The Effect of Surface Heterogeneity on Cloud Absorption Estimates

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Introduction

"Enhanced shortwave cloud absorption" (the difference between measured and model-calculated absorptions) has been a major concern in the climate community. The reason is that this excess absorption is always a bias on the order of 10 W/m^2 rather than a random error (Valero et al. 2003), and as a result, may have significant impact on climate modeling and remote sensing applications. Among various explanations for this bias, it has been suggested that inhomogeneous surface albedo could explain the excess shortwave cloud absorption (Li et al. 2003). However, up to now, there has been a lack of thorough analyses of the effects of surface albedo variability on cloud absorption estimates. This study attempts to provide a systematic and quantitative analysis to understand how accounting for surface heterogeneity affects cloud absorption, and to examine whether it can explain this shortwave cloud absorption discrepancy.

Approach

We use the discrete-ordinate-method radiative transfer (DISORT) model, a three-dimensional (3D) Monte Carlo method, and the Spherical Harmonic Discrete Ordinate Method (SHDOM) to calculate cloud absorption. Models were set up with clouds over a checkerboard albedo surface (Figure 1). Cloud optical properties are cloud optical depth τ and single-scattering albedo ϖ_0, and cosine of the solar zenith angle (SZA) is denoted as μ_0.

Based on energy conservation, cloud absorptance A can be computed from

$$A(\alpha) = 1 - R_0 - \frac{T_0\left[\alpha T_0 + (1-\alpha)\right]}{1-\alpha R^*} \qquad (1)$$

where α represents surface albedo; R_0 and T_0 are cloud reflectance and transmittance, respectively, in the case of "black" surface; and R^* describes the reflectance of isotropical illumination from below clouds. Note that R_0, R^*, and T_0 are independent of surface albedo α, and only depend on cloud properties and solar angles.

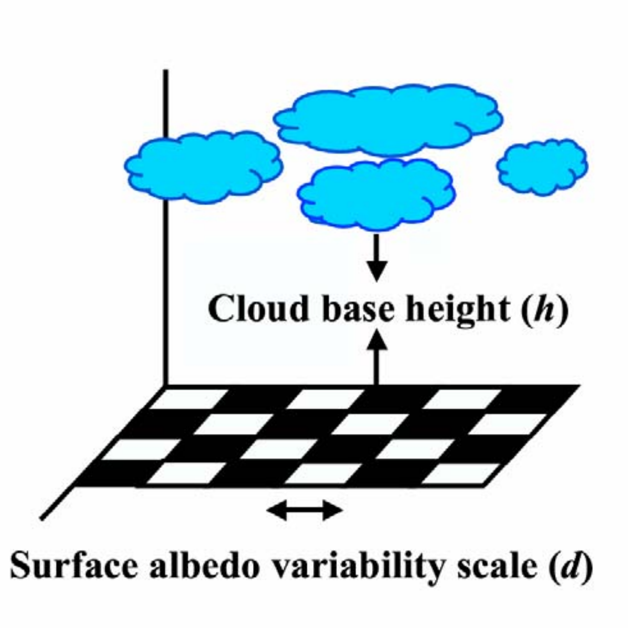

Figure 1. Schematic illustration of model setup.

There are three ways to estimate cloud absorption when surface albedo varies. One is made from the surface independent pixel approximation (SIPA), computing cloud absorption independently for each surface pixel, and then averaging them. The second method assumes homogeneous-surface (HS) and applies an average surface albedo. The third method involves 3D radiative transfer calculations. The following section gives quantitative comparisons of these three estimates for various cases, including extreme situations and the conditions similar to the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP) central facility.

Results

Homogeneous Clouds

Except for the trivial case of $\varpi_0 \rightarrow 0$ that corresponds to $A \rightarrow 0$, it follows from Eq.1 $A''(\alpha) > 0$, i.e., $A(\alpha)$ is a concave function. It leads to

$$A\left(\frac{\alpha_1 + \alpha_2}{2}\right) \leq \frac{A(\alpha_1) + A(\alpha_2)}{2} \qquad (2)$$

for any surface albedos $0 \leq \alpha 1$, $\alpha 2 \leq 1$. Obviously, the left-hand side of Eq. 2 represents the homogeneous-surface (HS) cloud absorption estimate, while the right-hand side corresponds to the SIPA estimate. Thus, averaging surface albedo will always decrease cloud absorption.

The above theoretical conclusions can be illustrated by DISORT numerical calculations. Figure 2 depicts the dependency of cloud absorption on surface albedo for examples of overhead sun illumination, an arbitrary optical depth τ of 16 and various cloud single-scattering albedo ϖ_0. Indeed, cloud absorption follows a concave relationship with surface albedo. Note that ϖ_0 values in Figure 2 are representative for shortwave spectrum. With an underlying black and white checkerboard surface, Figure 3 illustrates the difference of SIPA and HS as a function of τ for homogeneous clouds, overhead sun, and various ϖ_0. The bias between SIPA and HS is always positive, which is confirmed by Eq. 2. Over all reasonable sets of (τ, ϖ_0, μ_0) for shortwave radiation, the biggest absolute difference between SIPA and HS estimates occurs at (τ, ϖ_0, μ_0) = (16, 0.99, 1.0) with a value of 0.028. The difference associated with this particular cloud property and solar angle is the most pronounced impact of inhomogeneous surface albedo we can ever capture for homogeneous clouds. Thus, for convenience, we refer to this particular situation as the "biggest-effect" case hereafter.

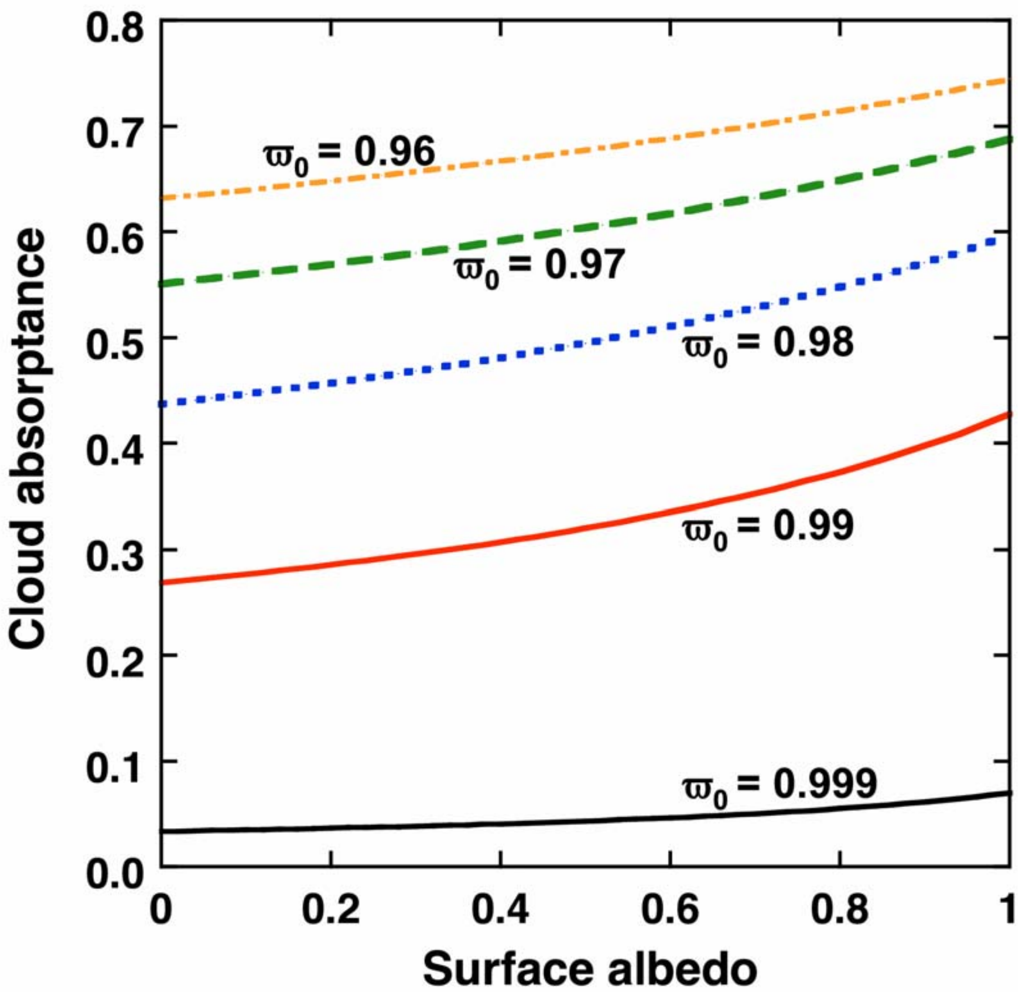

Figure 2. The relation of cloud absorption to surface albedo for overhead sun illumination, τ = 16, and various cloud single-scattering albedo ϖ_0. This plot is based on DISORT calculations.

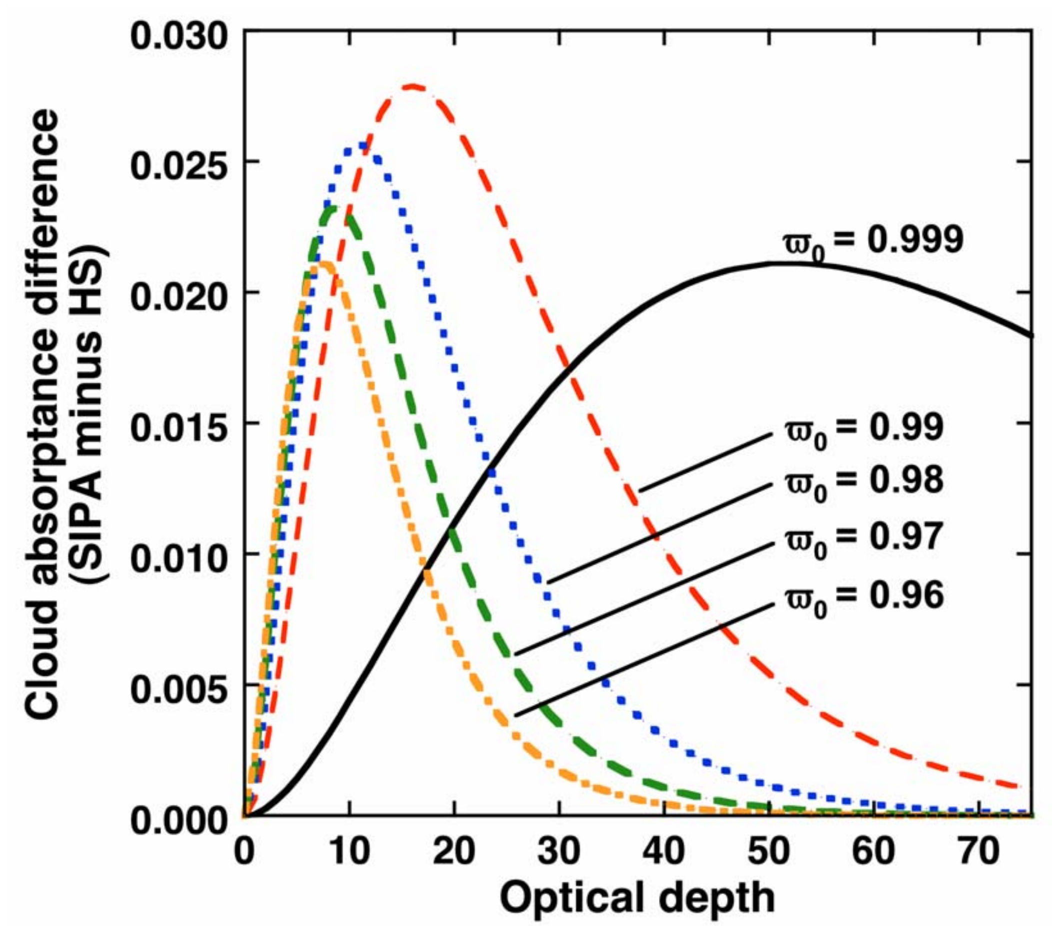

Figure 3. The difference between cloud absorptance based on the SIPA and the HS assumption, as a function of cloud optical depth τ. Results are obtained from DISORT assuming a black and white checkerboard surface, overhead sun illumination, and varying single scattering albedo ϖ_0 from 0.96 to 0.999.

The effects of surface albedo variability on homogeneous clouds from 3D modeling are demonstrated via a scale ratio *s*, defined as

$$s = h / d \tag{3}$$

where *h* denotes cloud base height, and *d* represents the horizontal scale of inhomogeneous surface (Figure 1). Figure 4 depicts a curve that relates cloud absorption to the scale ratio for the "biggest-effect" case. Results reveal that cloud absorptance decreases with increasing scale ratio, and the total change between two ends is around 8%. When the scale ratio decreases towards zero, the cloud absorptance is approaching the estimate of SIPA. This limiting case of small *s*, in which the cloud layer is low and thus most cloud absorption is attributed to photons directly from the underneath surface pixel, is close to the surface independent pixel assumption. On the contrary, cloud absorptance reaches the homogeneous-surface estimate in the limiting case of larger *s*. This case, in which the cloud base is high and surface albedo has a more atomic structure to the cloud, is close to the HS assumption.

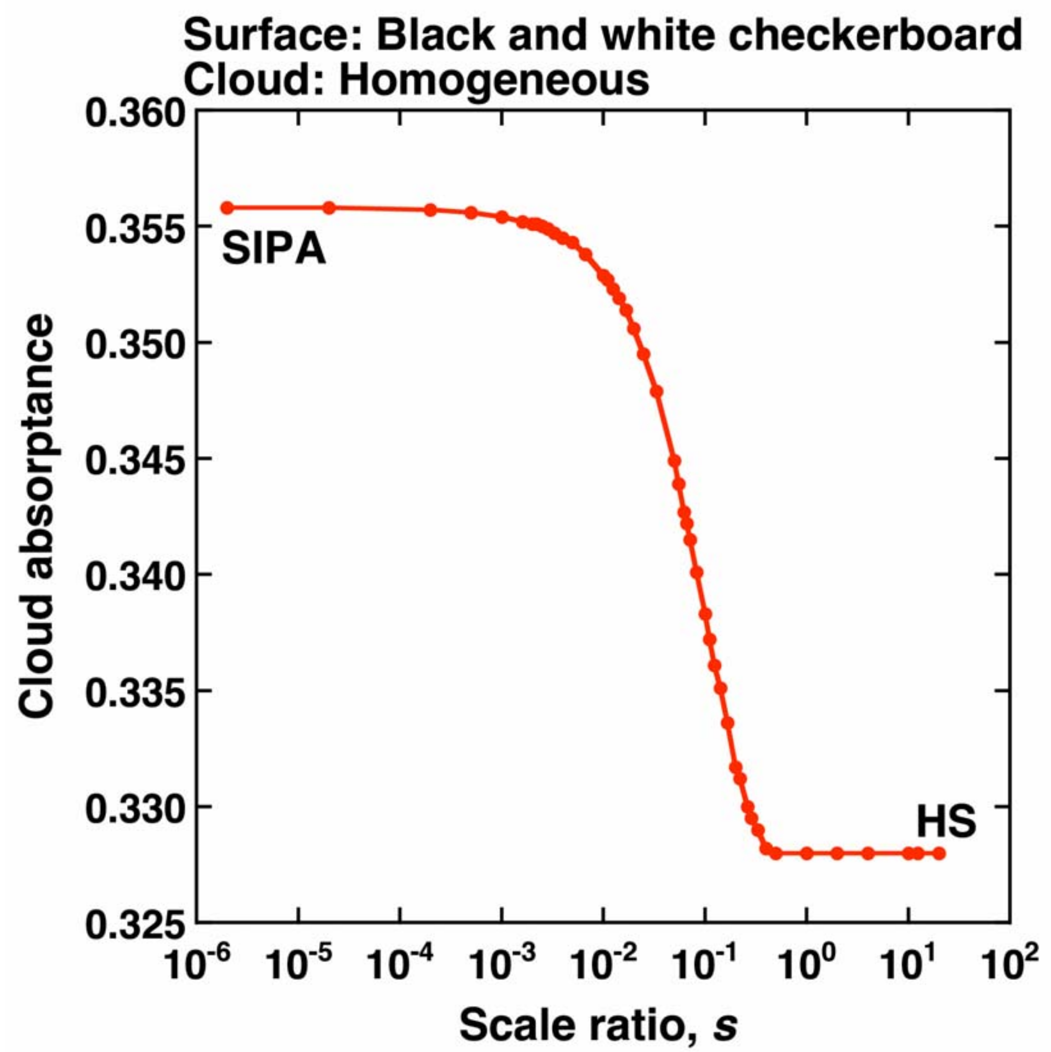

Figure 4. Cloud absorptance as a function of scale ratio *s* for the "biggest-effect" case: $(\tau, \varpi_0, \mu_0) = (16, 0.99, 1.0)$. *s* is the ratio of cloud base height to the scale of inhomogeneous surface albedo. SIPA indicates that cloud absorptance approaches to the estimate made by the surface independent pixel assumption in the limiting case of small *s*. HS shows that the cloud absorptance is toward the homogeneous-surface estimate in the limiting case of large *s*.

Inhomogeneous Clouds

To simulate cloud inhomogeneity, a fractionally integrated cascade model (Schertzer and Lovejoy 1987) was used to generate various cloud structures for a variety of cloud fractions. We find there is no significantly qualitative or quantitative difference in the effects of surface albedo inhomogeneity for fractal clouds rather than homogeneous clouds. In 3D clouds, 5% to 7% of change in cloud absorption is found between the two limiting cases of SIPA and HS (figures not shown).

Inclusions of Broadband Spectrum, Diurnal Cycle, and Varying Clouds

We have demonstrated the effects of surface heterogeneity on single-wavelength cloud absorptions for homogeneous and heterogeneous clouds with a black and white checkerboard surface. When considering all variability of τ, ϖ_0, and μ_0, by defining cloud absorptance as $A(\tau, \varpi_0, \mu_0)$; the overall cloud absorption can be computed by

$$\rangle A \langle = \int_{\varpi_0}\int_{\mu_0}\int_{\tau} A(\tau, \varpi_0, \mu_0, \alpha) \cdot P_\tau(\tau) P_{\mu_0}(\mu_0) P_{\varpi_0}(\varpi_0) d\tau d\mu_0 d\varpi_0 \qquad (4)$$

where P_τ, P_{μ_0}, and P_{ϖ_0} represent the probability density functions of τ, μ_0, and ϖ_0, respectively. P_τ was estimated from simulations of the fractionally integrated cascade model with a sample mean of 16. P_{μ_0} was approximated by equal weights of SZAs at 30, 45, and 60°. For P_{ϖ_0}, we divided solar spectrum into five intervals to find weighting factors for the corresponding averaged single-scattering albedo. Then, using a simple quadrature rule, the approximated cloud absorption can be obtained.

The resulting broadband cloud absorptance with black and white checkerboard surface revealed a reduced bias to less than 4% after including cloud inhomogeneity, diurnal cycle, and a broadband spectrum (figures not shown). Note that surface albedo changes with spectrum, and therefore should not be held as a constant during integrations. However, for simplicity, the black and white surface albedo was employed throughout the whole integrations. This simplification does not hinder our demonstration of surface effects on broadband cloud absorption since the true effects would be even less pronounced due to smaller contrast in surface albedo.

To this point, we used only black and white checkerboard surface. Since a range of 0.01 to 0.5 of spectral surface albedo was measured around the ARM SGP central facility (Li et al. 2002), another black and gray checkerboard with albedo of 0 and 0.5 was also tested to understand whether surface albedo variability could explain the observed excess cloud absorption in the ARM observation environment. Results (shown in Figure 5) indicate that the change of cloud absorption reduces to less than 1% between the smallest and largest scale ratios for both single-wavelength and broadband cases. This finding strongly suggests that the anomalous cloud absorption cannot be explained by surface heterogeneity.

Summary

This paper presents the first systematic and quantitative analysis of the effect of inhomogeneous surface albedo on shortwave cloud absorption. We provide theoretical proof and numerical calculations to demonstrate that the use of an averaged surface albedo always underestimates cloud absorption. We also find that in extreme cases, (e.g., with an underlying black and white checkerboard surface) inhomogeneous surface albedo can make a difference in cloud absorption estimates as much as 8% (10–20 W/m^2). However, in reality, the spectral surface albedo around the central facility is around 0.01–0.5. In that observation environment, for any situations of clouds and solar illuminations, the effect of surface heterogeneity on cloud absorption estimates is negligible (less than 0.5%, or ~1 W/m^2). This 1 W/m^2 difference attributed to surface albedo is not only less than the uncertainty caused from other variables such as water vapor and aerosols, and the errors from radiative transfer

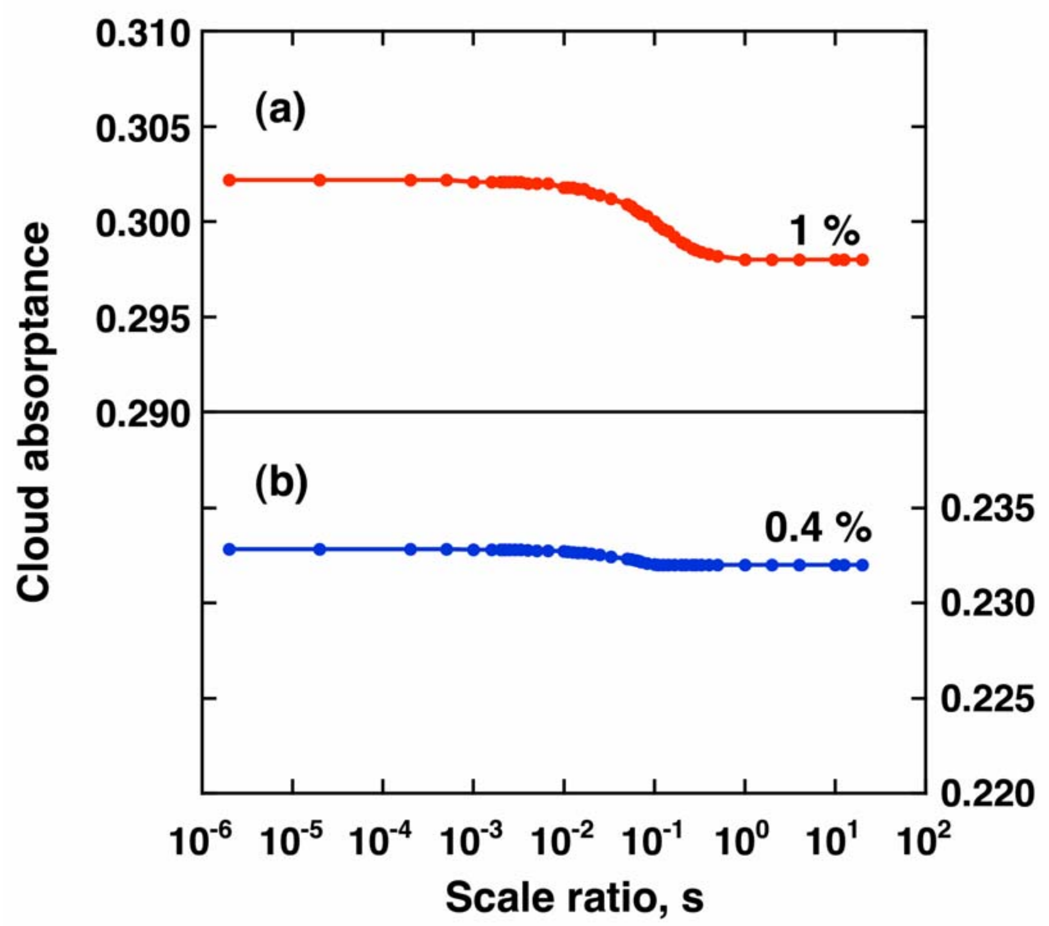

Figure 5. Cloud absorptance as a function of scale ratio with an underlying black and gray checker-board surface for (a) the case in which (τ, ϖ_0, μ_0) = (16, 0.99, 1.0), and (b) the case integrating over various clouds, wavelengths, and SZA. The percentage indicates the relative bias in percentage between the smallest and largest scale ratios.

model itself, but also much less than the discrepancy (order of 10 W/m^2) between measured and model-calculated cloud absorptions. Therefore, this study strongly suggests that accounting for surface heterogeneity cannot explain the shortwave cloud absorption discrepancy.

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