SIMULATION OF CLOUD'S VISIBLE REFLECTION USING MODIS CLOUD PRODUCTS

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ABSTRACT:

Radiative transfer modeling of ice clouds is developed. Ice clouds located near tropopause reflect most of sunlight, thus atmospheric and surface effects can be minimized. Cloud properties such as cloud optical thickness (COT) and effective radius are important parameters to determine the magnitude of reflectance, while atmospheric and surface parameters rarely affect reflectance value. For selected homogeneous cloud pixels of MODerate Resolution Imaging Spectroradiometer (MODIS) observation, reflectances are calculated using MODIS cloud products as inputs of radiative transfer model (RTM). For three types of phase function (Henyey-Greenstein, Garcia-Siewert, Baum) calculated reflectances are compared with observations for validation. All cases show linear relationship between simulated values and measured values, however each represent different bias and slope. The result shows that phase function determine angular distribution of reflectance.

1. INTRODUCTION

Deep convective clouds reflect most of sunlight, thus sunlight is scattered before reaching lower troposphere. This implies atmospheric and surface effects can be minimized for radiative transfer modeling of deep clouds. Cloud bidirectional reflectance distribution (BRDF) can be calculated if accurate cloud optical properties are available. That is, with reference satellite data especially cloud products, other collocated satellite radiances can be simulated using radiative transfer model (RTM). From this point of view, cloud BRDF simulation is applicable to vicarious calibration using cloud targets.

In this study, cloud bidirectional reflectances are calculated using Santa Barbara Disort Atmospheric Radiative Transfer (SBDART) and compared with observation and the accuracy of modeling is examined.

2. METHODOLOGY

2.1 Radiative Tranfer Equation

BRDF or normalized radiance leaving to direction (θ, Φ) is defined as

$$\mathrm{BRDF} = \frac{\pi I(\theta,\phi)}{F_0 \cos\theta_0} \tag{1}$$

where Φ is relative azimuth angle, θ is viewing zenith angle, θ_0 is solar zenith angle, and F_0 is direct beam intensity. Intensity I(θ, Φ) can be calculated from the following radiative transfer equation (RTE) where μ is cosine of θ.

$$\begin{aligned}\mu\frac{dI(\tau,\mu,\phi)}{d\tau} &= -I(\tau,\mu,\phi) + \frac{\omega_0}{4\pi}F_0 P(\mu,\phi;-\mu_0,\phi_0)e^{-\tau/\mu_0}\\ &+\frac{\omega_0}{4\pi}\int_0^{2\pi}\int_{-1}^{1} I(\tau,\mu',\phi')P(\mu,\phi;\mu',\phi')\,d\mu' d\phi'\end{aligned} \tag{2}$$

Since single scattering albedo ω_0 is close to 1, thus BRDF is primarily determined from optical thickness τ and phase function P(μ,Φ; μ',Φ'). SBDART provides two types of phase function, Henyey Greenstein (HG) function and Garcia-Siewert (GS) function (Garcia et al., 1985). HG function is parameterized function of asymmetry factor and this factor can be represented by effective size of cloud particles. GS function is calculated using Mie theory for water particles. It is not valid for ice clouds, however size distribution is based on *in-situ* measurements (Deirmendjian et al., 1964), GS function may provide reasonable accuracy. Cloud BRDF is less affected by cloud particle size for the case of GS function, because size distribution is fixed. In this study, additionally with Baum phase function (Baum *et al*, 2005a and 2005b; Yang *et al.*, 2003a and 2003b), three types of phase function are examined (Figure 1). Baum phase function is also based on reanalysis of *in-situ* data from a variety of midlatitude and tropical ice cloud field measurements.

2.2 Algorithm

MODIS cloud product is used not only for RTM inputs but also for selection of cloud pixels. The case which cloud top temperature (CTT) less than 205K, cloud top pressure (CTP) less than 213 hPa, and COT greater than 10 are considered as ice cloud. In addition, to choice horizontally homogeneous cloud pixels, the criteria which COT and CTP variation within surrounding 3x3 pixels are less than 10 and 30 hPa respectively are used. To avoid large effect of optical thickness, solar zenith angle (SZA) and viewing angle (VA) are limited under 30°. Less than 0.05% of all pixels met this criteria. After selecting carefully horizontally homogeneous and optically thick cloud pixels, reflectances of cloud pixels are calculated for MODIS geometry.

2.3 Data

From January to December in 2004, Level 1B radiance and level 2 cloud product of MODIS data are used. Equatorial ocean region centered in 125° E is investigated (Latitude 25°S~25°N, Longitude 95°E~155°E). All MODIS data is converted to 0.05° (~5 km) grid data and classified into clear and cloud pixels. For selected cloud pixel, satellite radiance is calculated using RTM and compared with MODIS measurements.

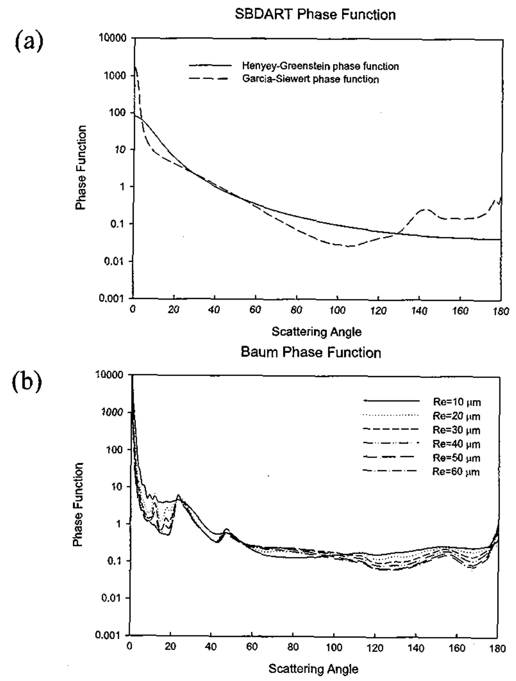

Figure 1. (a) Two types of cloud phase function which are provided in SBDART (b) Ice cloud phase function of Baum based on *in-situ* measurements

3. RESULTS

3.1 Simulation of cloud BRDF

Cloud BRDF is calculated using SBDART for three cases of phase functions (HG, GS, and Baum functions). Figure 2 represents cloud BRDF for various phase functions and cloud particle effective radii when solar zenith angle (SZA) = 30° and COT = 60. Each case shows different distribution from each other. For the case of HG function, strong reflection occurs in forward direction (Φ = 0°) while backward direction (Φ = 180°) for the cases of GS and Baum function as in King *et al* (1987). Such a maximum reflection occurs around viewing angle = 30° for all cases. It shows that the specular reflection is dominant than diffuse reflection. In Figure 2 (b), cloud BRDF is almost constant with respect to particle size because phase function is fixed and only asymmetry factor is slightly affected by effective radius. Baum function is similar with GS function when effective radius is small (less than 20 μm) because the range of size distribution used for calculation of GS phase function is from 0 to 20 μm.

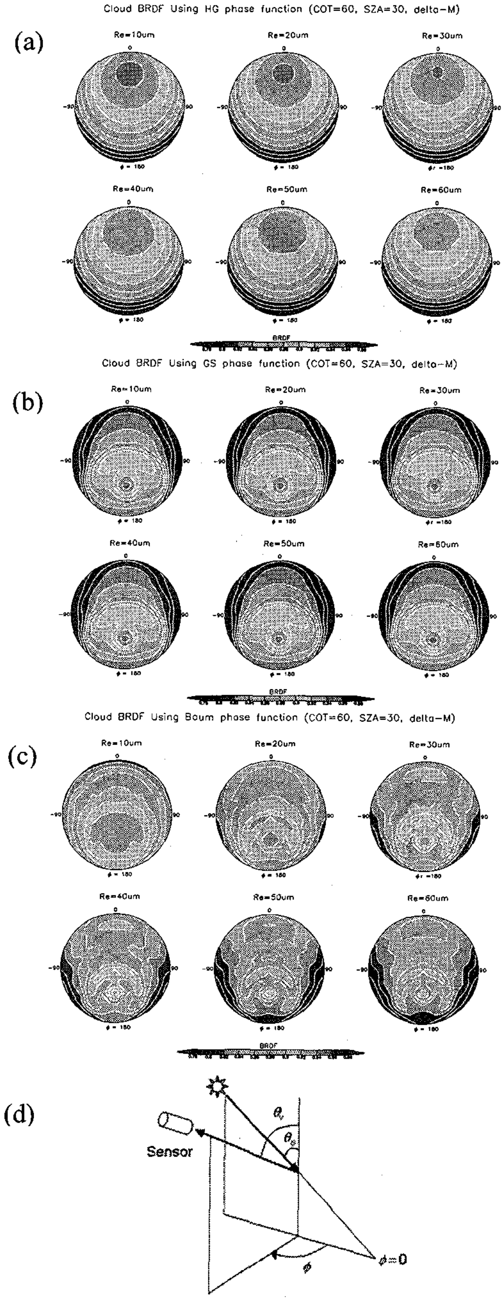

Figure 2. Cloud BRDF for COT = 60, solar zenith angle (SZA) = 30° using (a) Henyey-Greenstein function (b) Garcia-Siewert function (c) Baum function. Radial and tangential axes indicate sensor viewing angle (VA) and relative azimuth angle (RAA), respectively. RAA (Φ), VA (θ_V), and SZA (θ_S) are defined in (d).

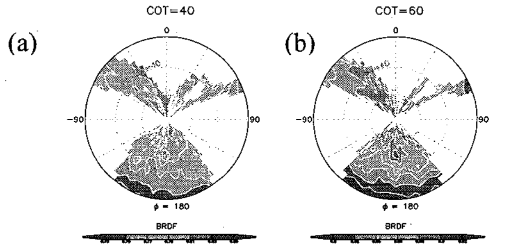

Figure 3. MODIS estimated cloud BRDF. One year MODIS data are collected to construct BRDF if 25 μm < R_e < 35 μm, 25° < SZA < 35°, CTP < 213 hPa, CTT < 205 K, and (a) 30 < COT < 50 (b) 50 < COT < 70.

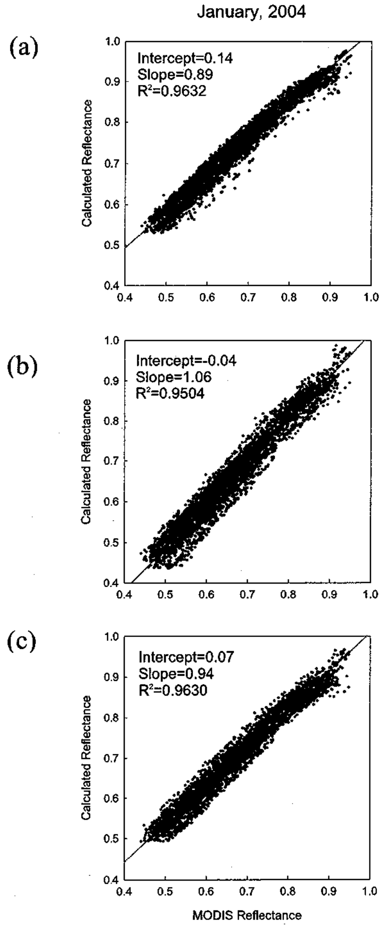

Figure 4. Scatter plots of calculated and observed radiances for three phase functions from January to July in 2004. Each case represents different bias and slope while all three cases clearly show a linear relationship between two variables. (a) HG phase function (b) GS phase function (c) Baum phase function

Contrary to simulated BRDF using RTM, observed reflectances are used to composite cloud BRDF. One year MODIS radiance data is used to make cloud BRDF only if 25 μm < effective radius (Re) < 35 μm, 25° < SZA < 35°, CTP < 213 hPa, and CTT < 205 K. Figure 3 (a) shows cloud BRDF for 30 < COT < 50, and Figure 3 (b) for 50 < COT < 70. Both cases show strong reflection in backward direction which is similar to GS and Baum cases. Henyey phase function cannot represent backward peak in Figure1 (a), thus Henyey case results in opposite reflection peak.

3.2 Simulation of cloud radiance for MODIS pixels

Radiances are calculated using RTM for each geometry of cloud pixels and compared with measurements. Figure 4 shows scatter plots of measured and simulated radiances on January in 2004. All three cases (HG, GS, Baum function) represent a linear relationship between observed and calculated values, however each has different bias and slope. The GS case represents the smallest bias while the HG function showed the largest bias and quadratic trend for high reflectance. However, we cannot conclude that GS function is the most realistic phase function because we did not examine various viewing geometry. In addition, we used MODIS cloud data which are adjusted values from observed radiance data; GS function may be the most similar phase function with the function used for the MODIS COT algorithm. We need a validation using other satellite data with various viewing geometry in order to determine the most appropriate cloud model and BRDF.

Figure 5 shows time series of averages of calculated and observed radiances. For all three cases, simulated values represent similar trends (or gross features) with observed values, however each case shows different bias as shown in Figure 4. Because reflected flux value is a primarily function of COT, COT produces similar trends of all three case. However each phase function creates different angular distributions, this may gives different biases.

Figure 6 shows COT-reflectance relationship. Reflectance is saturated as COT increase. HG function (solid line) produces the largest reflectance value and all three cases converge as COT increase. GS function (dotted line) and Baum function (dashed line) have similar trend with observation (dots) on June and December. RAA is set by 45° in Figure 6 (a) and 145° in Figure 6 (b) which are dominant relative azimuth angles of MODIS observation on June and December in 2004.

4. CONCLUSIONS

Ice clouds reflect most of visible light, thus we need only cloud parameters rather than atmospheric and surface parameters to model cloud influence on TOA radiance. Using MODIS cloud products, ice cloud BRDF is calculated using three types of phase functions. Phase function is one of the important parameters affecting angular distribution of reflectance. Cloud BRDF using HG function represents a forward peak reflection, where as GS function and Baum function produce backward peak reflections. Although cloud surface is rough, a strong reflection occurs around viewing angle of 30° when SZA is 30°. It shows that specular reflection is dominant than diffuse reflection. Specific reflectance or normalized radiance is calculated using MODIS observation geometry for three types of phase compared with observed values.

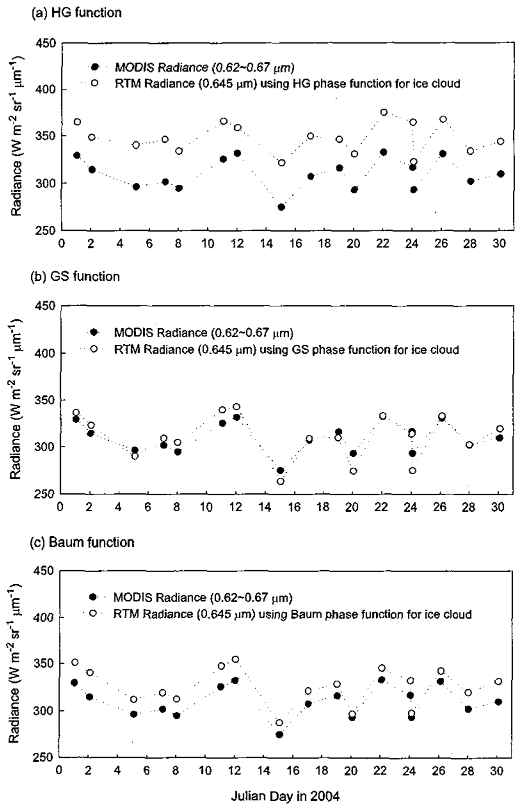

Figure 5. Daily mean variations of calculated and observed radiances for three phase functions (January, 2004): Pixel values are averaged only if the number of cloud pixels at time are greater than 50.

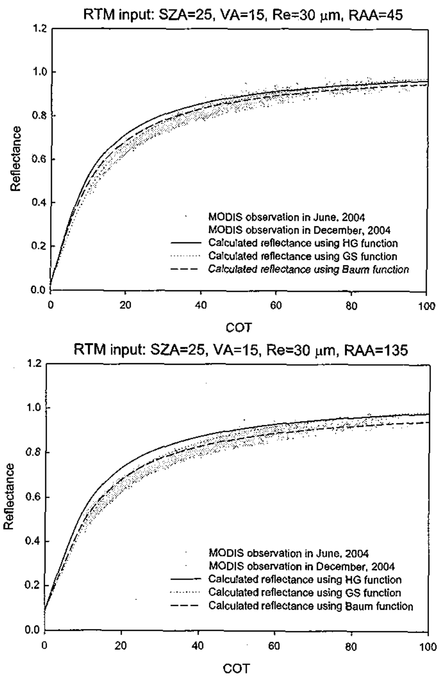

Figure 6. COT-reflectance relationship for June and December, 2004. Reflectances are calculated for average solar and sensor geometry: SZA = 25°, VA = 15°. (a) RAA = 45° (b) RAA = 135°.

It was noted that reflected fluxes are mainly a function of COT rather than phase function. However, it was found that angular distribution of bidirectional reflectance or radiance is strongly affected by the phase function. Thus all three cases show a similar trend (large changes) but different biases (small changes). Nonetheless we cannot draw a conclusion that the phase function is the most realistic function from the results because MODIS observations do not provide various satellite geometries. We need more validation efforts using other satellite data from which various geometry effects can be examined.

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Acknowledgments

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