Validation of MODIS and AHI Observed Water Cloud Properties Using Surface Radiation Data

Pradeep KHATRI, Tadahiro HAYASAKA, Hironobu IWABUCHI
Center for Atmospheric and Oceanic Studies, Tohoku University, Sendai, Japan

Tamio TAKAMURA, Hitoshi IRIE
Center for Environmental Remote Sensing, Chiba University, Chiba, Japan

and

Takashi Y. NAKAJIMA
Research and Information Center, Tokai University, Tokyo, Japan

(Manuscript received 2 June 2017, in final form 30 January 2018)

Abstract

The present study implements long-term surface observed radiation data (pyranometer observed global flux and sky radiometer observed spectral zenith transmittance data) of multiple SKYNET sites to validate water cloud optical properties (cloud optical depth COD and effective radius Re) observed from space by MODIS onboard TERRA and AQUA satellites and AHI onboard Himawari-8 satellite. Despite some degrees of differences in COD and Re between MODIS and AHI, they both showed common features when validated using surface based global flux data as well as cloud properties retrieved from sky radiometer observed zenith transmittance data. In general, CODs from both satellite sensors are found to overestimated when clouds are optically thin. Among a number of factors (spatial and temporal variations of cloud, sensor and solar zenith angles), the solar zenith angle (SZA) is found to have an impact on COD difference between reflectance based satellite sensor and transmittance based sky radiometer. The Re values from the sky radiometer and satellite sensor are generally poorly correlated. The difference in Re between the sky radiometer and satellite sensor is negatively correlated with COD difference between them, which is likely due to the inherent influence of Re retrieval precision on COD retrieval and vice versa in transmittance based sky radiometer.

Keywords cloud; AHI; MODIS; SKYNET

1. Introduction

Clouds are important components of the Earth’s atmosphere. They are known to profoundly affect the atmospheric heat budget, climate change, and the hydrological cycle (Rosenfeld et al. 2014). Their accurate representation remains one of the largest uncertainties in global climate models (Forster et al. 2007). The long-term observation of cloud microphysical and optical properties over a sufficiently wide area would improve our understanding of the influence of clouds on climate change and hydrological cycling. Advances in remote sensing technology, along with
sensors installed on several satellites, have enabled the wide-area monitoring of clouds from space. The algorithms that retrieve the physical parameters from observations of space-based satellite sensors are based on certain physical models or assumptions, which may not be fully applicable when the same sensor monitors the entire globe or a part of the globe for many years. Therefore, the satellite-sensor products must be validated with reliable surface-observation data. Validation not only confirms the accuracy and precision of the satellite-sensor products but also provides several clues for their advancement. Many attempts to validate the cloud properties observed from space have been published (e.g., Hayasaka et al. 1994; Nakajima and Nakajima 1995; Kuji et al. 2000; Kawamoto et al. 2001; Dong et al. 2002; Nakajima et al. 2005; Painemal and Zuidema 2011; King et al. 2013). Most of these studies validated the water cloud products of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the TERRA and AQUA satellites, usually over relatively short time periods. We believe that using the long-term data of multiple locations covered by the same instruments, the validation would resolve the target problem more precisely, accurately, and confidently in comparison with previous validations. Only a sophisticated ground-based observation network can provide such an opportunity. Among these networks is SKYNET (http://atmos3.cr.chiba-u.jp/skynet/), which has a very good facility for observing aerosols, clouds, and radiation over different locations by a wide range of instruments.

The proposed study validates the water cloud products of two satellite sensors, the Advanced Himawari Imager (AHI) onboard Himawari-8 and the MODIS sensor, with SKYNET data. We targeted AHI and MODIS cloud products owing to their significant applications in cloud research activities. AHI is a state-of-the-art optical sensor with high spatial and temporal resolutions. The spatial resolution is 0.5, 1, and 2 km in the visible, near-infrared, and infrared bands, respectively. The temporal resolution is approximately 10 minutes for the full disk and 2.5 minutes for sector regions (Bessho et al. 2016). As the fundamental cloud products can be operationally retrieved from observational data, validating them with reliable surface-observation data is urgently required. Meanwhile, the MODIS cloud products have been extensively used by research communities worldwide. It is of interest to validate such standard cloud products using surface observation data of SKYNET as well as to see how well the cloud products of AHI and MODIS agree.

The remainder of this study is organized as follows. Section 2 briefly describes the validation sites, data, and study method. Section 3 compares the cloud properties of AHI and MODIS, and Sections 4 and 5 provide the SKYNET validation results of the MODIS and AHI cloud properties, respectively. The main findings are summarized in Section 6.

2. Sites, data, and study method

2.1 Sites

The proposed study uses the data obtained from the following four SKYNET sites: Chiba (35.625°N, 140.104°E), Hedo-misaki (26.867°N, 128.248°E), Fukue-jima (32.752°N, 128.682°E), and Miyako-jima (24.737°N, 125.327°E) observed from 1 October 2015 to 31 December 2016. All sites are located within Japan, and have different atmospheric backgrounds. Chiba is an urban site located near Tokyo, and Hedo-misaki, Fukue-jima, and Miyako-jima are located along the coast of the East China Sea. The air masses at the three seaside sites depend on season, and include aerosols transported from the distant desert and continental regions of East Asia, especially at Fukue-jima site (Khatri et al. 2010, 2014). Although aerosol transport is outside the scope of this study, these sites were chosen for validation as they are “super sites”, potentially important sites for studying the characteristics of East Asian aerosols and their influences on cloud and regional climate, of SKYNET. Consequently, they are equipped with a wide range of instruments for observing the aerosols, clouds, and radiation. SKYNET has a good data archive, and all instruments are regularly inspected/calibrated to maintain the data quality.

2.2 Data

a. MODIS data

We used the MODIS Level 2.0 (collection 6) cloud products (Platnick et al. 2015) of both the TERRA and AQUA satellites. The sun synchronous, near-polar circular orbit of TERRA (AQUA) is timed to cross the equator from the north (south) to south (north) at approximately 10:30 A.M. (1:30 PM) local time. The spatial resolution of MODIS cloud products is 1 km × 1 km at nadir. The following two MODIS cloud products were selected for this study: the cloud optical depth (COD) and cloud-particle effective radius (Re). The COD and Re values are derived by combining the observed and forward model-generated reflectance data of water non-absorbing and absorbing wavelengths (Nakajima and King 1990). The water non-absorbing wavelengths are 0.66, 0.87, and 1.2
µm for the remote sensing of clouds over land, ocean, and ice surfaces, respectively. The COD and Re are derived at a given non-absorbing wavelength and the water-absorbing shortwave infrared (SWIR) wavelengths of 1.63, 2.13, and 3.79 µm. The COD and Re retrievals require various types of ancillary data, such as pressure and temperature of the cloud top, cloud mask data, land and sea surface temperatures, atmospheric temperature and moisture profile, and spectral surface albedo. The necessary atmospheric correction is based on the data computed from the MODTRAN 4 radiative transfer model (Berk et al. 1998). The ancillary data sources and a detailed theoretical explanation are provided in King et al. (1997).

b. AHI data

Unlike TERRA and AQUA, Himawari-8 is a geostationary satellite. At all sites selected in this study, AHI observation data are collected at an interval of 2.5 minute. The cloud properties (COD and Re) from the AHI observations are derived by the Comprehensive Analysis Program for Cloud Optical Measurements (CAPCOM) algorithm, developed by Nakajima and Nakajima (1995) and Kawamoto et al. (2001). Similar to the MODIS cloud retrieval algorithm, CAPCOM employs a look up table (LUT) of water-absorbing and water non-absorbing wavelengths (Nakajima and King 1990); however, the two algorithms differ in their wavelengths, ancillary data sets, atmospheric correction method, surface albedo treatment, and other data processes. The CAPCOM algorithm uses measurements collected in the visible, SWIR, and infrared (IR) spectra. CAPCOM developed for AHI is descended from the cloud retrieval algorithm developed for Global Imager (GLI) of the Advanced Earth Observing Satellite-II (ADEOS-II), which had measurements at 0.65 (band 3), 3.7 (band 7), and 11 µm (band 14) (Nakajima et al. 2009). Bands 3, 7, and 14 of AHI share similarities with the corresponding bands of GLI/ADEOS-II. The observation signal at 3.9 µm includes both the reflected solar component and undesired emitted thermal component. The thermal component is removed using the cloud-top temperature measured at 11.2 µm. Meanwhile, the COD and Re are simultaneously obtained using the LUT of the water-non-absorbing and water-absorbing wavelengths. Besides the satellite-observed reflectance signals, the calculations need ancillary data, such as the vertical temperature, pressure, water-vapor profiles, and the ground albedo (Nakajima et al. 2009). The necessary atmospheric correction is performed by Rstar radiative transfer code (Nakajima and Tanaka 1986, 1988). Like MODIS, CAPCOM can retrieve the Re values from data collected at different water-absorbing SWIR wavelengths; however, in the present study, the Re values are derived from data at a single SWIR wavelength (3.9 µm).

The CAPCOM based cloud properties have been used to retrieve global, direct, and diffuse fluxes at the surface and top of the atmosphere (Takenaka et al. 2011). We further used such CAPCOM cloud product based surface global-flux data. All AHI-related data applied in this study are spatially resolved to 1 km × 1 km at nadir.

c. SKYNET data

This study employed two types of SKYNET data, i.e., the surface global flux and spectral zenith transmittance. At each site, the surface global flux covers a spectral range of 0.315 to 2.8 µm at a temporal resolution of 20 seconds. The data were measured by a pyranometer manufactured by Kipp and Zonen (Holland). The spectral zenith transmittances at each site were measured by a sky radiometer (Model: POM-02) manufactured by PREDE Co. Ltd. (Japan). The COD and Re values were retrieved from zenith transmittances at wavelengths of 0.87, 1.02, and 1.627 µm using a new method developed by Khatri et al. (2017). The previous method proposed by Kikuchi et al. (2006) retrieves the COD and Re from a LUT of 1.02 µm (non-absorbing) and 1.627 µm (absorbing) zenith transmittances; however, the LUT approach has several drawbacks. For example, one set of observation data can result more than one set of COD and Re due to overlapping lines in LUT, and the choice of the most plausible result is technically difficult. These drawbacks have been overcome by a new algorithm that uses the transmittances at three wavelengths. This algorithm is based on the maximum a posteriori method in Bayesian theory, as outlined by Rodgers (2000). We further developed an on-site calibration technique (Khatri et al. 2017) for the 1.627 µm wavelength channel, which allows temporally variant calibration constants in long-term observation analysis. This study analyzes the sky-radiometer data of only three sites (Chiba, Hedo-misaki, and Fukue-jima) The temporal resolution of the sky-radiometer data is 10 minutes.

2.3 Study method

Spatial and temporal mismatch cause uncertainties when comparing different cloud products. If the satellite sensor’s viewing angle from nadir is large, parallax is present between cloud and underlying

surface levels; longitude and latitude at the cloud level should be shifted from those at the surface. The parallax has been corrected for data of both MODIS and AHI sensors by using information of cloud top height, sensor’s zenith and azimuth angles, and latitude and longitude of target location (validation site). After that, we compared MODIS cloud product with the mean value of AHI cloud product by selecting data in such a way that the pixel center difference and the observation time difference between AHI and MODIS should be less that 1 km and 5 minutes, respectively, and there should be at least one observation from each of them with time difference less than 1 minute. For comparing satellite sensor products with surface observation data, the distance between the pixel center and site location should be less than 1 km, and the maximum time difference between the surface and satellite observations should be less than 1.25 minute, which is half of AHI temporal resolution over Japan.

3. Comparison between MODIS and AHI cloud properties

3.1 Cloud optical depth

The left panel of Fig. 1 compares the COD data of MODIS and AHI at the Chiba, Hedo-misaki, Fukue-jima, and Miyako-jima sites. Among three types of MODIS COD products, this study uses the data obtained from the pair of specific water non-absorbing wavelength, which depend on the underlying surface type and water-absorbing wavelength of 2.13 μm, which corresponds to the standard MODIS Re product. Note that the retrieved COD is much less sensitive to the absorbing wavelength. The right panel of Fig. 1 compares the COD product with the satellite signals of non-absorbing visible wavelengths (Nakajima and Nakajima 1995), especially when the cloud is optically thin. The sources of the ancillary data, including the surface albedo and atmospheric correction model, differ in the MODIS and AHI cloud retrieval algorithms, as detailed in King et al. (1997) and Nakajima et al. (2009). For example, the CAPCOM algorithm assumes the Lambertian surface reflectance (Nakajima et al. 2009; Takenaka et al. 2011), whereas the MODIS collection 6 cloud products use the bidirectional reflectance distribution function, which is characterized by combining the TERRA and AQUA data (Collection 5) (Platnick et al. 2015). The ancillary data, such as the vertical profiles of temperature, pressure, and relative humidity, are sourced from the Japan Meteorological Agency reanalysis (Nakajima et al. 2009) in the CAPCOM algorithm, and from the outputs of the Global Data Assimilation System run by the National Centers for Environmental Prediction (Platnick et al. 2015) in MODIS algorithm. From the observation side, the viewing angle and field of view differ between the two satellite sensors. The signals received by satellite sensors with different viewing geometries are affected by cloud inhomogeneity, which in turn affects the retrieved products, including the COD (Iwabuchi and Hayasaka 2002).
Fig. 1. Correlative comparisons of COD (left panels) and normalized frequency distributions of COD (right panels). The COD results of AHI (Himawari-8) were correlated with those of MODIS (TERRA + AQUA) at the Chiba, Hedo-misaki, Fukue-jima, and Miyako-jima sites of SKYNET. The AHI CODs of ± 5 minutes centered at the MODIS observation time were averaged for the comparison. Color bars indicate the standard deviations in the AHI COD results. The symbols “N” and “r” denote the data number and correlation coefficient, respectively.
3.2 Effective radius

Figures 2, 3, and 4 show comparisons between MODIS and AHI Re values. In Figs. 2, 3, and 4, MODIS Re corresponds to 2.13 µm, 3.79 µm and 1.63 µm, respectively. Similar to Table 1, Table 2 shows the statistical analysis results of the Re comparisons. The color bars in the figures indicate the standard deviations of the AHI Re values observed within ±5 minutes of the centering MODIS observation time. Since the vertical penetration of photons through cloud depends on the absorbing wavelength, the retrieved Re values depend on the absorbing wavelengths (Platnick 2000). Among three MODIS absorbing wavelengths, 3.79 µm captures the cloud properties near the cloud top, whereas 2.13 µm and 1.63 µm can contain more contribution from lower cloud layers. Though AHI Re from 3.9 µm and MODIS Re values from 2.13 µm and 1.63 µm originate from different cloud depths, AHI Re values from 3.9 µm are still compared with MODIS Re values from those wavelengths for the following reasons: First, the comparison results provide a reference for quantifying the agreement between the Re values of AHI and MODIS at consistent wavelengths. Second, as 2.13 µm is the standard wavelength for Re retrieval by MODIS, it is of interest to see how well AHI Re values from 3.9 µm agree with MODIS Re values corresponding to the standard wavelength and the next absorbing wavelength nearest to it, i.e., 1.63 µm. As shown in Figs. 2–4, the data samples for the comparison study differ for each MODIS wavelength. These differences are attributed to the cloud retrievals in MODIS, whose failure patterns are highly sensitive to the selected wavelength pair in the LUT (Platnick et al. 2015). For example, if any non-absorbing wavelength is paired with an absorbing wavelength of 1.63 µm, the observed reflectances can lie outside the COD–Re solution space of the LUT, i.e., the retrieval fails. However, if the same non-absorbing wavelength is paired with an absorbing wavelength of 2.13 or 3.79 µm, the retrieval may succeed. Similarly to the present study, Platnick et al. (2015) showed that an absorbing wavelength of 1.63 µm yields fewer successful retrievals than the next two absorbing wavelengths.

For typical stratocumulus clouds, characterized by adiabatically distributed liquid water and a positive relation between Re and cloud height, the retrieved Re should be larger at 3.79 µm than at 2.13 and 1.63 µm. However, the Re retrieved by MODIS is smaller at 3.79 µm than at the two shorter wavelengths (see Table 2). This discrepancy likely results from drizzle, which can modify the vertical structure of cloud and/or the cloud-top mixing, thereby reducing the Re near the cloud top (Nakajima et al. 2010). As seen in Figs. 2–4 and Table 2, the AHI Re values are closer to the MODIS Re values obtained at 3.79 µm than to the MODIS Re values obtained at 2.13 µm and 1.63 µm. The AHI Re acquired at 3.9 µm and MODIS Re acquired at 3.79 µm are statistically consistent, i.e., their means and RMSDs differ by no more than 1 µm and 5 µm, respectively, at all sites (Table 2). In contrast, the Re means and RMSDs significantly differ between the AHI data at 3.9 µm and the MODIS data at 2.13 and 1.63 µm. Moreover, at a MODIS wavelength of 3.79 µm, the slope of the AHI versus MODIS plot is closer to 1, and the percentage counts indicate that data are more homogeneously distributed about the 1:1 line than at the shorter MODIS wavelengths.

Comparing Fig. 3 (MODIS wavelength: 3.79 µm), Fig. 2 (MODIS wavelength: 2.13 µm), and Fig. 4 (MODIS wavelength: 1.63 µm), we find that the AHI versus MODIS plots deviate more from the 1:1 line at higher Re than at lower Re. To discuss this behavior quantitatively, we merged the data for all sites and calculated the slopes (AHI/MODIS values) for low, medium, and high classes of MODIS Re. The merging is justified because the results at the different sites are qualitatively identical. For Re < 10 µm, 10 µm ≤ Re < 20 µm and Re ≥ 20 µm, the slopes were 1.09, 0.91, and 0.77 respectively at 3.79 µm, 1.07, 0.75, and 0.52 respectively at 1.6 µm, and 1.0, 0.77, and 0.66 respectively at 2.1 µm, where the wavelengths are the MODIS observation wavelengths. These data suggest that at common absorption wavelengths, the Re values of MODIS and AHI are reasonably consistent. Under
Fig. 2. Correlative comparisons of Re (left panels) and normalized frequency distributions of Re (right panels). The Re results of AHI (Himawari-8) were correlated with those of MODIS (TERRA + AQUA) at the Chiba, Hedo-misaki, Fukue-jima, and Miyako-jima sites of SKYNET. The AHI Re values of ±5 minutes centered at the MODIS observation time were averaged for the comparison. Color bars indicate the standard deviations in the AHI Re results. The MODIS Re results were determined at 2.13 µm. The symbols “N” and “r” denote the data number and correlation coefficient, respectively.
Fig. 3. Same as Fig. 2, but for MODIS Re values determined at 3.79 µm.
Fig. 4. Same as Fig. 2, but for MODIS Re values determined at 1.63 µm.
this assumption, we can attribute the abovementioned increasing deviation from the 1:1 line with increasing Re at distinctly different absorbing wavelengths to the Re dependence on the absorbing wavelength, which is more pronounced when the cloud droplets are large. Therefore, the appropriateness of the selected absorbing wavelength in cloud remote sensing might critically depend on the cloud-droplet size. To the best of our knowledge, the previous literatures have discussed only the importance of photon-penetration depth on the absorbing wavelength. However, the chosen absorbing wavelength can largely influence the quantitative estimates of pristine clouds, which generally contain large droplets. Such wavelength effects can then affect the aerosol indirect effect evaluation as well. Thus, the absorbing wavelength is critical not only for capturing clouds at different levels but also for adequately capturing cloud droplets of different sizes. According to the frequency distributions in the right panels of Figs. 2–4, the MODIS Re values are bounded within 4–30 µm, whereas the AHI Re values extend beyond these boundaries. The Re data of AHI follow a log-normal distribution with a mean of ~ 8 µm. The MODIS Re data also follow a log-normal distribution with a peak of 8–10 µm, but are more irregularly distributed than the AHI data.

The Re difference between AHI and MODIS can arise from both algorithm- and observation-related factors, as described in Subsection 3.1. The Re retrieval can be further affected by the technique of removing the thermal emission contribution from the ground and cloud layers at ~ 3.7 µm, and by the assumed size distribution of the cloud droplets.

4. Validation of MODIS cloud properties using surface-observation data

4.1 Using global-flux data

The global flux observed at the surface is strongly modulated by clouds (Khatri and Takamura 2009). Therefore, comparison of global flux calculated using satellite sensor based cloud properties with surface observation data can allow one to evaluate the satellite sensor based cloud properties qualitatively. A quantitative evaluation is difficult because the global flux measuring pyranometer covers a wide field of view, which may include the scattering effect of cloud edges. The observed global flux can also be contributed by aerosols, water vapor, and atmospheric gases; moreover, it prohibits the separate evaluation of COD and Re. It is worth mentioning that the downwelling surface global flux is significantly more contributed by the COD than the Re (Fig. 5). Figure 5 shows the calculated downwelling surface global fluxes at the solar zenith and azimuth angles of 30° and 0°, respectively for different values of COD and Re and assumed precipitable water content (PWC) of 1.0 cm, Lambertian surface albedo of 0.1, and mid-latitude summer atmospheric model. The calculation adopted the SBDART radiative transfer model (Ricchiazzi et al. 1998). As the COD dominated the Re (Fig. 5), we used the global-flux data to qualitatively evaluate the satellite-sensor based CODs and to cross check the sky radiometer results.

To calculate the downwelling global surface fluxes in the 0.315–2.8 µm spectral range, we combined the standard MODIS cloud products at each site with

| Table 2. Statistical analysis results of the Re comparison between AHI (Himawari-8) and MODIS shown in Figs. 2–4. |
| Site name | AHI (µm) | MODIS (µm) | Slope (Offset = 0) | RMSD (µm) | %count (AHI > MODIS) |
|-----------|----------|------------|-------------------|-----------|----------------------|
| MODIS wavelength (µm) | Ave. ± Std.dev | Ave. ± Std.dev | MODIS | MODIS | MODIS | MODIS | MODIS |
| Chiba     | 2.13     | 10.7 ± 4.5 | 13.5 ± 5.8 | 0.71     | 6.5 | 23 |
|           | 3.79     | 10.6 ± 4.2 | 11.5 ± 4.8 | 0.84     | 4.7 | 38 |
|           | 1.63     | 10.8 ± 4.7 | 14.6 ± 6.2 | 0.65     | 7.8 | 26 |
| Hedo-misaki | 2.13    | 11.6 ± 7.1 | 14.2 ± 5.6 | 0.78 | 5.3 | 17 |
|           | 3.79     | 12.1 ± 5.6 | 12.4 ± 4.9 | 0.94     | 4.8 | 36 |
|           | 1.63     | 11.0 ± 4.4 | 15.4 ± 6.2 | 0.66     | 7.2 | 15 |
| Fukue-jima | 2.13   | 10.4 ± 5.8 | 12.8 ± 5.8 | 0.77 | 5.5 | 22 |
|           | 3.79     | 10.4 ± 4.9 | 11.2 ± 4.3 | 0.89     | 4.7 | 37 |
|           | 1.63     | 9.7 ± 5.2  | 13.5 ± 6.4 | 0.62     | 7.4 | 22 |
| Miyako-jima | 2.13 | 10.8 ± 3.9 | 13.9 ± 5.1 | 0.74 | 4.9 | 16 |
|           | 3.79     | 11.5 ± 5.3 | 11.6 ± 4.2 | 0.98     | 3.6 | 40 |
|           | 1.63     | 10.3 ± 3.6 | 14.8 ± 6.0 | 0.64     | 6.8 | 11 |
the radiosonde-observed PWC at the nearest location (http://weather.uwyo.edu/upperair/sounding.html) and the MODIS spectral surface reflectances (product name: MCD43A4). In this calculation, we assumed an aerosol-free atmosphere and applied the atmospheric model of mid-latitude summer or mid-latitude winter, depending on the observation day. For comparison with the calculated values, we averaged the surface-observation data of the ±1.25 minute window centered on the MODIS observation time. To avoid the scattering effect of discrete cloud edges as far as possible, the results were compared only for observed global fluxes with standard deviations below 20 W m$^{-2}$. The modeled and observed global fluxes at the four sites are compared in Fig. 6. The model tended to overestimate (underestimate) global fluxes above (lower) ~700 W m$^{-2}$. As the comparison results are qualitatively same at the different sites, the data of all sites were merged for a quantitative analysis. The means and standard deviations (in W m$^{-2}$) of the MODIS (surface) fluxes in these five classes were 161.54 ± 95.43, 344.79 ± 114.27, 478.82 ± 117.41, 737.88 ± 81.56 (660.81 ± 50.64), and 76.45, respectively, with slopes (MODIS/Surface) of 1.34, 1.24, 1.00, 0.54, and 0.76, respectively. The high (low) global fluxes correspond to optically thin (thick) clouds, indicating the MODIS overestimates (underestimates) the CODs when the clouds are optically thin (thick). Owing to the strong dependence of global flux on solar zenith angle and on other atmospheric and surface parameters, the boundary COD that discriminates thin and thick clouds is difficult to determine. A direct comparison of the CODs obtained by MODIS and an independent instrument such as a sky radiometer would more accurately validate the MODIS CODs.

4.2 Using the sky-radiometer data

a. Cloud optical depth

The left panel of Fig. 7 compares the CODs obtained by MODIS and the sky radiometer at three sites: Chiba (upper), Hedo-misaki (middle), and Fukue-jima (lower). The statistical analysis results of these comparisons are summarized in Table 3. As shown in the left panel of Fig. 7, the MODIS CODs are overestimated when the clouds are optically thin. In particular, the MODIS CODs are sharp and high when the sky-radiometer CODs are below ~5. Even at radiometer CODs below 10, a considerable number of the MODIS CODs were overestimated. The statistical comparison between the MODIS and sky-radiometer CODs yielded mixed results (Table 3). For example, the means and percentage counts indicate higher CODs from MODIS than from the radiometer, but the slopes indicate the reverse. These ambiguous results are due to the non-systematic differences between the MODIS and sky radiometer CODs, possibly due to the MODIS and sky radiometer perform spatial and point observations, respectively. To ascertain the quality of the comparison results over different COD ranges, the data for quantitative estimates were grouped into the following five categories of sky radiometer CODs: COD < 10, 10 ≤ COD < 20, 20 ≤ COD < 30, 30 ≤ COD < 40, and COD > 40. As the comparison results at different sites are qualitatively same (Fig. 7, left panel), the data of all sites were merged in the quantitative estimates. The mean and standard deviations of the MODIS (sky radiometer) CODs in the above-mentioned ranges were 13.04 ± 10.18 (2.98 ± 2.09), 15.81 ± 8.89 (15.00 ± 2.87), 26.48 ± 19.27 (24.65 ± 3.65), 23.89 ± 9.77 (35.22 ± 3.24), and 38.37 ± 16.17 (47.44 ± 5.22), respectively. These data imply that the MODIS CODs are higher (lower) than the sky radiometer values when the cloud is optically thin (thick). The boundary COD
that discriminates thin and thick cloud lies between 5 and 10. Painemal and Zuidema (2011) and King et al. (2013) validated the MODIS CODs using the aircraft-observed size distribution of cloud droplets. They reported that almost all of the MODIS CODs were overestimated, with a very small minority of underestimated values. However, previous validation studies were generally performed on small-sample datasets with CODs not exceeding ~30. As indicated in the above quantitative estimates, the CODs from MODIS and sky radiometer are not significantly different in the 10–30 range, but for CODs below 10, the overestimated CODs from MODIS are consistent with those of past studies.

b. Effective radius
The right panel of Fig. 7 compares the Re values obtained by MODIS and sky radiometer. These results are less correlated than the corresponding COD results. According to the literature, Re values estimated from ground and aircraft observations are generally smaller than those estimated from satellite observation (e.g., Takamura et al. 2009; Painemal and Zuidema 2011; Chiu et al. 2012; King et al. 2013). The Re values of MODIS are retrieved from reflected signals, which are mainly sourced from the upper portions of clouds, whereas the sky radiometer receives transmitted signals from the whole cloud. This detection difference most plausibly explains the inconsistent Re values between the space and surface observations. The Re comparison results are site dependent (see right panel of Fig. 7 and Table 3). Chiba is an urban site and Hedo-misaki can be considered as a maritime site. The Fukue-jima site, although located

Fig. 6. Correlative comparisons of shortwave global fluxes calculated from MODIS cloud properties and surface observation values at the (a) Chiba, (b) Hedo-misaki, (c) Fukue-jima, and (d) Miyako-jima sites. For details, see text.
Fig. 7. Correlative comparisons of COD (left panel) and Re (µm; right panel) between MODIS (TERRA + AQUA) and the sky radiometer at the Chiba (upper), Hedo-misaki (middle) and Fukue-jima (lower) sites of SKYNET. For details, see text.
in a remote area, is frequently visited by heavy air pollutants from the continental regions of East Asia (Khatri et al. 2010, 2014). Hedo-misaki is a relatively pristine site at which almost all of the MODIS values are overestimated. This result accords with the commonly accepted hypothesis that Re values are larger in satellite observations than in surface observations. The relatively few data samples at the Chiba site almost preclude a concrete conclusion, but the sky radiometer overestimated a significant number of values at the Fukue-jima site, hinting that the Re values retrieved by the sky radiometer are affected by aerosols. Unlike the satellite sensor, the sky radiometer retrieves the Re by combining relatively short wavelengths in the visible and near-infrared spectra with relatively long wavelength of near-infrared spectra, so can easily receive the influence of aerosols. Moreover, as aerosols generally concentrate near the surface below the cloud, they affect the transmittance more than the reflectance. The presence of absorbing aerosols, which are ubiquitously present in the air masses from the continental regions, can reduce the transmittance by absorption. As the present sky-radiometer algorithm does not account for light-absorbing aerosols, the Re values retrieved by the sky radiometer are likely be overestimated in aerosol-loaded atmospheres. To match the observation data, this algorithm may reduce the transmittance of the water-absorbing wavelength (1.627 µm) by increasing the cloud-droplet size. The aerosol effect on ground-based remote sensing should be clarified in future comparison studies.

4.3 Factors responsible for inconsistent cloud properties between MODIS and the sky radiometer

This section attempts to understand the factors affecting the comparison results between the MODIS and sky radiometer shown in Fig. 7. Noting that the sky radiometer and MODIS make point and space observations, respectively, we first consider the effect of cloud heterogeneity by computing the coefficient of variation (COV), defined as the ratio of the standard deviation to the mean value. The COV is calculated from 9 MODIS pixels centered at the observation site (the target pixel of the sky radiometer). Panels a1 and b1 of Fig. 8 show the relation between the COV values and differences between the sky radiometer and MODIS results shown in the left and right panels of Fig. 7, respectively. The COV increases with increasing cloud heterogeneity. If the inconsistent values in Fig. 7 are caused by cloud heterogeneity, large differences should correlate with high COVs and vice versa. As such trends are absent in a1 and a2 of Fig. 8, this possibility is ruled out. We next investigate the effect of cloud temporal variation. For this purpose, we used the AHI cloud data because temporally variant cloud data of very fine resolution at a fixed location are difficult to extract from MODIS. The COVs of the COD and Re values were calculated from an AHI cloud data of ± 5 minutes centered on the MODIS observation time. The results were then correlated with the sky radiometer and MODIS differences, (Fig. 8a2, b2). Like cloud heterogeneity, temporal variation is unlikely to explain the inconsistent COD and Re results shown in Fig. 7. Third, we investigated the role of the sensor zenith angle (SNZA) by plotting the differences between the sky radiometer and MODIS results against SNZA. The results of the COD and Re differences are plotted in panels c1 and c2 of Fig. 8, respectively. The data are quite scattered with no specific relation, indicating that the SNZA hardly explains the inconsistent sky-radiometer and MODIS results of Fig. 7. Although Liang and Girolamo (2013) reported that SNZA can affect COD retrieval, but this effect is very complicated and depends on multiple other factors. The SNZA bias in the COD values becomes noticeable only at angles larger than 70.5° (Liang and Girolamo 2013). Finally, panels d1 and d2 of Fig. 8 plot the COD and Re differences between MODIS and sky radiometer, respectively, against the

| Site name    | Parameter | Sky radiometer | MODIS       | Slope (Offset = 0) (MODIS/Skyrad.) | RMSD (MODIS > Skyrad.) | %count (MODIS > Skyrad.) |
|--------------|-----------|----------------|-------------|-----------------------------------|------------------------|--------------------------|
| Chiba        | COD       | 18.7 ± 15.1    | 18.7 ± 12.6 | 0.84                              | 10.8                   | 59                       |
|              | Re        | 9.9 ± 6.1      | 11.7 ± 5.1  | 0.83                              | 8.5                    | 55                       |
| Hedo-misaki  | COD       | 14.8 ± 15.7    | 18.2 ± 15.4 | 0.89                              | 14.4                   | 70                       |
|              | Re        | 9.8 ± 6.3      | 14.0 ± 5.6  | 1.04                              | 9.0                    | 80                       |
| Fukue-jima   | COD       | 17.8 ± 16.1    | 20.3 ± 14.2 | 0.83                              | 15.4                   | 56                       |
|              | Re        | 12.2 ± 6.5     | 11.2 ± 4.8  | 0.74                              | 7.7                    | 50                       |

Table 3. Statistical analysis results of the COD and Re comparisons between the sky radiometer and MODIS shown in Fig. 7.
Fig. 8. COD (left) and Re (right) differences between the sky radiometer and MODIS results. (a1) COD and (a2) Re versus COV of spatial variations; (b1) COD and (b2) Re versus COV of temporal variations; (c1) COD and (c2) Re versus sensor zenith angle; (d1) COD and (d2) Re versus SZA.
solar zenith angle (SZA). The correlation coefficient of both plots is relatively strong. This result may be plausibly explained by the retrieval system; cloud retrievals using reflected signals and assuming plane-parallel cloud layers yield artificially large CODs at high SZAs (Loeb and Davies 1997; Loeb and Coakley 1998; Seethala and Horvath 2010; Grosvenor and Wood 2014). On the other hand, our numerical test revealed no SZA effect on the CODs obtained from zenith transmittance data.

Figure 9 plots the COD differences between the sky radiometer and MODIS versus those of Re. The differences are negatively related with $r = -0.52$, possibly reflecting the aerosol effect on the cloud properties retrieved from the sky radiometer. Note that increasing the cloud-droplet size will increase and decrease the transmittances of the water non-absorbing wavelengths (0.87 and 1.02 µm) and the water-absorbing wavelength (1.627 µm), respectively (Chiu et al. 2012). As light-absorbing aerosols decrease the zenith transmittance at the surface, the cloud retrieval algorithm of the sky radiometer might misinterpret the transmittance of the water-absorbing wavelength lowered by light-absorbing aerosols as the effect of large-sized cloud droplets. Consequently, the algorithm tends to inflate the Re. Meanwhile, a high Re is associated with increased transmittances of the non-absorbing wavelengths, with consequent reduction of the COD. When finding the optimum solution among the observed signals by accounting for the measurement errors and surface and atmospheric parameters, an overestimated Re can underestimate the COD and vice versa. Thus the retrieval accuracy and precision of one parameter can be interlinked with the next parameter in transmittance-based remote sensing. This phenomenon should be elucidated by further comparisons in future work.

5. Validation of AHI cloud properties using surface-observation data

5.1 Using global-flux data

Similar to Fig. 6, Fig. 10 compares the calculated global fluxes derived from the AHI cloud products (Takenaka et al. 2011) with the surface-observed values. The comparison results in Fig. 10 are qualitatively same at all sites, so the data were merged and classified into five categories of surface-observed flux (F): $F < 200$ W m$^{-2}$, $200$ W m$^{-2} \leq F < 400$ W m$^{-2}$, $400$ W m$^{-2} \leq F < 600$ W m$^{-2}$, $600$ W m$^{-2} \leq F < 800$ W m$^{-2}$, and $F \geq 800$ W m$^{-2}$. The means and standard deviations (in W m$^{-2}$) of the AHIs (surface observations) in the abovementioned classes are $128.37 \pm 98.89$ (88.36 ± 53.93), $315.48 \pm 161.87$ (278.75 ± 55.45), $445.59 \pm 182.49$ (475.57 ± 56.32), $495.55 \pm 193.52$ (694.18 ± 57.32), and $628.26 \pm 192.11$ (934.75 ± 91.07), respectively. The corresponding slopes of the comparison plots (AHI/Surface) are 1.29, 1.12, 0.93, 0.71, and 0.67, respectively. These statistical estimates indicate the similar features of Figs. 6 and 10, including the underestimation of the calculated global flux at relatively large flux values. The global flux can be raised in optically thin clouds, suggesting that the CODs determined from AHI data are overestimated when the clouds are optically thin. Recall that MODIS also overestimates the CODs in optically thin clouds, as discussed in Subsections 4.1 and 4.2. This behavior typifies the CODs calculated from satellite sensors using reflected signals.

5.2 Using sky-radiometer data

a. Cloud optical depth

Similar to the left panels of Fig. 7, the left panels of Fig. 11 compare the CODs between the AHI and sky-radiometer data at the Chiba (upper), Hedo-misaki (middle), and Fukue-jima (lower) sites. As sufficiently many data samples are available for comparison, the frequency distributions are also shown. Table 4 summarizes the statistical analysis results of the COD comparisons. The mean COD values determined from the AHI data are smaller than the sky radiometer values (RMSD ~ 12). However, examining the left panel of Fig. 11 in detail, one finds both underestimated and overestimated AHI CODs. Similarly to Fig. 6, the AHI CODs are overestimated (underestimated) when the clouds are optically thin (thick). At all sites,
Sky-radiometer CODs below ~5 correspond to sharp, high COD values from AHI. Even when the sky-radiometer CODs are below 10, a considerable number of the AHI data samples exceed their corresponding sky-radiometer values. To clarify the quality of the comparison results in different ranges of COD values, the data for quantitative estimates was grouped into five categories of sky-radiometer CODs: COD < 10, 10 ≤ COD < 20, 20 ≤ COD < 30, 30 ≤ COD < 40, and COD > 40. As the comparison results in the left panel of Fig. 11 are site-independent, the data of all sites were merged for the quantitative estimates. The means and standard deviations of the AHI (sky radiometer) CODs in the five categories are 8.97 ± 7.34 (3.47 ± 1.93), 11.62 ± 8.20 (15.22 ± 2.86), 16.44 ± 11.19 (24.34 ± 2.82), 19.66 ± 11.61 (34.55 ± 2.90), and 23.28 ± 14.19 (47.58 ± 5.30), respectively, with corresponding slopes (AHI/Skyrad) of 1.95, 0.75, 0.67, 0.57, and 0.49, respectively. Those quantitative estimates suggest that the CODs estimated by AHI can be higher (lower) than the sky radiometer values when the clouds are optically thin (thick). Such overestimated AHI CODs can explain the underestimated calculations of the relatively high global fluxes in Fig. 10. The left panels of Fig. 11 strengthen our findings in Subsections 4.1 and 4.2, namely, that the satellite sensor-based CODs retrieved from reflected signals are overestimated for optically thin clouds.

b. Effective radius

We now compare the Re values estimated by the sky radiometer and AHI. The results are plotted in the right panels of Fig. 11. Qualitatively, the comparison results of the AHI and sky radiometer are consistent with those of the MODIS sensor and sky radiometer shown in the right panels of Fig. 6. The statistical analysis results of the AHI–radiometer comparison are summarized in Table 4. The RMSDs are ~9 µm at each site, slightly larger than in the Re comparisons between the sky radiometer and MODIS data (Table 3). On the other hand, the average Re values obtained by the AHI and sky radiometer are nearly equal, and the slopes (AHI/skyrad) are below 1 (Table 4). The AHI and sky radiometer differ not only by their wavelengths but also by their fields of view and viewing geometries. Consequently, the comparisons in the
right panel of Fig. 11 are poorly correlated. Importantly, 3.9-mm photons have a lower vertical penetration depth than 2.1-mm photons. This phenomenon explains why the Re values from the sky radiometer and AHI data differ more widely than the Re values from the sky radiometer and MODIS data. Moreover, the right panels of Fig. 11 reveal a considerable number of high Re values from the sky radiometer, especially at the Fuke-jima and Chiba sites. We speculate that the Re values estimated from the radiometer data were influenced by the aerosol effect, as discussed in Subsections 4.2 and 4.3.

Fig. 11. Correlative comparisons of COD (left panels) and Re (right panels) between the AHI (Himawari-8) and sky radiometer at the Chiba (upper), Hedo-misaki (middle), and Fukue-jima (lower) sites. For details, see text.
5.3 Factors responsible for inconsistent cloud properties between AHI and the sky radiometer

The inconsistent cloud properties derived from the AHI and sky radiometer data can be explained by the phenomena described in Subsection 4.3. We can elaborate the earlier discussion by exploiting the large data volume of AHI. In Subsection 4.3, we mentioned that the SZA can feasibly explain the different cloud properties obtained by the sky radiometer and the satellite. To consolidate this inference, we plot the SZA dependence of the COD difference between the sky radiometer and AHI in Fig. 12. The results are presented for each site. The mean and standard deviations in each 10° intervals of SZA are also presented. As observed for the MODIS comparison, the COD difference between the AHI and sky radiometer depends on the SZA. At each site, the differences and SZAs are negatively correlated. A clear negative correlation also exists for the mean values. Although the COD difference between the sky radiometer and AHI gradually decreases with increasing SZA, this trend is reversed at high SZA. The next important result in Subsection 4.3 was the negative relation between the COD and Re differences. Similar to Fig. 9, Fig. 13 plots the Re difference between the sky radiometer and AHI against the COD difference between these two instruments. The means and standard deviations at 10-COD intervals are also plotted. Again, the COD and Re differences are negatively related to both their means and instantaneous values. The possible reasons for these trends were discussed in Subsection 4.3.

6. Conclusions

The major findings of this study are summarized below:

1. The CODs determined from MODIS (TERRA and AQUA) and AHI (Himawari-8) observations were reasonably consistent. Both the AHI and MODIS results implied the frequent presence of optically

Table 4. Statistical analysis results of the COD and Re comparisons between the sky radiometer and AHI (Himawari-8) shown in Fig. 11.

| Site name | Parameter | Sky radiometer | AHI | Slope (Offset = 0) (AHI/Skyrad.) | RMSD | %count (AHI > Skyrad.) |
|-----------|-----------|----------------|-----|----------------------------------|------|------------------------|
| Chiba     | COD       | 13.5 ± 12.5    | 13.2 ± 10.3 | 0.70                            | 12.2 | 52                     |
|           | Re        | 12.1 ± 7.8     | 12.9 ± 6.0  | 0.78                            | 9.3  | 54                     |
| Hedo-misaki | COD      | 14.5 ± 13.8    | 12.5 ± 10.2 | 0.61                            | 13.2 | 48                     |
|           | Re        | 10.6 ± 7.0     | 12.5 ± 5.4  | 0.82                            | 9.1  | 64                     |
| Fukue-jima | COD       | 17.7 ± 13.3    | 12.2 ± 9.7  | 0.56                            | 13.6 | 33                     |
|           | Re        | 13.1 ± 7.8     | 12.9 ± 6.1  | 0.74                            | 9.5  | 51                     |

Fig. 12. COD difference between the sky radiometer and AHI (Himawari-8) versus SZA at the (a) Chiba, (b) Hedo-misaki, and (c) Fukue-jima sites. The means and standard deviations were determined by binning the data into 10° intervals of SZA.
thin clouds (COD < 5) over Japan.

2. The MODIS effective radius (Re) products were obtained at three absorbing wavelengths, 1.63, 2.13, and 3.79 µm. Among these products, the 3.79 µm MODIS product best matched the Re product of AHI at 3.9 µm. The remaining two MODIS Re products were larger than the AHI Re product, and especially deviated at large Re (> 20 µm). According to statistical analyses of the Re values from MODIS and AHI, the typical Re over Japan is approximately 8 µm.

3. The shortwave infrared (SWIR) absorbing wavelength must be properly chosen in cloud remote sensing, as it is important not only from the viewpoint of photon penetration cloud depth but also from the viewpoint of cloud-droplet size. For instance, the quantitative estimate of Re is more sensitive to large droplets, which generally reside in pristine clouds, than small droplets, which typify polluted clouds, for certain choices of the absorbing wavelength.

4. In comparisons with the surface-observed global fluxes and cloud properties retrieved from the zenith transmittances measured by the sky radiometer, both MODIS and AHI overestimated the CODs of optically thin clouds.

5. The COD differences between the sky radiometer, which uses transmitted signals, and the MODIS and AHI satellite sensors, which use reflected signals, clearly depend on the SZA.

6. The Re differences between the sky radiometer and satellite sensors are negatively correlated with the COD differences between the two types of instruments. We surmised that the accuracy/precision of the Re retrieval inherently influences the accuracy/precision of the COD retrieval (and vice versa) in transmittance-based sky radiometer results.

**Acknowledgments**

This research was supported by a Grant-in-Aid for Scientific Research (C) 17K05650 from Japan Society for the Promotion of Science (JSPS), JAXA research fund of specification number JX-PSPC-434817, “Virtual Laboratory for Diagnosing the Earth’s Climate System” program of MEXT, Japan, Grant-in-Aid for Scientific Research (B) 16H04046 from Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research (B) 17H02963 from Japan Society for the Promotion of Science (JSPS), and CREST/JST research fund of grant number JPMJCR15K4. Authors would like to express sincere thanks to Dr. Hideaki Takenaka (JAXA/EORC) for suggestions and constructive discussions.

**References**

Berk, A., L. S. Bernstein, G. P. Anderson, P. K. Acharya, D. C. Robertson, J. H. Chetwynd, and S. M. Adler-Golden, 1998: MODTRAN cloud and multiple scattering upgrades with application to AVIRIS. Remote Sens. Environ., 65, 367–375.

Bessho, K., K. Date, M. Hayashi, A. Ikeda, T. Imai, H. Inoue, Y. Kumagai, T. Miyakawa, H. Murata, T.
Ohno, A. Okuyama, R. Oyama, Y. Sasaki, Y. Shimazu, K. Shimoji, Y. Sumida, M. Suzuki, H. Taniguchi, H. Tsuchiyama, D. Uesawa, H. Yokota, and R. Yoshida, 2016: An introduction to Himawari-8/9–Japan’s new generation geostationary meteorological satellites. J. Meteor. Soc. Japan, 94, 151–183.

Chiu, J. C., A. Marshak, C.-H. Huang, T. Varnai, R. J. Hogan, D. M. Giles, B. N. Holben, E. J. O’Connor, Y. Knyazikhin, and W. J. Wiscombe, 2012: Cloud droplet size and liquid water path retrievals from zenith radiance measurements: Examples from the Atmospheric Radiation Measurement Program and the Aerosol Robotic Network. Atmos. Chem. Phys., 12, 19163–19208.

Dong, X., P. Minnis, G. G. Mace, W. L. Smith, Jr., M. Poeliot, R. T. Marchand, and A. D. Rapp, 2002: Comparison of stratus cloud properties deduced from surface, GOES, and aircraft data during the March 2000 ARM Cloud IOP. J. Atmos. Sci., 58, 3265–3284.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D. W. Fahey, J. Haywood, J. Lean, D. C. Lowe, G. Myhre, N. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, 2007: Changes in atmospheric constituents and in radiative forcing. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, USA, 131–217.

Grosvenor, D. P., and R. Wood, 2014: The effect of solar zenith angle on MODIS cloud optical and microphysical retrievals within marine liquid water clouds. Atmos. Chem. Phys., 14, 7291–7321.

Hayasaka, T., M. Kuji, and M. Tanaka, 1994: Air truth validation of cloud albedo estimated from NOAA advanced very high resolution radiometer data. J. Geophys. Res., 99, 18685–18693.

Iwabuchi, H., and T. Hayasaka, 2002: Effects of cloud horizontal inhomogeneity on the optical thickness retrieved from moderate-resolution satellite data. J. Atmos. Sci., 59, 2227–2242.

Kawamoto, K., T. Nakajima, and T. Y. Nakajima, 2001: A global determination of cloud microphysics with AVHRR remote sensing. J. Climate, 14, 2054–2068.

Kikuchi, N., T. Nakajima, H. Kumagai, H. Kuroiwa, A. Kamei, R. Nakamura, and T. Y. Nakajima, 2006: Cloud optical thickness and effective particle radius derived from transmitted solar radiation measurements: Comparison with cloud radar observations. J. Geophys. Res., 111, D07205, doi:10.1029/2005JD006363.

Khatri, P., and T. Takamura, 2009: An algorithm to screen cloud-affected data for sky radiometer data analysis. J. Meteor. Soc. Japan, 87, 189–204.

Khatri, P., T. Takamura, A. Shimizu, and N. Sugimoto, 2010: Spectral dependency of aerosol light-absorption over the East China sea region. SOLA, 6, 1–4.

Khatri, P., T. Takamura, A. Shimizu, and N. Sugimoto, 2014: Observation of low single scattering albedo of aerosols in the downwind of the East Asian desert and urban areas during the inflow of dust aerosols. J. Geophys. Res., 119, 787–802.

Kawamoto, K., T. Hayasaka, H. Iwabuchi, T. Takamura, H. Irie, T. Y. Nakajima, H. Letu, and Q. Kai, 2017: Cloud parameters from zenith transmittances measured by sky radiometer at the surface: Method development and satellite product validation. Proceedings of 19th EGU General Assembly, Vienna, Austria, EGU2017–6727.

King, M. D., S.-C. Tsay, S. E. Platnick, M. Wang, and K.-N. Liou, 1997: Cloud retrieval algorithms for MODIS: Optical thickness, effective particle radius, and thermodynamic phase. MODIS Algorithm Theoretical Basis Document, ATBD-MOD-05, MOD06-Cloud product, NASA, 78 pp.

King, N. J., K. N. Bower, J. Crosier, and I. Crawford, 2013: Evaluating MODIS cloud retrievals with in situ observations from VOCALS-REx. Atmos. Chem. Phys., 13, 191–209.

Kuji, M., T. Hayasaka, N. Kikuchi, T. Nakajima, and M. Tanaka, 2000: The retrieval of effective particle radius and liquid water path of low-level marine clouds from NOAA AVHRR data. J. Appl. Meteor., 39, 999–1016.

Liang, L., and L. Di Girolamo, 2013: A global analysis on the view-angle dependence of plane-parallel oceanic liquid water cloud optical thickness using data synergy from MISR and MODIS. J. Geophys. Res., 118, 2389–2403.

Loeb, N. G., and R. Davies, 1997: Angular dependence of observed reflectances: A comparison with plane parallel theory. J. Geophys. Res., 102, 6865–6881.

Loeb, N. G., and J. J. Coakley, Jr., 1998: Inference of marine stratus cloud optical depths from satellite measurements: Does 1D theory apply? J. Climate, 11, 215–233.

Nakajima, T., and M. Tanaka, 1986: Matrix formulation for the transfer of solar radiation in a plane-parallel scattering atmosphere. J. Quant. Spectrosc. Radiat. Transfer, 35, 13–21.

Nakajima, T., and M. Tanaka, 1988: Algorithms for radiative intensity calculations in moderately thick atmospheres using a truncation approximation. J. Quant. Spectrosc. Radiat. Transfer, 40, 51–69.

Nakajima, T., and M. D. King, 1990: Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part I: Theory. J. Atmos. Sci., 47, 1878–1893.

Nakajima, T. Y., and T. Nakajima, 1995: Wide-area determination of cloud microphysical properties from NOAA AVHRR measurement for FIRE and ASTEX regions. J. Atmos. Sci., 52, 4043–4059.

Nakajima, T. Y., A. Uchiyama, T. Takamura, N. Tsujioka, T. Takemura, and T. Nakajima, 2005: Comparisons of
warm cloud properties obtained from satellite, ground, and aircraft measurements during APEX intensive observation period in 2000 and 2001. *J. Meteor. Soc. Japan, 83*, 1085–1095.

Nakajima, T. Y., H. Matsunaga, and T. Nakajima, 2009: Near-global scale retrievals of the cloud optical and microphysical properties from the Midori-II GLI and AMSR data. *J. Remote Sens. Soc. Japan, 29*, 29–39.

Nakajima, T., K. Suzuki, and G. L. Stephens, 2010: Droplet growth in warm water clouds observed by the A-Train. Part I: Sensitivity analysis of the MODIS-derived cloud droplet sizes. *J. Atmos. Sci., 67*, 1884–1896.

Painemal, D., and P. Zuidema, 2011: Assessment of MODIS cloud effective radius and optical thickness retrievals over the Southeast Pacific with VOCALS-REx in situ measurements. *J. Geophys. Res., 116*, D24206, doi:10.1029/2011JD016155.

Platnick, S., 2000: Vertical photon transport in cloud remote sensing problems. *J. Geophys. Res., 105*, 22919–22935.

Platnick, S., M. D. King, K. G., Meyer, G. Wind, N. Amarasinghe, B. Marchant, G. T. Arnold, Z. Zhang, P. A. Hubanks, B. Ridgway, and J. Riedi, 2015: *MODIS cloud optical properties: User guide for the collection 6 Level-2 MOD06/MYD06 product and associated level-3 datasets, Version 1.0*. C6MOD96OPUserGuide, NASA, 141 pp.

Ricchiazzi, P., S. Yang, C. Gautier, and D. Sowle, 1998: SBDART: A research and teaching software tool for plane-parallel radiative transfer in the Earth’s atmosphere. *Bull. Amer. Meteor. Soc., 79*, 2101–2114.

Rodgers, C. D., 2000: *Inverse Methods for Atmospheric Sounding*. World Scientific, 238 pp.

Rosenfeld, D., M. O. Andreae, A. Asmi, M. Chin, G. de Leeuw, D. P. Donovan, R. Khan, S. Kinne, N. Kivekäs, M. Kulmala, W. Lau, K. S. Schmidt, T. Suni, T. Wagner, M. Wild, and J. Quass, 2014: Global observations of aerosol-cloud-precipitation-climate interactions. *Rev. Geophys., 52*, 750–808.

Seethala, C., and Á. Horváth, 2010: Global assessment of AMSR-E and MODIS cloud liquid water path retrievals in warm oceanic clouds. *J. Geophys. Res., 115*, D13202, doi:10.1029/2009JD012662.

Takamura, T., H. Takenaka, Y. Cui, T. Y. Nakajima, A. Higurashi, S. Fukuda, N. Kikuchi, T. Nakajima, I. Sano, and R. T. Pinker, 2009: Aerosol and cloud validation system based on SKYNET observations: Estimation of shortwave radiation budget using ADEOS-II/GLI data. *J. Remote Sens. Soc. Japan, 29*, 40–53.

Takenaka, H., T. Y. Nakajima, A. Higurashi, A. Higuchi, T. Takamura, R. T. Pinker, and T. Nakajima, 2011: Estimation of solar radiation using a neural network based on radiative transfer. *J. Geophys. Res., 116*, D08215, doi:10.1029/2009JD013337.