

Research Article

Assessment and Validation of i-Skyradiometer Retrievals Using Broadband Flux and MODIS Data

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Ground-based network of cloud measurements is presently limited and there exists uncertainty in the cloud microphysical parameters derived from ground-based measurements. Bias in the i-skyradiometer derived cloud optical depth (τ_c) and droplet effective radius (R_{eff}) and the importance of these parameters in the parameterization of clouds in climate models have made us intend to develop a possible method for improving these parameters. A new combination method, which uses zenith sky transmittance and surface radiation measurements, has been proposed in the present study to improve the retrievals. The i-skyradiometer derived parameters τ_c and R_{eff} have been provided as a first guess to a radiative transfer model (SBDART) and a new retrieval algorithm has been implemented to obtain the best combination of τ_c and R_{eff} having minimum bias (-0.09 and -2.5) between the simulated global and diffuse fluxes at the surface with the collocated surface radiation measurements. The new retrieval method has improved τ_c and R_{eff} values compared to those derived using the transmittance only method and are in good agreement with the MODIS satellite retrievals. The study therefore suggests a possible improvement of the i-skyradiometer derived cloud parameters using observed radiation fluxes and a radiative transfer model.

1. Introduction

The main challenges in numerical weather prediction using general circulation models are the representation of clouds and cloud related small-scale processes. Out of many cloud microphysical parameters, cloud optical depth (τ_c) and cloud droplet effective radius (R_{eff}) are the key parameters, which determine the radiative properties of clouds such as reflection, transmission, and absorption of solar radiation [1]. The effects of the cloud related subgrid scale processes are mainly parameterized in terms of these bulk model variables, R_{eff} and τ_c . However, the climate models poorly simulate these variables [2, 3], but a better representation of R_{eff} is essential to parameterize cloud microphysical process in numerical weather prediction and climate models [4, 5].

Sparse observations of cloud microphysical parameters using both ground-based instruments and remote sensing methods make it more difficult to improve the model simulations of these parameters. Even though satellite retrievals provide cloud microphysical properties globally, its coarse spatial and temporal resolution makes it insufficient to study the cloud microphysical properties in detail. Hence, accurate ground-based measurements of the cloud microphysical parameters on both local and global scales are important for validation of satellite retrievals, aerosol indirect effect estimates, and also for the improvement of model predictions [6].

Several methods have been used to retrieve cloud optical properties using ground-based and aircraft measurements. [7] derived τ_c from aircraft mounted solar radiometric measurements. The main drawback of this method

includes limited temporal coverage and increased expense. Retrievals of cloud optical depth and effective cloud fraction using ground-based measurements of zenith radiance have been reported by [8]. Total liquid water path measured by microwave radiometer has also been used to obtain the R_{eff} and this retrieval was applied to ARM (atmospheric radiation measurement) data to derive τ_c [9]. Recently, [10] reported that the τ_c retrieved from AERONET (AEROSOL ROBOTIC NETWORK) zenith radiance observations at 440 and 870 nm compared well with ARM MFRSR (multifilter rotating shadowband radiometer) observations.

The i-skyradiometer (POM-02) used in SKYNET is a unique instrument that can measure zenith transmittances at 1.6 and 2.2 μm wavelengths similar to those of MODIS (moderate resolution imaging spectroradiometer) and can derive τ_c and R_{eff} simultaneously. [11] compared R_{eff} retrieved from the i-skyradiometer channels 1.6 and 2.2 μm with R_{eff} retrieved from radar reflectivity alone, radar reflectivity constrained with microwave radiometer (MWR) column liquid water path (LWP), and MODIS satellite and reported a bias in the POM-02 retrievals of R_{eff} compared to the cloud radar and MODIS retrievals. Their study points towards the need for improvement of τ_c and R_{eff} derived from i-skyradiometer. The present study is therefore aimed at providing a new method to improve the retrievals of τ_c and R_{eff} from i-skyradiometer (POM-02) using a radiative transfer model in conjunction with collocated ground-based measurements of global and diffuse shortwave fluxes.

2. Data and Instrumentation

Observations of zenith sky transmittance and global and diffuse short-wave radiative fluxes carried out over two stations, (i) Chiba (35.7°N, 139.7°E), an urban site in Japan, and (ii) Cape Hedo (26.87°N, 128.25°E), a marine environment as part of the SKYNET (<http://atmos.cr.chiba-u.ac.jp/>) programme, [12] have been used in the present study. The study also utilizes measurements of cloud base and top heights and transmittance measurements. In this study, nonprecipitating water clouds with base below 2 km have been considered. For Chiba station, observations, during 4 days in April, May, and July of 2007 and, in Cape Hedo, 10 days during February, March, and April of 2008, have been considered for the analysis.

Shortwave pyranometer (made by Kipp and Zonen (model CM21)) has been used to measure global radiation over Chiba. It measures the global radiation in the spectral range 0.3 to 3.0 μm on a plane surface, which results from the direct and diffuse solar radiation incident from the hemisphere above, with a spectral sensitivity of 7 to 14 $\mu\text{V}/\text{W}/\text{m}^2$. Since the diffuse radiation was not available over Chiba during the analysis period, global solar radiation measurements were used in the study. A shaded Pyranometer (made by Kipp and Zonen (model CM21)) under a shading ball is used to measure the diffused radiation over Cape Hedo. Cloud base and cloud top heights were derived from frequency modulated continuous millimeter wave cloud radar (FMCW); a threshold radar reflectivity of -15 dBZ was used

for selection of nonprecipitating clouds. Detailed technical description of FMCW radar and its comparison with a monostatic 95 GHz cloud radar SPIDER can be obtained from [13].

τ_c and R_{eff} were retrieved from the ground-based measurements of the transmitted solar radiation using Sun/Sky scanning radiometer called i-skyradiometer (POM-02). The POM Sun/Sky radiometer is manufactured by Prede Co., Ltd., Tokyo, which comes under the Asia-Pacific SKYNET network for aerosol monitoring and satellite ground-truth around the world. It has a narrow field of view (1.2°) that makes measurements in several narrow spectral bands in the ultraviolet visible and near-infrared parts of the spectrum. POM includes a dedicated sun tracker, which can follow the sun for direct radiation measurements and can also make programmed scans across the sky at defined angles away from the sun. There exist two versions of the POM sky radiometer, POM-01 and POM-02. The POM-01 sky radiometer uses a single detector and a rotating filter wheel to measure radiation in seven narrow bands from 0.315 μm to 1.020 μm (0.315, 0.4, 0.5, 0.675, 0.87, 0.940, and 1.02 μm). It is connected to a computer running the operating software in order to make measurements and store data. The POM-02 has all the features of the POM-01, but with an extended wavelength range and has a second optical system with an indium gallium arsenide infrared detector. The filter has 11 wavebands, such that it can measure sky radiance and transmittance at 1.02, 1.6, and 2.2 μm . For simultaneous determination of τ_c and R_{eff} from transmittance measurements, it is necessary to adopt both absorbing and nonabsorbing wavelength. At water-absorbing wavelength, water droplet absorbs more solar radiation as particle increases in size compared to nonabsorbing wavelength, which absorbs less solar radiation. Among the three near-infrared wavelengths (1.02, 1.6 and 2.2 μm), 1.02 μm has been adopted as nonabsorbing wavelength, while the other two are water-absorbing wavelengths. Zenith sky cloud transmittance measurements at 1.02, 1.6 and 2.2 μm were used to derive τ_c and R_{eff} [1]. The retrieval procedure compares measurements of the cloud transmittance from the ground at water-absorbing and nonabsorbing wavelengths with look-up tables of the transmittance precomputed for plane-parallel, vertically homogeneous clouds using a radiative transfer code *r-star4b* [14]. Details of the retrieval algorithm are available in [1].

The i-skyradiometer is a radiance-based instrument, which works best for overcast conditions; hence overcast cases are considered in the study. The accurate determination of sky condition is desirable for identifying cloud type and cloud coverage. The whole sky imager (WSI) is a ground-based system, which enables temporal and spatial high-resolution sky observations. It provides real time processing and display of daytime sky conditions using common image processing algorithm, which estimate the cloud cover fraction. The WSI consists of a web camera, which looks down at a slowly rotating mirror that has a black strip to occlude the direct solar irradiance from the camera. The images of the sky are collected by a local computer and processed into percent cloud cover data. The digital image analysis was based on red to blue ratio, which is used to distinguish between



FIGURE 1: Whole sky images for April 4, 2008, over Cape Hedo, Japan.

clear and cloud pixels [15]. WSI data captured at every 10 minutes were used for selecting cloud cases. Figure 1 shows an example of cloud cases selected for April 4, 2008 at Cape Hedo, Japan. Further, satellite measurements are the only means of getting the global coverage of τ_c and R_{eff} . Hence, a comparison of the improved retrieval has been carried out with MODIS (Terra) level 2 products, with a spatial resolution of 1 km (MOD06). The swath data is averaged over an area of 4 km with experimental site as center and is compared with the improved retrieval.

3. Methodology

An assessment of the retrieval of cloud microphysical parameters from POM-02 and a new retrieval procedure has been proposed for improving the retrievals of τ_c and R_{eff} in conjunction with ground-based radiation measurements. A radiative transfer model, Santa Barbara discrete-ordinate atmospheric radiative transfer code (SBDART) [16], which simulates global and diffuse solar radiative fluxes at the surface and the collocated surface radiation measurements, has been used in the study [17–19]. A detailed description of SBDART uncertainty is available in [20–22]. The cloud optical parameters, τ_c and R_{eff} retrieved from i-skyradiometer were assumed as a first guess (retrieval from skyradiometer) for the SBDART model. In addition, cloud base and top heights derived from a Frequency modulated continuous wave millimeter wave cloud radar (MMCR), MODIS column integrated water vapor, TOMS ozone, and climatological values of green house gases such as CO_2 , CH_4 , and N_2O were also constrained as inputs to the model [16]. Integrated water vapor is an important constituent of the atmosphere, which has high absorptivity of solar radiation. Its effect on aerosol optical depth and surface irradiance should be considered if the data from different months are mixed together [23]. Due to the complexity in the distribution of green house gases across the globe and the lack of availability of these parameters, we used default values, which is independent of season and geographic location.

Global and diffuse fluxes simulated by SBDART model (global fluxes over Chiba and diffuse fluxes over Cape Hedo) are compared with observed fluxes for different combinations of τ_c and R_{eff} . The new retrieval algorithm has been introduced for obtaining different combinations of the cloud microphysical parameters. Considering the fact that there is an underestimation in R_{eff} , the initial value of R_{eff} has been incremented up to $8 \mu\text{m}$ at an interval of $1 \mu\text{m}$. Several studies have reported a threshold value of R_{eff} less than $12 \mu\text{m}$ for nonprecipitating clouds [24]. Since only nonprecipitating clouds have been considered in the study, R_{eff} greater than

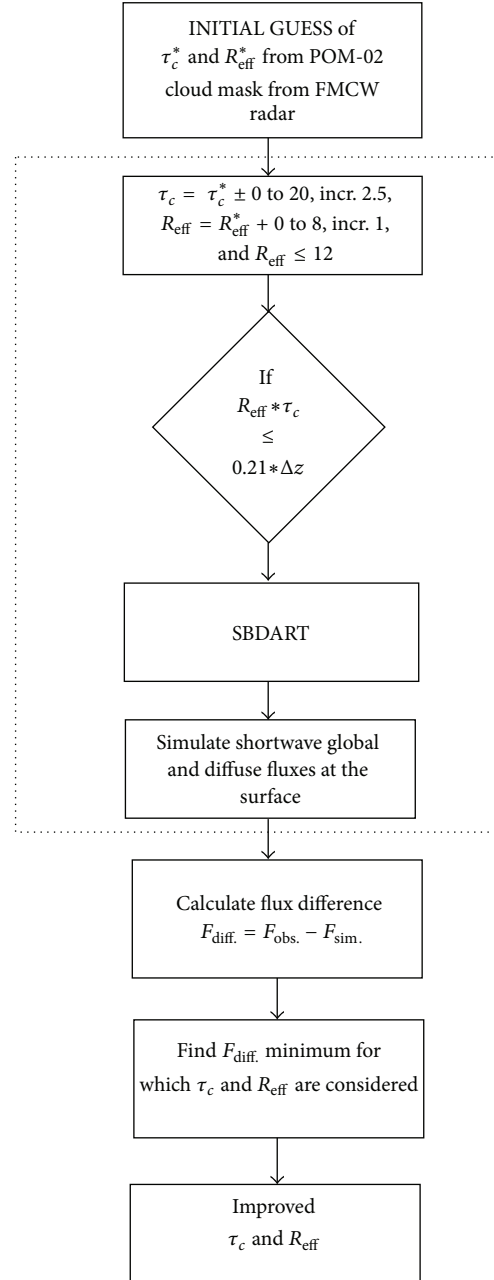


FIGURE 2: Flow chart of new retrieval algorithm for improved τ_c and R_{eff} .

$12 \mu\text{m}$ is ignored during each step procedure [25]. The R_{eff} computation was performed only in forward direction as the R_{eff} values obtained from POM-02 (initial guess) were mostly found to be in the lower range; also the lower limit for R_{eff} in SBDART model is $2 \mu\text{m}$. However, forward and backward step have been performed for τ_c up to 20 at an interval of 2.5. Earlier studies reveal that R_{eff} and τ_c are related through the equation $\tau_c = 1.5 * \text{LWP} / \rho_l * R_{\text{eff}}$ [26], where ρ_l is density of liquid water and LWC can be obtained through the equation $\text{LWP} = 0.14 * \Delta z$ [27], where Δz is cloud depth. Hence, R_{eff} and τ_c computed after each step are checked for whether

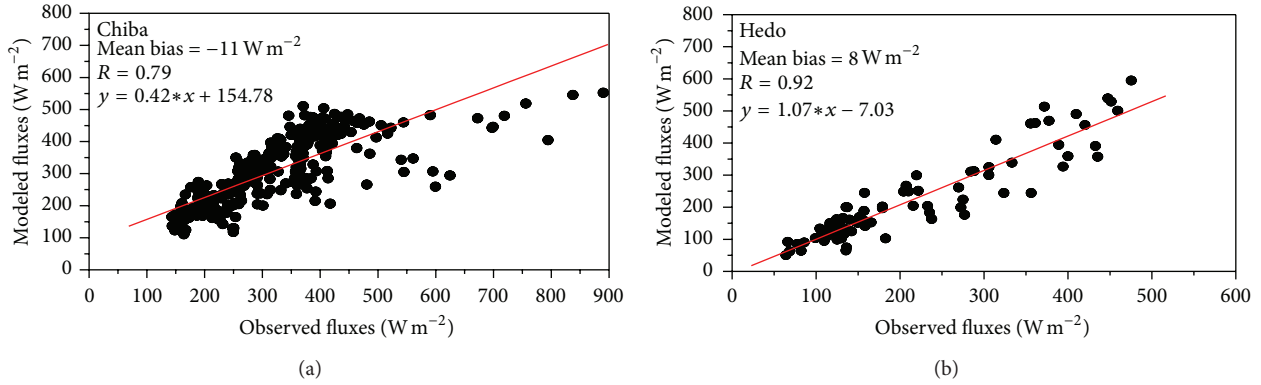


FIGURE 3: Comparison of observed and model simulated fluxes using initial guess of τ_c and R_{eff} over (a) Chiba (global fluxes) and (b) Hedo (diffuse fluxes).

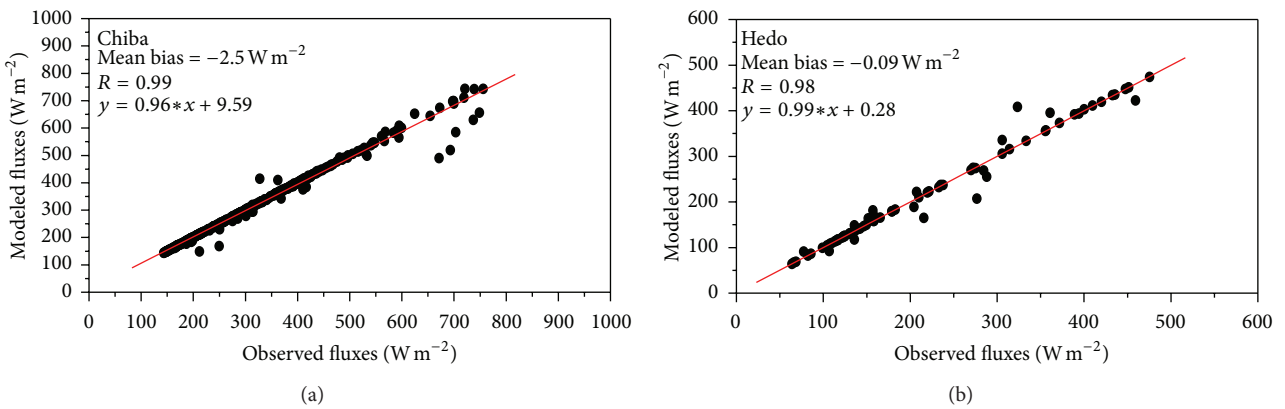


FIGURE 4: Comparison of observed and model simulated fluxes using the best combinations of τ_c and R_{eff} over (a) Chiba (global fluxes) and (b) Hedo (diffuse fluxes).

the parameters hold the relationship, $\tau_c * R_{\text{eff}} \leq 0.21 * \Delta z$, obtained from the above equations provided by [26, 27]. After each iteration, SBDART simulated short-wave global and diffuse sky fluxes at the surface using different combinations of τ_c and R_{eff} that are compared with the observed fluxes and the best combination of τ_c and R_{eff} , which simulates the fluxes having the least bias with observations, were selected as the most accurate retrievals. A flow chart illustrating the new retrieval procedure using the radiative transfer model, SBDART, is shown in Figure 2.

4. Results and Discussions

Initial retrievals of τ_c and R_{eff} from i-skyradiometer using [1] have been used as first guess in SBDART to simulate shortwave fluxes (diffuse and global) at the surface and the comparison of SBDART simulated global (over Chiba) and diffuse fluxes (over Cape Hedo) with that of observation is presented in Figure 3. It can be noted from the figure that there is large difference between the observed and model derived initial fluxes (from initial guess values) over both regions. The mean bias in the model simulated fluxes was found to be -11 W m^{-2} over Chiba and 8 W m^{-2} over Cape Hedo while the correlation coefficients between the observed

and model simulated initial fluxes were obtained as 0.79 and 0.92 over Chiba and Cape Hedo, respectively. The large bias indicates that there is an uncertainty in retrieved products of τ_c and R_{eff} .

In the improved retrieval algorithm, the i-skyradiometer derived cloud optical properties (τ_c and R_{eff}) were used as the first guess for SBDART model (Figure 2) and the combination of τ_c and R_{eff} having the least bias in simulated fluxes has been estimated as the best combination. The fluxes simulated by the radiative transfer model using the best estimates of τ_c and R_{eff} over Chiba and Cape Hedo have shown good agreement with observation (Figure 4). The improved retrieval algorithm has made a reduction in mean bias of simulated flux over Chiba from -11 to -2.5 W m^{-2} (global) and also over Cape Hedo from 8 W m^{-2} to -0.09 W m^{-2} (diffuse). The correlation coefficients between the improved and observed fluxes have been increased to 0.99 and 0.98 over Chiba and Cape Hedo, respectively. The best estimated values of τ_c and R_{eff} from the new retrieval method were found to be improved as compared to those of the transmittance only retrievals obtained from POM-02. A better comparison of the improved retrievals of τ_c and R_{eff} with that of initial retrievals can be obtained from Figures 5 and 6. The R_{eff} retrieval from transmittance method [1] is found to be lower as compared

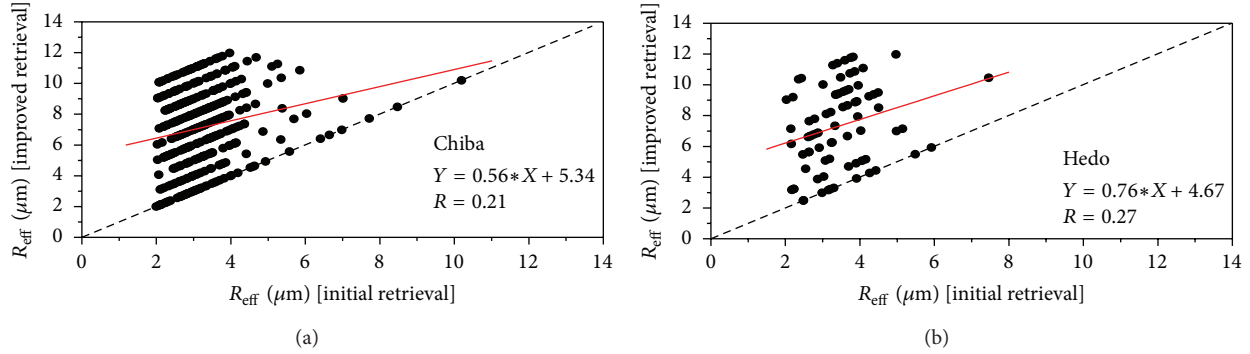


FIGURE 5: Initial and improved retrievals of cloud droplet effective radius over (a) Chiba and (b) Cape Hedo.

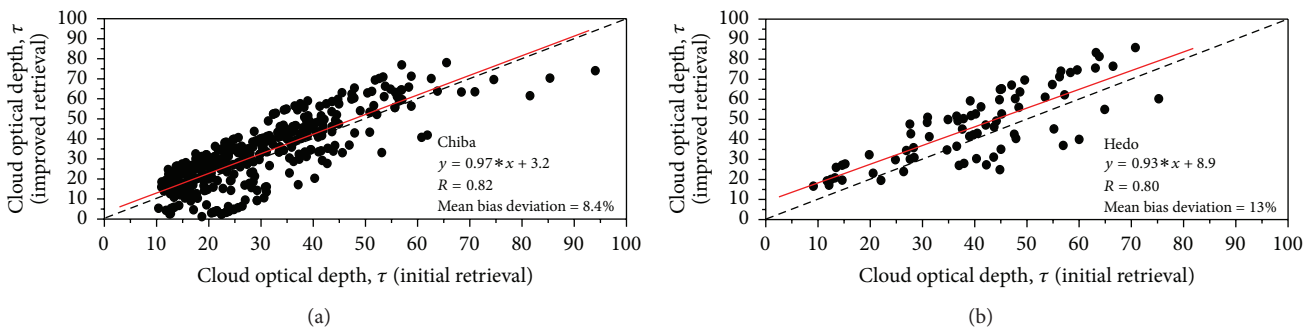


FIGURE 6: Initial and improved retrievals of cloud optical depth over (a) Chiba and (b) Cape Hedo.

to improved retrievals (Figure 5). The increase in improved retrievals of R_{eff} is almost about double, which is in good agreement with radar and satellite retrievals reported by [11]. The improved retrievals for τ_c values have shown an increase of 8.4% over Cape Hedo and 13% over Chiba (Figure 6).

The retrievals of R_{eff} and τ_c from both methods are compared with satellite retrievals and four cases (two from Chiba site (11 April and 18 May, 2007) and two from Cape Hedo site (28 February and 10 April, 2008)) are presented in Figures 7 and 8, respectively. The R_{eff} derived using [1] method has shown values, between 2 and 4 μm , much lower than the MODIS derived R_{eff} , between 6 and 11 μm . The improved retrieval of R_{eff} has shown considerable increase from the initial values [1] in all the cases over both stations, with a magnitude between 3 and 12 μm (Figure 7). In all of the four days, the satellite had overpass during morning hours between 10:30 and 11:50 over the sites and improved retrievals have shown good agreement with the MODIS derived cloud effective radius during those hours. Comparison of the improved retrieval of τ_c has been carried out with the initial and satellite derived τ_c and is provided in Figure 8. In all of the four cases, the values of τ_c from improved retrieval method are found to be comparable with those derived from MODIS. Over Chiba station, the MODIS derived τ_c is found to be 20 on May 18, 2007. But the initial value derived by [1] method is much lower (14.5) and new retrieval technique has improved τ_c to 17.25, more close to the MODIS derived value. However, on April 11, 2007, τ_c derived using the three

methods was comparable, the MODIS observation and the τ_c derived using [1] method were in good agreement, and the improved algorithm has not made any considerable change in the initial value. The new retrieval method has improved τ_c over Cape Hedo station also. On April 10, 2008, the MODIS derived τ_c over Cape Hedo was 19 and the initial value was 10. The new retrieval method has made an increase in τ_c to 20, which is closer to MODIS observation. Even though the new retrieval method produced considerable improvements in R_{eff} on February 28, 2008, the method could not improve τ_c considerably (Figure 8).

Further, sensitivity of the retrieved cloud microphysical parameters to the errors in observed fluxes used for improving the initial guess has also been carried out for understanding the robustness of the retrieved parameters. A sensitivity experiment has been conducted by introducing an error of 5% in the observed flux and found that it can induce an error of 2.5 units in the retrieved τ_c (with constant R_{eff}), whereas in R_{eff} an error of 2.0 μm can occur (with constant τ_c). The error associated with the assumption of vertical inhomogeneity in the retrieval of τ_c using Kikuchi et al. [1] method is within 2% and it is argued that the cloud optical depth could be derived accurately from the measurements of transmittance [1]. Our analysis suggests that the POM-02 derived τ_c and R_{eff} can be improved by utilizing collocated radiation measurements. The methodology proposed here for finding the best combination of τ_c and R_{eff} using POM-02 retrievals as first guess and radiative fluxes as reference can

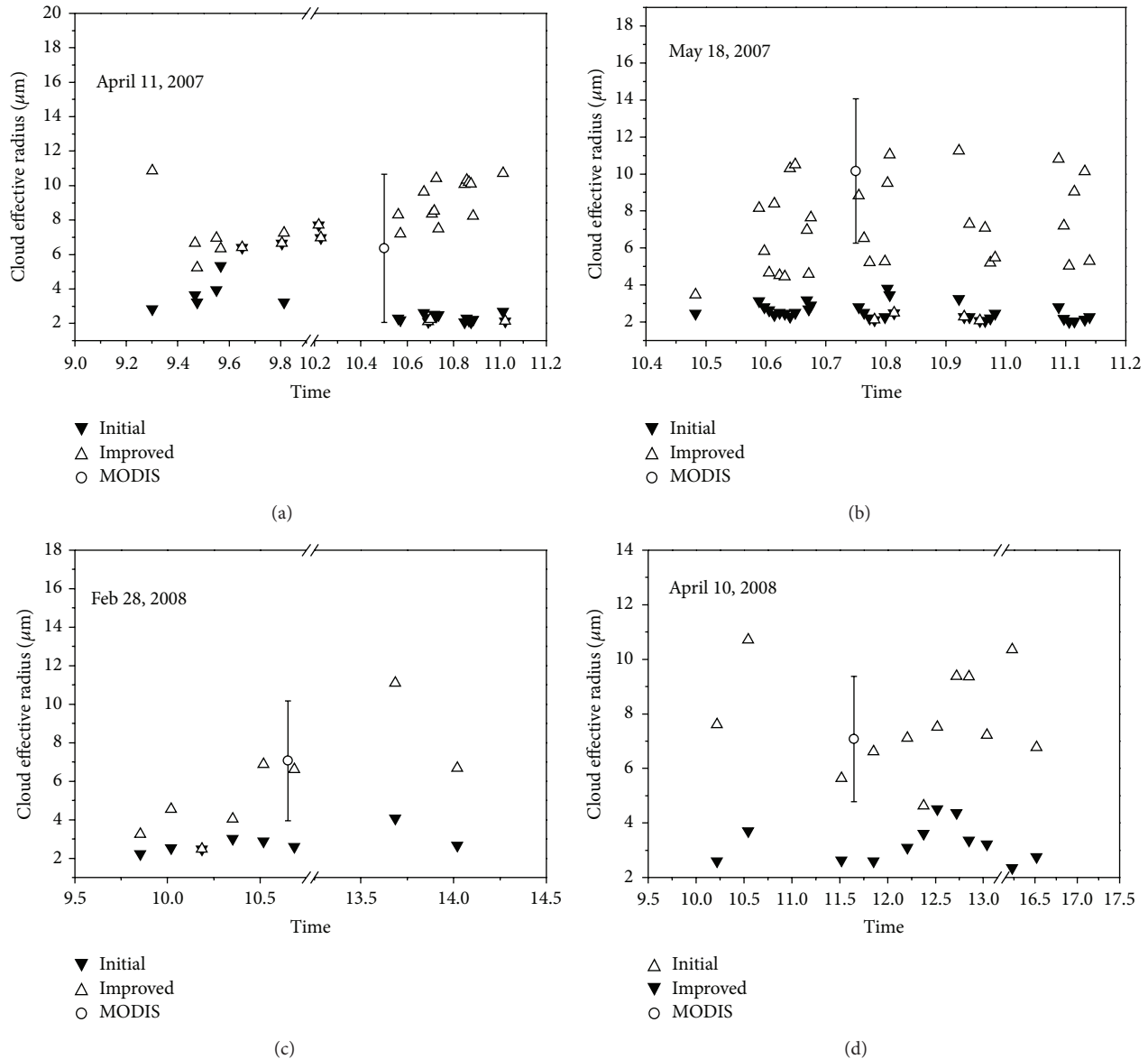


FIGURE 7: Initial, improved and satellite derived cloud droplet effective radius for Chiba (11 April and 18 May, 2007) and Cape Hedo (28 February and 10 April, 2008).

be used for improving the POM-02 retrievals, as accurate radiative flux observations are available in SKYNET sites.

5. Summary

Clouds remain the greatest source of uncertainty in global climate change research. Limited observations using ground-based instruments and the coarse resolution of satellite measurements add more uncertainty in the estimation and prediction of cloud microphysical parameters. Bias in the cloud parameters, τ_c and R_{eff} , derived using i-skyradiator (a unique instrument that can measure zenith sky transmittances at 1.6 and 2.2 μm wavelengths and can derive τ_c and R_{eff} simultaneously) made it important to provide a technique for improving these parameters. A new combination method,

which uses zenith sky transmittance and surface radiation (global and diffuse) measurements, has been proposed to improve the retrievals of τ_c and R_{eff} . The method uses a radiative transfer model (SBDART) and the i-skyradiator derived τ_c and R_{eff} have been provided as first guess. Further, a new retrieval method has been implemented to obtain the best combination of τ_c and R_{eff} having less bias between the simulated global and diffuse fluxes at the surface with the collocated surface radiation measurements.

The τ_c and R_{eff} derived using the new retrieval method have shown considerable improvement compared to the parameters derived using [1] method and the instantaneous values are seen in good agreement with the MODIS satellite observations. The new retrieval of R_{eff} has shown an increase in the magnitude of R_{eff} with values between 3 and 12 μm ,

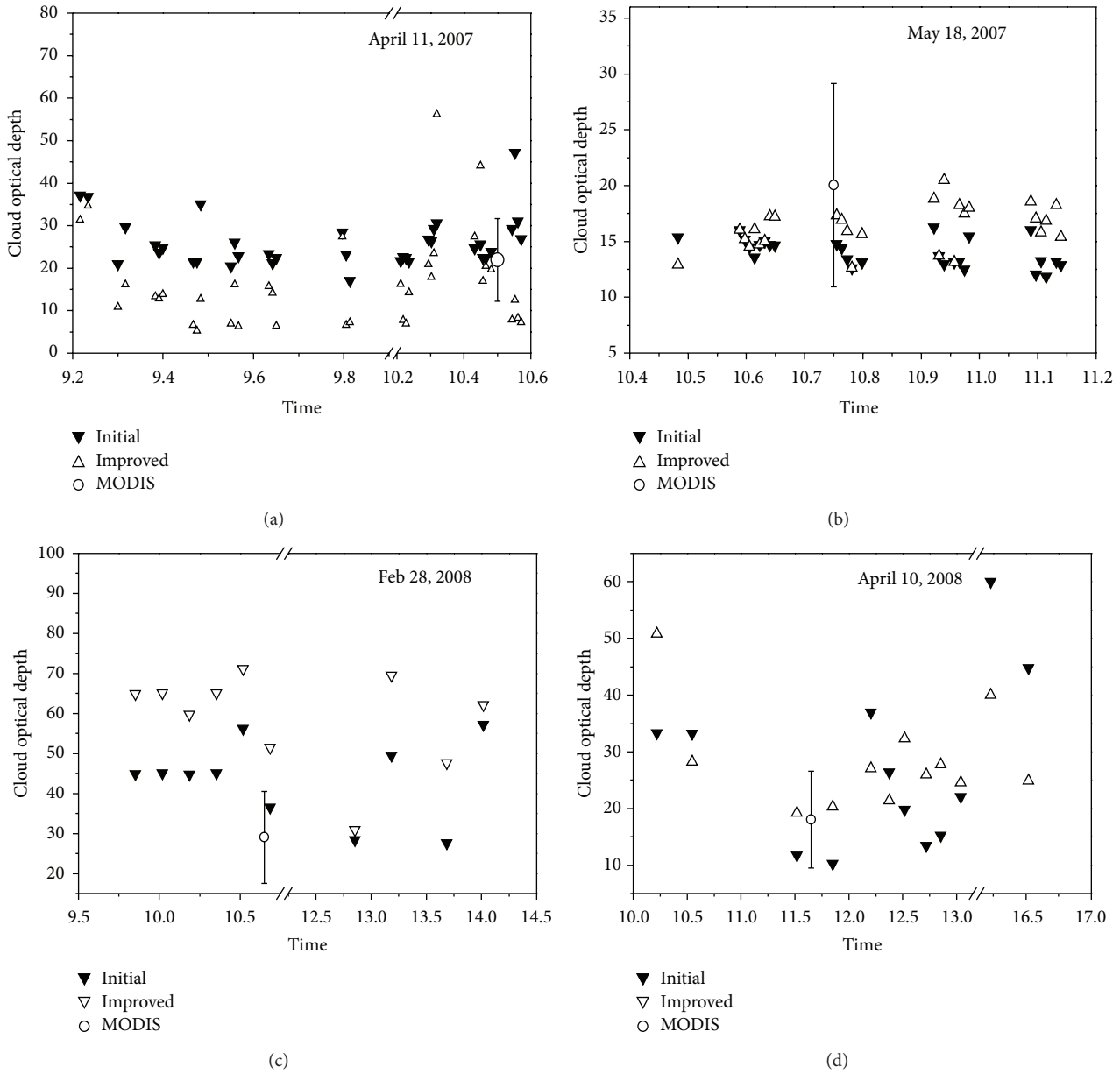


FIGURE 8: Initial, improved and satellite derived cloud optical depth for Chiba (11 April and 18 May, 2007) and cape Hedo (28 February and 10 April, 2008).

which is more closer to the MODIS derived R_{eff} between 6 and 11 μm , while the R_{eff} derived using [1] method is in the range of 2 to 4 μm . The MODIS satellite observed τ_c lies between 15 and 30 and the τ_c derived using the improved retrieval method has been found to be closer to MODIS observations compared to that obtained from [1] method. Our study therefore suggests that the POM-02 derived τ_c and R_{eff} can be improved. The retrieval method suggests that POM-02 derived τ_c and R_{eff} can be improved by utilizing the collocated radiation measurements. Indeed, this result may also be used to improve the retrieval algorithm of skyradiometer for more robust cloud retrievals and hence, better retrievals of cloud parameters especially in SKYNET; an

Asian surface network for aerosol-radiation measurements can be achieved.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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