©2009 RSSJ Journal of The Remote Sensing Society of Japan Vol. 29 No. 2 (2009) pp. 392-397

Original Paper

Cloud Optical Thickness Estimation from GMS-5/SVISSR

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Abstract

To assess environmental change at global scale, accurate estimates of surface radiative fluxes at high temporal resolution are needed. An algorithm for the estimation of the shortwave radiation budget from the GMS-5/SVISSR data has been developed. In this study, a component of this algorithm used for deriving COT is evaluated. The COT retrieved from the GMS-5/SVISSR is compared with similar parameters derived from Terra/MODIS during APEX-E2. It was found that the assumption on the effective radius of clouds as well as the sensor quantization noise can introduce a large error in COT derived from GMS-5/SVISSR. In the present analysis we show that the errors in COT of area-level clouds in the aggregate due to unknown effective radius can be reduced progressively as compared to errors of pixel-level ones.

Keywords : estimation of cloud optical properties ; cloud optical thickness ; cloud droplet effective radius ; quantization noise of satellite sensor

1. Introduction

Clouds play an important role in the radiation balance and energy balance of the Earth surface and at the top of the atmosphere. In order to estimate the impact of clouds on the global climate, it is necessary to estimate the physical properties of clouds at high spatial and temporal resolutions. Recent progress in General Circulation Models (GCM) led to more precise high resolution representation of physical processes. The cloud has a big influence in the radiation budget of the Earth[1)2)]. The effect is connected complexly with various climatic elements. Wetherald and Manabe[3)] indicated the cloud feedback process using two models. The two-model comparison (with and without feedback) shows the importance of cloud feedback process in Earth system. Tsushima and Manabe[4)] discussed the influence of cloud feedback process for global mean surface temperature. The cloud feedback in GCM has a strong sensitivity for the global mean surface temperature. However, it was seen to be negligible in the observational analysis using ERBE. Cloud has the big uncertainty in Earth's energy budget, it perturbs the long term analysis of climate change. To evaluate such models there is a need in corresponding satellite data at similar time and space resolutions for the better understanding the Earth system. The accuracy of the physical parameters, especially instantaneous data, derived from satellite needs to be known and error estimation is necessary. In the present study, an error analysis will be performed for the estimation of Cloud Optical Thickness (COT) using hourly Geostationary Meteorological Satellite - 5/Stretched Visible and Infrared Spin-Scan Radiometer (GMS-5/SVISSR, hereafter SVISSR) data. Such information can be used to produce high temporal radiation budgets. However, SVISSR lacks a channel for water droplet absorption at 3.7μm, which is useful for estimating the effective radius of clouds. The effect of this disadvantage will be analyzed by comparison with Terra/MODerate resolution Imaging Spectro-radiometer (Terra/MODIS, hereafter MODIS) during Asian Atmospheric Particle Environment change EXperiment (APEX) using co-located data[5)]. APEX was a comprehensive project aimed at better understanding of the relationship of physical and chemical characteristics of aerosols, clouds and radiation in the atmosphere. Used were simultaneous observations from satellites, aircraft and ground. Terra/MODIS has 3.7μm channel and can estimate cloud droplet effective radius. It enables the estimation of the cloud optical characteristic of highly accurate using multi-channel method. The COT derived from SVISSR was evaluated by Terra/MODIS. Dim et al.[6)] discussed based on cloud top three dimensional structure for COT difference of both satellites

(Received January 29, 2008. Accepted November 25, 2008)

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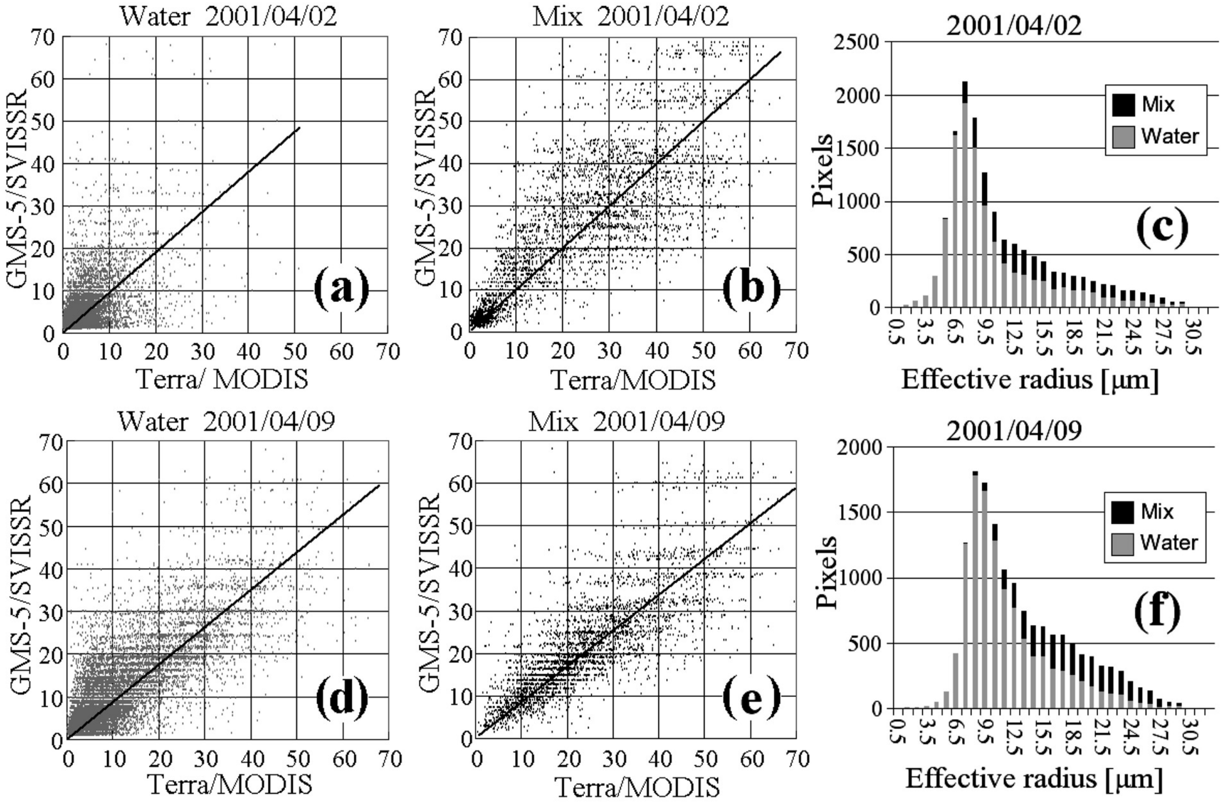

Fig. 1 Comparison of cloud optical thickness from GMS-5/SVISSR and Terra/MODIS. (a), (d) : water clouds [no dimension] ; (b), (e) : mixed phase [no dimension] ; (c), (f) : frequency of cloud droplet effective radius from MODIS [μm].

(MODIS and SVISSR). In this study, we discuss quantitatively the influence of the cloud optical characteristics based on cloud phase using the radiative transfer simulation. The estimation accuracy of cloud parameters depends not only on an effective radius but also the quantization noise of SVISSR because of its coarse resolution (6bit : $2^6=64$ steps) of the A/D converter on-board. The quantization of the satellite was also considered in this study.

2. Estimation and validation of cloud optical thickness

SVISSR has four channels : visible broadband channel in 0.55 to 0.90μm, 6.7μm water vapor channel and split window channels at 10 to 12μm[7]. Initially, COT has been estimated from SVISSR data under the assumption that the effective radius of cloud particle is 10μm. Results were compared to those from MODIS during the APEX intensive field campaign over the East China Sea. In the present study, the satellite data are analyzed for a period of APEX-E2 (April 2001) over a limited region of East China Sea (125°E-135°E, 25°N-35°N). The algorithm for COT estimation is the same for both satellite systems with the exception of the assumption on cloud droplet effective radius for the SVISSR-derived COT. The retrieval algorithm has been developed based on solar reflection method, i.e., the Comprehensive Analysis Program for Cloud Optical Measurement (CAPCOM)[8) 9)]. Clouds are assumed to be plane-parallel and single layered, based on the radiative transfer code RSTAR4b[10) 11)]. This algorithm is also adopted as one of the standard algorithms in ADvanced Earth Observing Satellite-II/GLobal Imager (ADEOS-II/GLI) standard products[12)]. The sensitivities of the SVISSR sensors are adjusted using ISCCP calibration coefficients[13)] with the initial (pre-launch) response functions of each channel because the SVISSR has no information on sensor degradation or on-board calibration.

In order to evaluate the validity of the COT estimated from SVISSR during the APEX-E2, we use the COT derived from MODIS as retrieved by the CAPCOM algorithm (not the standard product as provided by NASA). Both retrieved COTs are consistent in the analytical procedure, except that the effective radius of SVISSR is assumed to be 10μm based on ISCCP[14)]. All the cloudy days (April 2, 4, 8, 9, 14, 23, 25, 27, and 30) during APEX-E2 period are analyzed ; the time difference for the two satellite observations is less than 15 minutes.

Figure 1 shows a comparison of COT and r_{eff} for a thin (April 2, 2001) and thick cloud (April 9, 2001) cases. Thin cirrus clouds are rejected by using split window analysis.

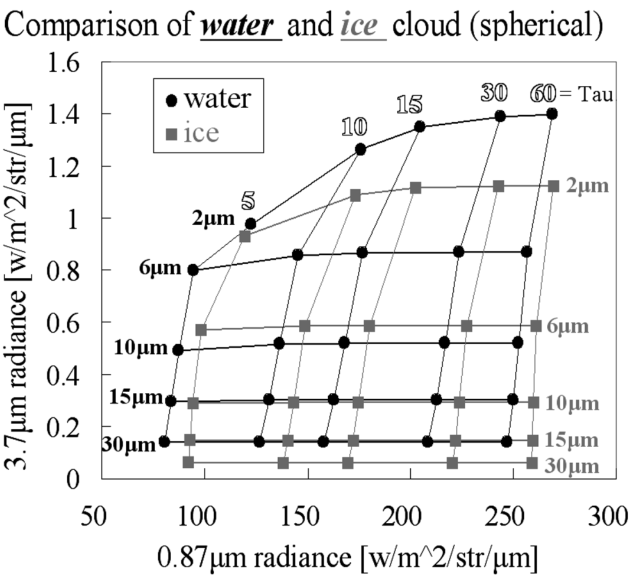

Fig. 2 Comparison of radiative characteristics of water and ice clouds (spherical shape) calculated with the radiative transfer code RSTAR4b and assumed 3.7μm and 0.87μm channels (delta functions). Solar zenith angle=25°, Satellite zenith angle=45°, Relative azimuthal angle=90°. Atmospheric model : US-Standard Atmosphere. Surface albedo : 0.1 (Lambertian).

Other clouds are classified into two types according to the brightness temperature. Water cloud : higher than 273K ; mixed phase cloud : 250K to 273K. Super-cooled droplet clouds in the mixed phase are discussed also. Figures 1a and 1d show a scatter plot of COT derived from both satellites on April 2 (a) and April 9 (d), respectively. A common feature in the figures is that water clouds are concentrated in a relatively narrow COT region as compared to mixed phase clouds (Figs.1b and 1e). The regression lines are similar between both cloud types. On April 2, 2001 the slopes of the regression are 0.94 (r=0.513) and 0.99 (r=0.763) for water and mixed-phase cloud cases, respectively, and 0.87 (r=0.783) and 0.84 (r=0.785) on April 9, 2001. One of the major reasons for the difference in the slopes is related to the assumption on r_{eff} in the SVISSR analysis. Figures 1c and 1f show a frequency histogram of the effective radius from MODIS on April 2 (c) and 9 (f), which shows that the water cloud has a peak of r_{eff} in the range of about 7 to 8μm. The histograms for both days have a similar pattern in water cloud cases, but the mode radius of April 9 shifts to larger values. The effect on the retrieval of the COT is discussed in the following sections.

The frequency histograms of r_{eff} for mixed phase cases, shown in Figs.1c and 1f, are scattered in the larger radius region when compared with water cloud cases. Figure 2 shows a diagram to infer COT and r_{eff} from the satellite data using a visible (0.87μm) and near-infrared (3.7μm) channel for water and ice cloud particle (assuming spherical particle). The diagram in the figure provides a quantitative error estimate as caused by particle radius and droplet phase. An assumption of 10μm for SVISSR analysis produces overestimate in COT for smaller particles than the assumed case and vice versa. The phase of the particles also has a significant impact on the quantitative estimation of COT and r_{eff}. These might be overestimated when an ice particle is analyzed using the water cloud algorithm. Figure 1 shows that the differences between both satellite data in the mixed clouds are not so big which may suggest that the mixed cloud consists of many super-cooled particles.

3. Ambiguity in COT retrieval due to assumed effective radius

The assumed effective radius in the estimation of COT introduces errors, as described in the previous section. The quantitative estimate of error in COT due to this effect needs to be known. A numerical simulation has been performed to estimate this error using the radiative transfer code (RSTAR 4b) with the response function (pre-launch) of the SVISSR visible sensor. The COT retrieved from the simulated data by the present algorithm is compared with the initial COT for several kinds of effective radii ranging from 2 to 30μm.

The function of the nominal reflectance (smoothed) of SVISSR for COT is shown in Figure 3, it is quantized by the quadratic relation of the SVISSR A/D converter. Figure 4 depicts the difference/error patterns compared with a case of 10μm-radius. It varies from about −25% to 150% depending on r_{eff}, ranging from 2μm to 30μm. There is a jagged change in each different r_{eff}, which is due to quantization noise. This error produces non-negligible effect on the COT estimation, but may diminish with time- and space-averaging. Another feature shows a non-linear effect differing from a referred r_{eff}, 10μm. The radius effect is much more severe, especially for particles smaller than 10μm, compared with the error for those larger than 10μm. The difference of the efficiency is due to an optical effect of Mie scattering.

In the above, the error caused by different effective radii for each pixel was discussed. The error should also be estimated for an image scene statistically in order to evaluate the effect on the radiation budget with a combination of frequency histogram of r_{eff}. The mode peak radius of r_{eff} in the histogram, as shown in Figure 1 is from 7.5 to 8.5μm, of which radius are smaller than the size assumed for SVISSR-analysis (Table 1). The target area-average r_{eff}, however, is 9.9μm for April 2 and 11.5μm for April 9, respectively, close to the initial assumption. In both cases, if the assumed r_{eff} is appropriate, the expected error of COT for the targeted area gets

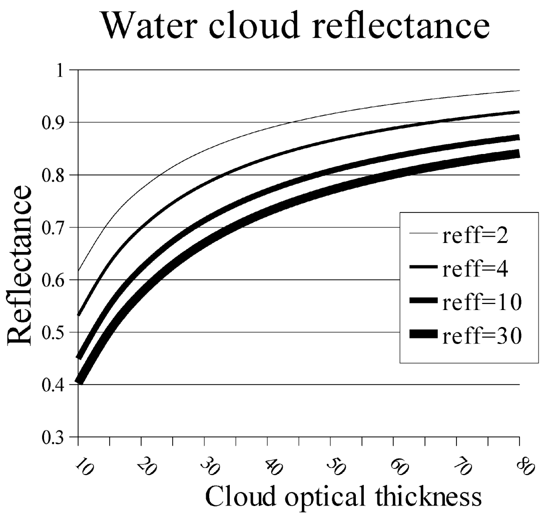

Fig. 3 Water cloud reflectance calculated by RSTAR4b : Solar zenith angle=25°, Satellite zenith angle=37°, Relative azimuthal angle=174°, Atmosphere model : US-Standard Atmosphere, Surface albedo : 0.1 (Lambertian).
The kind of lines indicates the difference of a cloud droplet effective radius “peff” [μm].

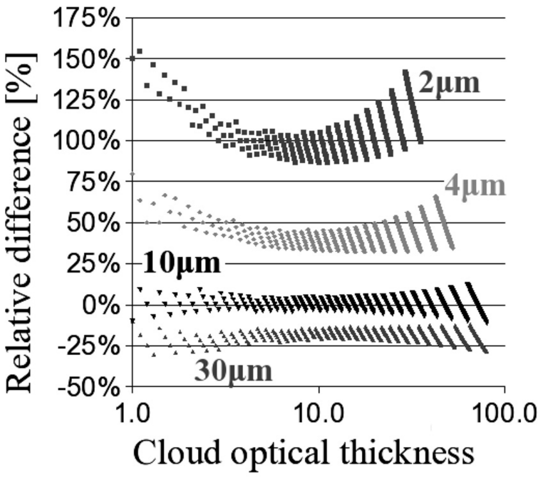

Fig. 4 Relative difference of cloud optical thickness at cloud droplet effective radius of 2μm, 4μm, 10 μm, 30μm. Solar zenith angle=25°, Satellite zenith angle=37466, Relative azimuthal angle=174466, Atmosphere model : US-Standard Atmosphere. Surface albedo : 0.1 (Lambertian).

Table 1. Cloud droplet effective radius on SVISSR (assumed) and MODIS (observation).
Peak : Peak point of effective radius in histogram of study area (25–35°N, 125–135°E).
Ave : Averaged value of all cloud droplet effective radii at study area (25–35°N, 125–135°E).

	SVISSR (assumed)	**MODIS (April 02)**	**MODIS (April 09)**
Peak	10.0 µm	7.5 µm	8.5 µm
Ave	10.0 µm	9.9 µm	11.5 µm

closer to about ±15%. Ambiguity due to the quantization is also dependent on COT. The histogram derived from MODIS data is shown in Figure 5 for both days. The peak of COT is around 3 to 5, and the relative error can be estimated from the figure depending on COT and r_{eff} (Fig.1c and 1f). Because the peak of the radius reff is enough sharp (Fig.1cf) for the error (Fig.4), the aggregate error in the target area will become smaller than ±15%.

As a reference, the following equation expresses the integrated influence of individual pixel error for both days :

$$EE=\frac{\sum Err(r_i, \tau_j)N_{ij}}{\sum N_{ij}}$$

where $Err(r_i,\tau_j)\%$ is the error corresponding to each r_{eff} (i) and τ_j (cloud optical thickness), and N_{ij} a number of pixels having its r_i and τ_j. The values of weighted mean EE are +6.1% and −1.5% for April 2 and April 9, respectively. In the estimation of the radiation budget and the analysis of long term change, it is important to reduce the aggregate error. The aggregate error will be able to be improved by setting the assumed effective radius to mode peak (Fig.1cf). The EE in both cases is consistent with the previous discussion, but for more quantitative estimates, other factors such as the three-dimensional effect of clouds and sensor calibration should be considered in the COT retrieval.

In this study, the analysis for mixed phased clouds is appropriate for the water cloud algorithm. However non-spherical effect of ice crystal was not discussed in this study. It may be impossible to disregard it under condition with rich ice crystals. In the future, the non-spherical effect in the analysis of mixed phase cloud should be incorporated.

4. Summary

COT is estimated from the GMS-5/SVISSR data during the APEX-E2 experiments in the Asian region. It was compared with Terra/MODIS. The largest error in the SVISSR-derived COT might be introduced by the assumption on cloud droplet size as well as due to quantization errors. The error caused by SVISSR quantization is about ±5% to ±15% as functions of COT and r_{eff}. It should be noted that in the SVISSR analysis the ambiguity in COT is increasing with higher cloud reflectance, namely, thicker clouds. The error in COT reaches about +150% and −25% for 2 and 30μm of effective radius, respectively when the effective radius in SVISSR analysis is

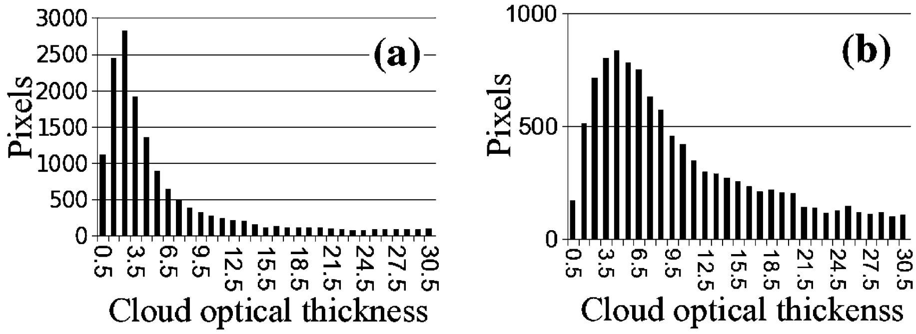

Fig. 5 Histogram of cloud optical thickness : (a) April 2, 2001 (b) April 9, 2001.
Location : 25–35°N,125–135°E.

assumed to be 10μm. The estimated aggregate error EE for SVISSR based on MODIS data was smaller than them. It has decreased because the r_{eff} value close to 10μm was predominant (mode peak is 7.5μm and 8.5μm). Therefore the aggregate error will be able to reduce by setting the assumed effective radius to most predominant mode peak.

Improvement in accuracy can be achieved if the radius mode peak is close to the assumed size. In order to estimate an accurate COT using SVISSR data, it might be better to classify first the cloud type for better guess of a suitable r_{eff}.

Acknowledgement

We would like to express our sincere gratitude to Prof. R. T. Pinker of University of Maryland.
Her valuable comments and advice encouraged us and improved this manuscript.

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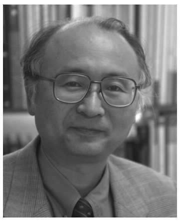

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