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Retrieval of Cloud Optical Thickness and Effective Radius from Geostationary Satellite Data

This report documents an effective algorithm to retrieve cloud optical thickness and effective radius from geostationary satellite data. The algorithm will be used as a part of the COMS meteorological data processing system in KMA. This paper also summarizes the algorithm theoretical basis, pre-performed retrieval results, and their validation results.

Retrieval of Cloud Optical Thickness and Effective Radius from Geostationary Satellite Data

1 Introduction

A new operational algorithm of cloud optical depth (COT) and effective radius (ER) has been developed to simultaneously use cloud-reflected radiance components at visible and near-infrared channels centered at 0.6 and 3.7 μm—the so-called sun reflection method. It is a challenge in the method decoupling the desired cloud-reflected components from undesirable components such as the ground-reflected, and the cloud and ground thermal radiances. Our algorithm resolved this concern by using the empirical relationship between the observed 10.8-μm radiance and 3.7-μm thermal radiance. The algorithm is fairly effective because it employs only one lookup library that consists of 0.6- and 3.7-μm radiances, various geometric angles (0, 20, 40, 60, and 80°), and ground albedo (A_g = 0 and 0.5).

2 Using a 3.7-μm band

Since the determination of the scaled COT using a nonabsorbing visible wavelength 0.6-μm band is introduced, this simple method has been operationally used for the geostationary meteorological satellite imagery. The COT is solely retrieved by this method assuming the effective particle radius of all clouds to be 10 μm. Later, the retrieval method for both COT and ER have developed by combining water-absorbing near IR wavelengths such as 1.6, 2.2, and 3.7 μm with the reflected radiance at 0.6 μm. Unlike 1.6 and 2.2 μm, the radiance at 3.7 μm contains large thermal components emitted from both the surface and the cloud top. The price of the removal of the thermal components is importing other variables such as the ground or cloud top temperature, so that the accuracy of the products may decrease depending on these factors. For that reason, the algorithm of Moderate Resolution Imaging Spectroradiometer (MODIS) uses a near-infrared 2.2 μm band, which is free of such components, together with visible 0.6 or 0.8 μm band. Unfortunately, most of geostationary meteorological imagers do not contain 1.6 or 2.2 μm, but the 3.7-μm band.

Although a 3.7-μm band has undesirable components for the sun reflection method, retrieval of COT and ER by making use of 0.6 and 3.7 μm seems to be practical. Figure 1 shows the radiative transfer model 'Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART)' simulation of clouds with a variety of COT and ER for 0.6-, 1.6-, 2.2-, and 3.7-μm radiances under the condition of specific angular variables. It is clearly shown that the cloud with a larger COT (ER) has a greater (smaller) 0.6-μm (3.7-μm) radiance. The sensitivity of the nonabsorbing and absorbing channels to COT and ER is almost orthogonal for optically thick clouds (COT ≥ ~16). For optically thin clouds (COT < ~16), the sensitivity of the 0.6-μm and 2.2-μm (or 3.7-μm) channels is more orthogonal than that of the 1.6-μm channel. This orthogonality assures independent retrieval of COT and ER. On the other hand, the intensity (i.e. radiance) at 3.7-μm itself is 10-digits smaller in comparison to other absorbing channels. Thus, using 3.7 μm requires highly sensitive manipulation to prevent a large uncertainty in the retrieved COT and ER.

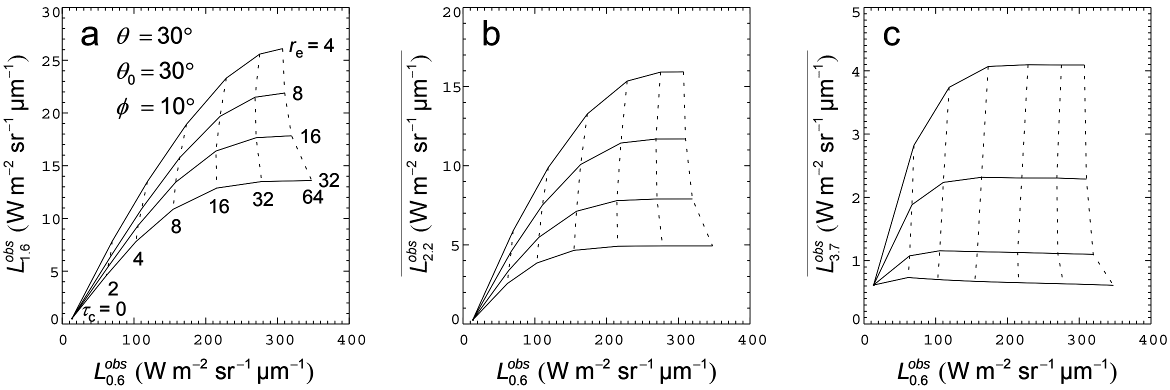

Figure 1 Comparison of 1.6-, 2.2-, and 3.7-μm radiances as a function of cloud optical thickness (0, 2, 4, 8, 16, 32, 64) and effective radius (4, 8, 16, 32) with the angular variables of the satellite zenith angle (θ) = 30°, the solar zenith angle (θ_0) = 30°, and the azimuth angle of the satellite relative to the sun (ϕ) = 10°.

3 Algorithm description

The sun reflection method using 0.6 and 3.7 μm uses solar radiation only, reflected by cloud layer, and accompanies an essential process to undertake decoupling undesirable radiation components: (1) ground-reflected radiation, (2) cloud and ground thermal radiation. Based on the radiative transfer theory for plane-parallel layers with an underlying Lambertian surface, the decoupled radiances for 0.6- and 3.7-μm wavelengths are simply given as follows

$$L_{0.6} = L_{0.6}^{obs} - L_{0.6}^{sr} \qquad (1)$$

$$L_{3.7} = L_{3.7}^{obs} - L_{3.7}^{sr} - L_{3.7}^{th} \qquad (2)$$

where L^{obs} is the satellite-received radiance, L^{sr} the ground-reflected radiance, and L^{th} the cloud and ground thermal radiance. The radiance is a function of COT, ER, the angular variables (θ, θ_0, ϕ). Cloud fraction reduces L^{obs} if a pixel is partially cloudy, which will consequently causes an underestimation upon COT. Because there is not yet a way to completely pick out such partial-cloudy pixels, we assume that cloudy pixels are fully overcast in Eqs. (1) and (2).

This method is certainly applicable to the COMS algorithm because it has all the channels needed. The observed radiances are explicitly decoupled from undesirable radiation components that are estimated by the direct use of climatological A_g and 10.8-μm radiance by Eqs. (3) and (4), respectively. Ground-reflected radiance L_i^{sr} at i channel (e.g. 3.7 or 10.8 μm) can be estimated by

$$\begin{aligned} L_i^{sr} &\cong A_g L_i^{sr}(A_g = 1) \\ &= A_g\left[(L_i + L_i^{sr}(A_g = 1)) - (L_i + L_i^{sr}(A_g = 0))\right] \end{aligned} \qquad (3)$$

where multiple reflection between ground surface and the upper layer is assumed to be very small, then L_i^{sr} changes almost linearly in proportion to A_g according to the RT theory applied to Eqs. (1) and (2). We may derive an extended formula further, as shown in Eq. (3), with respect to thermal-free radiance that is the sum of cloud- and ground-reflected radiances ($L_i + L_i^{sr}$). Note that L_i^{sr} is zero for $A_g = 0$ and that L_i is cancelled out in the extended formula of Eq. (3). On the basis of the extended form of Eq. (3), we can use only one lookup table, which contains the angular variables and their corresponding thermal-free radiances for two reference values of A_g (0 and 1) and for a variety of τ_c (0 to 64) and r_e (0 to 32 μm). Once angular variables and A_g are known, the simulated thermal-free radiance for $A_g = 0$ is subtracted from that for $A_g = 1$ in the lookup table and multiplied by given A_g (Eq. (3)).

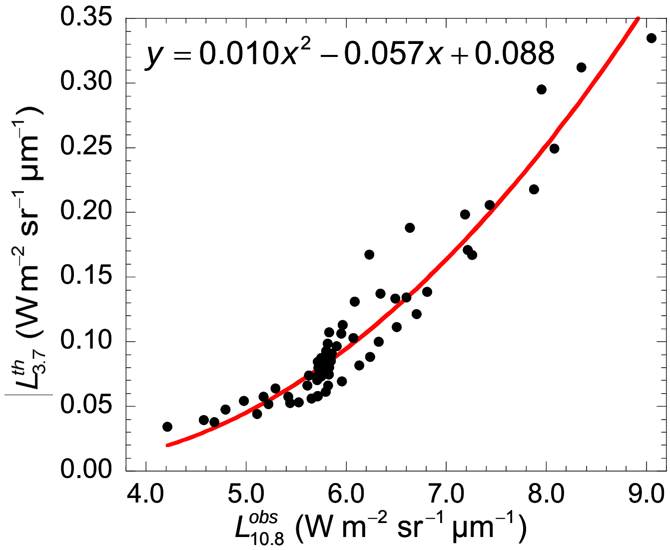

Figure 2 Sensitivity of 3.7-µm thermal radiances to 10.8-µm satellite-received radiances for the clouds with a variety of cloud optical thickness (0 to 64) and effective radius (0 to 32 µm) under diverse cloud top temperature and ground temperature. The solid line is the 2nd-order polynomial regression line of the plots.

Cloud and ground thermal radiance at 3.7 µm is inferred by the following:

$$L_{3.7}^{th} \cong a \cdot {L_{10.8}^{obs}}^2 + b \cdot L_{10.8}^{obs} + c \qquad (4)$$

where $L_{10.8}^{obs}$ is the 10.8-µm satellite-received radiance, and a, b, and c are regression coefficients. Eq. (4) is based on a hypothesis that both $L_{3.7}^{th}$ and $L_{10.8}^{obs}$ are proportional mainly to the Plank function of T_g and T_c. In this relation, different transmissivity of atmosphere and cloud layer, and ground emissivity at between 3.7 and 10.8 µm would give rise to regression errors as revealed in figure 2. The figure shows the result of the SBDART calculation for the sensitivity of the thermal radiance $L_{3.7}^{th}$ to $L_{10.8}^{obs}$. The calculations are carried out for clouds with a variety of COT (0 to 64) and ER (0 to 32 µm) under diverse cloud top temperature (220 to 290 K) and ground temperature (250 to 300 K). The $L_{3.7}^{th}$ increases with the 2nd order polynomial relation when $L_{10.8}^{obs}$ rises. The mean error range of $L_{3.7}^{th}$ for all the $L_{10.8}^{obs}$s is about 0.02 W m^{-2} µm^{-1} sr^{-1}, which causes 2% uncertainty in the final r_e. Also, this decoupling method implies, in figure 2, that the error of $L_{3.7}^{th}$ would be even larger for cold surface (i.e. cold $L_{10.8}^{obs}$). The decoupling method using such a simple relation between $L_{3.7}^{th}$ and $L_{10.8}^{obs}$ is fairly effective in time. Finally, we remove undesirable components from the observed radiance by Eqs. (1) and (2) with the aid of Eqs. (3) and (4).

4 Pre-calculated retrieval results with MTSAT-1R imagery

Using the full-disk imagery of Multi-functional Transport Satellite (MTSAT-1R) calibrated radiance for the month of August, 2006, we retrieved COT and ER only in limited daytime field of view with solar and satellite zenith angles < 60°. An example of the retrieved COT and ER for 0333 UTC 7 August 2006 are shown in figure 3. The final COT (ER) in the centers of tropical cyclones and ITCZ is more close to the MODIS-retrieved data than the COT (ER) retrieved without the decouple method.

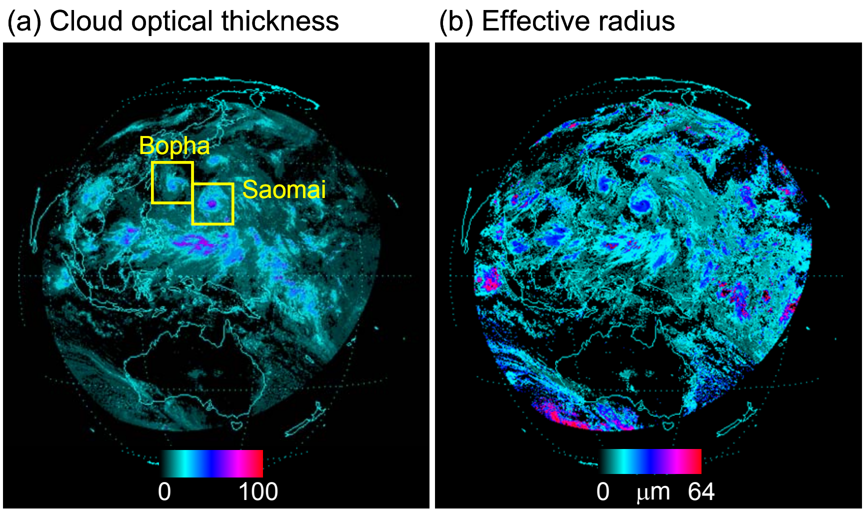

Figure 3 The retrieved cloud optical thickness and effective radius from the MTSAT-1R imagery for 0333 UTC 7 August 2006. Shown are tropical cyclones: Saomi and Bopha centered in 18°N, 139°E, and 23°N, 129°E, respectively.

5 Validation

Figures 4a and 4b respectively show the comparison of COT and ER from the new algorithm with those of MODIS. The COT from the new algorithm is in fairly good agreement with MODIS COT for optically thin clouds (COT < ~20). For thick clouds, the COT deviates even more from the linear relation. The mean root-mean-square errors of COT for thin and thick clouds are 1.39 and 5.38, respectively. This low accuracy for thick clouds results from $L_{0.6}$ itself increasing slightly for a constant ER when the COT rises over 20, as shown in the radiative transfer modelling result of figure 1. On the other hand, ER from the new algorithm is in accord with MODIS ER for small particles (ER < ~12 μm). For large particles, the deviation of ER is increased due to a similar reason as stated above for COT. Namely, $L_{3.7}$ itself decreases slowly when ER rises over about 12 μm (see figure 1). The mean root-mean-square errors in ER for small and large particles are 0.83 and 1.76 μm.

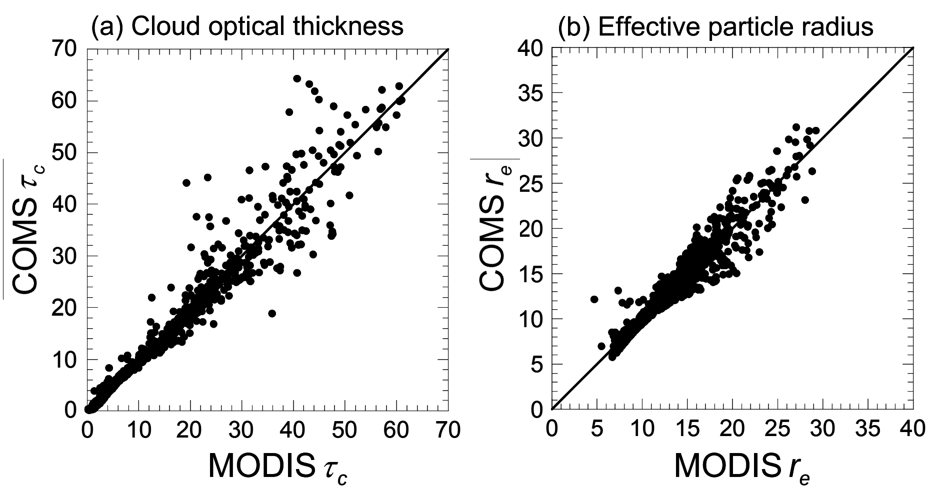

Figure 4 Comparison between MODIS-retrieved and COMS-retrieved cloud optical depth (a), and effective radius (b).

6 Summary

The retrieval of COT and ER using cloud-reflected 0.6- and 3.7-μm radiances is achieved by the rapid removal of undesirable radiance components. These components are obtained from a lookup table composed of angular variables, climatological A_g, and 10-μm radiance measured for a coincident pixel. The COT (ER) attained by this algorithm has shown the valid relation, better below 20 (12 μm) than MODIS-retrieved COT (ER) in its validation analysis using the available data. However, the decouple method lowers slightly the accuracy of COT and ER. In particular, the ER can accumulate more noise by the additional removal of thermal components at 3.7-μm. As a result, the COT (ER) over about 20 (12 μm) deviates more from the MODIS products.

7 Reference

Choi, Y.-S., C.-H. Ho, M.-H. Ahn, and Y.-M. Kim (2007), An exploratory study of cloud remote sensing capabilities of the Communication, Ocean and Meteorological Satellite (COMS) imagery, International Journal of Remote Sensing (in press).