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# On the sensitivity of cloud effective radius retrieval based on spectral method to bi-modal droplet size distribution: A semi-analytical model

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ABSTRACT

The bi-spectral solar reflective method is widely used to infer cloud optical thickness ($\tau$) and effective radius ($r_e$) from satellite cloud reflectance observations. An important assumption often made in this method is that cloud droplet size distribution (DSD) follows the monomodal Gamma or Lognormal distributions, with a fixed variance. However, it is known that the warm rain processes, e.g., collision–coalescence, can broaden cloud DSD and even lead to bi-modal size distribution. In this study, a semi-analytical model is developed to better understand the retrieved $r_e$ based on the monomodal DSD assumption when the true DSD is bi-modal. The results based on this model agree well with the results from rigorous radiative transfer simulations. The model reveals that the $r_e$ retrieval based on the monomodal DSD assumption tends to underestimate the $r_e$ of the true bi-modal DSD. This bias is due to the nonlinear relationship between cloud droplet single-scattering albedo and cloud droplet size. The degree of this underestimation is found to increase with $r_e$ and the width of the DSD. The model also indicates that the underestimation more strongly affects the 3.7 μm band than in the 2.1 μm band retrievals; leading to smaller 3.7 μm band $r_e$ retrieval than that based on 2.1 μm. It is also demonstrated through numerical tests that cloud optical thickness retrieval shows little sensitivity to the cloud microphysics assumption and is relatively accurate. This is probably because the asymmetry factor of cloud droplet varies within a relatively small range, and therefore limits the impact of cloud microphysics on $\tau$ retrieval. This study has several implications, in particular for understanding the potential impact of drizzle on cloud $r_e$ retrieval. Future work is needed to evaluate the model in more realistic cloud field.

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## 1. Introduction

Among many satellite-based cloud remote sensing techniques, the bi-spectral solar reflective method ("bi-spectral method" hereafter) is widely used to infer cloud optical thickness ($\tau$) and cloud droplet effective radius ($r_e$) from satellite observation of cloud reflectance [1–3]. The $\tau$ is column-integrated variable defined as $\tau = \int_0^{z_h} \beta_e(z)dz$, where $\beta_e$ is cloud extinction coefficient and $z_h$ is the thickness of cloud. The $r_e$ is defined as [4]:

$$r_e = \frac{\int_0^\infty r^3 n(r)dr}{\int_0^\infty r^2 n(r)dr} = \frac{\langle r^3 \rangle}{\langle r^2 \rangle}, \tag{1}$$

where $n(r)$ is the cloud droplet size distribution (DSD) and $\langle r^n \rangle = \int_0^\infty r^n n(r)dr$ is the $n$th moment of the DSD. In addition to $r_e$, several other parameters are also often used to describe the shape of cloud DSD. For example, the effective

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variance $v_e$ defined as

$$v_e = \frac{\int_0^\infty (r - r_e)^2 r^2 n(r) dr}{r_e^2 \int_0^\infty r^2 n(r) dr}, \quad (2)$$

is a measure of the width of cloud DSD. In the bi-spectral method, $\tau$ and $r_e$ are simultaneously retrieved from a pair of passive cloud reflection measurements [1]. One measurement is usually made in the visible or near-infrared spectral region (for example, 0.86 μm), where water absorption is negligible and therefore cloud reflection is mainly determined by $\tau$, and the other in the shortwave infrared (SWIR) (for example, 2.1 μm or 3.7 μm), where water has significant absorption and cloud reflectance decreases with increasing cloud droplet size. The $\tau$ and $r_e$ retrievals based on the bi-spectral method are widely used for validating climate models [5,6], studying aerosol–cloud interactions [7,8] and facilitating other cloud remote sensing techniques [9].

The bi-spectral method is built upon several fundamental assumptions about clouds. It is often assumed that clouds are plane-parallel and vertically homogenous. Numerous studies have investigated what happens when clouds in reality deviate from these assumptions, i.e. the impacts of 3-D radiative effects [10–14] and cloud vertical inhomogeneity e.g., [15,16] on the bi-spectral method.

In this paper, I focus on the cloud microphysical assumptions. In the bi-spectral method, it is usually assumed that the cloud DSD follows a monomodal Gamma or Lognormal distributions, because these distributions can reasonably represent the DSD of *non-precipitating* water clouds [17–19] and are mathematically convenient. In the operational cloud property retrieval algorithm for the Moderate Resolution Spectroradiometer (MODIS), cloud DSD is assumed to be monomodal Gamma distribution [20],

$$n(r) = N r^{\frac{1-3v_e}{v_e}} exp\left(-\frac{1}{v_e}\frac{r}{r_e}\right), \quad (3)$$

where $N$ is a constant and $v_e$ is the effective variance in Eq. (2). Previous studies have shown that the cloud reflectance in SWIR band is much more sensitive to $r_e$ than $v_e$ [1,4]. For this reason, the $v_e$ is often assumed to be constant in the bi-spectral algorithm. For example, $v_e = 0.1$ is assumed in the MODIS operational algorithm [20], which is in the range of in situ measurement of warm stratocumulus cloud reported in [21].

In reality, cloud DSD may be different from the assumed monomodal Gamma or lognormal distributions. In fact, it is known that warm rain processes such as collision–coalescence could broaden DSD giving rise to a second mode of larger drops, the so-called drizzle or rain mode, thus creating *bi-modal* DSD [18,22,23]. How does the difference between the assumed and the actual cloud DSD affect the $r_e$ retrieval based on the bi-spectral method? Only a few numerical studies have explored this question. Chang and Li [24] investigated how the width of cloud DSD (i.e., value of $v_e$) affects the $r_e$ retrieval. They found that when the true DSD is wider than the assumed DSD, the $r_e$ retrieval tends to underestimate the true $r_e$. It is also found that the underestimation increases with increasing $r_e$. Minnis et al. [25] developed a series of theoretical bi-modal DSDs with increasing magnitude of the precipitation mode. Then, they performed $r_e$ retrieval based on monomodal DSD assumption for these bi-modal DSDs. It is found that the retrieved $r_e$ is close to the $r_e$ of the cloud mode and substantially smaller than the true $r_e$ of the bi-modal DSD. Another interesting finding from their test is that the magnitude of this $r_e$ retrieval bias is dependent on the spectral band used for $r_e$ retrieval. It is smaller in the less absorbing 1.6 μm MODIS band and larger in the more absorbing 3.7 μm band. Recently, the impact of precipitation mode on $r_e$ retrieval received increasing attention and was investigated in a number of studies [14,26,27]. These studies agree qualitatively that the inclusion of a precipitation mode in the otherwise monomodal DSD increases the retrieved $r_e$, although the magnitudes of this effect reported in these studies are remarkably different, ranging from a fraction of micron to a couple of tens of microns. The abovementioned studies have shed some light on the question of how bi-modal DSD affect the $r_e$ retrieval based on the bi-spectral method. However, these numerical case studies provided no theoretical explanation of why and how bi-modal DSD affects the $r_e$ retrieval. As a result, many questions related to the underlying physics remain unanswered. Why does underestimation of $v_e$ lead to underestimated $r_e$ retrieval? When cloud DSD is bi-modal, why is the $r_e$ retrieval substantially smaller than the true $r_e$? How can the spectral dependence of the $r_e$ retrieval bias be explained? More importantly, is it possible to quantitatively predict the retrieved $r_e$ for a given DSD with arbitrary shape and how could that be done?

The primary objective of this study is to establish and test a theoretical framework to describe, and more importantly to predict quantitatively, the impact of the bi-modal DSD on $r_e$ retrieval. The paper is organized as follows: Section 2 describes the problem formulation. A semi-analytical model is derived in Section 3 to illustrate the sensitivity of cloud effective radius retrieval based on the bi-spectral method to bi-modal DSD. In Section 4, the analytical formulation is evaluated in a numerical test. Section 5 summarizes the findings from this study and discuss their implications.

## 2. Statement of the problem

As aforementioned, the bi-spectral method is built upon the assumptions that clouds are plane-parallel and vertically homogenous. The deviation of cloud in reality from these assumptions could lead to substantial errors in the retrieved $\tau$ and $r_e$, which has been discussed in numerous previous studies and is not the focus of this study. With this in mind, I shall keep these assumptions throughout this paper in order to focus on microphysical aspect of the retrieval. To further simplify the problem I also assume that the retrieval of $r_e$ is independent of $\tau$ retrieval. This assumption could be problematic for small $\tau$ where the SWIR band cloud reflectance is dependent on not only $r_e$ but also $\tau$, but it holds well for large $\tau$ where SWIR band cloud reflectance is dependent primarily on $r_e$ and almost invariant with $\tau$.

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