565–9	ITD 609, 2015			
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Table 2. Quantity of AERONET inversion data for the 26 aerosol models. "H", "M", and "N" mean "Highly absorbing", "Moderately absorbing", and "Non-absorbing" models, respectively.

		FMF (550 nm)								
		0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1.0
SSA (440 nm)	0.85–0.90	H1 3298	H2 4309	H3 1960	H4 1360	H5 1151	H6 1256	H7 2145	H8 3420	H9 1933
	0.90–0.95	M1 5699	M2 6111	M3 2396	M4 1606	M5 1185	M6 1431	M7 2344	M8 5520	M9 6641
	0.95–1.00		N1 558	N2 366	N3 289	N4 279	N5 382	N6 845	N7 2643	N8 7585

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Title	Page				
Abstract	Introduction				
Conclusions	References				
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Back	Close				
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Discussion Paper

Table 3. LUT dimensions.

Variable	Number of entries	Entries
Wavelength	8	412, 443, 490, 555, 660, 680, 765, 870 nm (considering spectral response function)
Solar zenith angle	8	0, 10,, 70° (10° interval)
Satellite zenith angle	8	0, 10,, 70° (10° interval)
Relative azimuth angle	19	0, 10,, 180° (10° interval)
AOD	9	0.0, 0.1, 0.3, 0.6, 1.0, 1.5, 2.1, 2.8, 3.6 at 550 nm
Aerosol model	26	In Table 2.
Surface reflectance (only for land LUT)	4	0.0, 0.1, 0.2, 0.3
Terrain height (only for land LUT)	2	0, 5 km
Wind speed (only for ocean LUT)	6	1, 3, 5, 7, 9, and 20 m s ⁻¹

Table 4. Output aerosol types for (GOCI YAER according to FMF	and SSA.
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No.	Aerosol Type	FMF (550 nm)	SSA (440 nm)
1	Dust	$0.0 \le FMF < 0.4$	SSA ≤ 0.95
2	Non-absorbing coarse type	$0.0 \le FMF < 0.4$	0.95 < SSA < 1.00
3	Mixture	$0.4 \le FMF < 0.6$	
4	Highly-absorbing fine type	$0.6 \le FMF < 1.0$	SSA < 0.90
5	Moderately-absorbing fine type	$0.6 \le FMF < 1.0$	$0.90 \le SSA < 0.95$
6	Non-absorbing fine type	$0.6 \le FMF < 1.0$	SSA ≥ 1.00

Discussion Pa	AMTD 8, 9565–9609, 2015 GOCI Yonsei Aerosol Retrieval (YAER) algorithm and validation M. Choi et al.			
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Paper	Title	Page		
—	Abstract	Introduction		
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Figure 1. Flow-chart for GOCI YAER algorithm.





Figure 2. Surface reflectance on 15th of the month, 13:30 local standard time (LST) at 443 nm (left column) and 660 nm (right column): March (upper row), April (middle row), and May (lower row).











Figure 4. $\Delta \rho_{660}$ and DAI images at 13:30 LST on **(a, b)** 26 April 2012 (no dust case) and **(c, d)** the following day (dust case), respectively.





Figure 5. 25 March 2012, 13:30 LST (a) true color image and (b) $\Delta \rho_{660}$.





Figure 6. Images of **(a)** GOCI true color, **(b)** AOD at 550 nm, **(c)** FMF at 550 nm, **(d)** AE between 440 and 870 nm, **(e)** SSA at 440 nm, and **(f)** type for 6 May 2012, 13:30 LST. Aerosol types are colored yellow (Dust), green (Mixture), orange (Non-absorbing coarse type), blue (Non-absorbing fine type), purple (Moderately absorbing fine type), and red (Highly absorbing fine type).





Figure 7. As Fig. 6 except for 27 April 2012.





Figure 8. Comparison of AOD between AERONET and (a) GOCI for all QA, (b) GOCI for QA = 3 only. (c) MODIS DT, and (d) MODIS DB. Colored pixels represent a bin size of 0.02. The blue solid line is the linear regression line. Black dashed and dotted lines are the one-toone and expected error lines, respectively.



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Figure 9. Comparison of AOD between **(a)** MODIS DT and GOCI over ocean, **(b)** MODIS DT and GOCI over land, and **(c)** MODIS DB and GOCI over land. Color pixels represent a bin size of 0.02. The blue solid line is the linear regression line. The black dashed line is the one-to-one line.





Figure 10. Comparison of AE between direct AERONET and GOCI for **(a)** all AERONET AOD range, and **(b)** only for AERONET AOD > 0.3. **(c)** AE inter-comparison between MODIS DT and GOCI over ocean only for GOCI AOD > 0.3. Colored pixels represent a bin size of 0.05. Wavelengths of Angstrom exponents are 440 and 870 nm for AERONET and GOCI, and 550 and 860 nm for MODIS DT over ocean. Dashed and solid lines are the same as Fig. 9.





Figure 11. Comparison of FMF between **(a)** SDA AERONET and GOCI, and **(b)** inversion AERONET and GOCI only for AERONET AOD > 0.3. **(c)** FMF inter-comparison between MODIS DT and GOCI over ocean only for GOCI AOD > 0.3. Colored pixels represent a bin size of 0.05. Dashed and solid lines are the same as Fig. 9.





Figure 12. Comparison of SSA between inversion AERONET and GOCI. Colored pixels represent a bin size of 0.005. Dashed and solid lines are the same as Fig. 9. Red and blue dotted lines are the ± 0.03 and ± 0.05 ranges, respectively.







AMTD

8, 9565-9609, 2015

GOCI Yonsei Aerosol

Retrieval (YAER)

Discussion Paper

Figure 13. Difference in AOD between GOCI and AERONET according to (a) AERONET AOD, (b) scattering angle, and (c) NDVI. Each point is the median value from 200 collocated data sorted in ascending order of each x axis value. Lower and upper bounds of the error bar at each point correspond to the 16 and 84 % points of each bin, respectively (1 σ interval).