remote sensing

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Technical Note

Effect of Partially Melting Droplets on Polarimetric and Bi-Spectral Retrieval of Water Cloud Particle Size

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Abstract: Water droplet size, or effective radius, of water clouds can be retrieved using measurements of the total reflectance in near-infrared channels (bi-spectral method) or the linearly polarized radiance of the cloud rainbow (polarimetric method). The retrieved droplet sizes from the bi-spectral method can be significantly larger than those from the polarimetric method. Droplet size vertical heterogeneity is considered as a likely cause of this difference. In this radiative transfer theoretical study, we find that partially melting droplets in mixed-phase clouds can be another cause of this difference. The theoretical study suggests that, when the clouds are dominated by large particles, the existence of partially melting droplets could cause the polarimetric method to underestimate the particle size; but for moderate-sized particles, the polarimetric method should be able to retrieve accurate particle size no matter if the clouds consist of partially melting droplets or not. However, the droplet effective radius of partially melting droplets retrieved by the bi-spectral method can be overestimated if the infrared channel of the bi-spectral method is at 1.6 μm, but is relatively insensitive to the presence of partially melted spherical droplets when the infrared channel is at 2.1 μm. The retrieved droplet size difference between droplet sizes from 1.6 μm and 2.1 μm channels can be used for detecting partially melting droplets.

Keywords: melting droplets; cloud particle size; polarimetric retrieval; lidar retrieval; layered spheres; scattering; enhanced backscatter

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1. Introduction

Water clouds cover ~50% of the globe according to satellite observations. These low-level clouds are extremely important for the Earth's energy balance, since water clouds strongly reflect incoming solar radiation, but only exert a small effect on outgoing long-wave radiation to space. A ~4% increase in coverage by water clouds will offset the 2–3 K rise in global temperature due to the doubling of CO_2 concentration [1,2].

Cloud droplet size distribution is influenced by aerosol, turbulence, entrainment, updraft, and downdraft. A change in the droplet size would affect the development of cloud precipitation and modify the lifetime of a cloud. The long-term interaction of the cloud life cycle and radiation influences a wide range of motion, ranging from individual mesoscale convection systems, tropical hurricanes, and mid-latitude cyclones to global atmospheric circulation.

Since water cloud droplet size is an important parameter for climate, atmospheric radiation, and aerosol-cloud interaction studies, remote sensing methods have been developed to retrieve it from satellite data. The primary method is based on the bi-spectral technique of Nakajima and King [3], which can retrieve cloud optical depth (COD) and droplet effective radius (R_e) from visible/near-infrared (VNIR) and shortwave infrared (SWIR) radiances, i.e., cloud optical thickness (τ_c) and effective particle radius (r_e) of water clouds are determined solely from reflectance measurements at 0.75, 1.65, 2.16, or 3.7 μm. This method has been applied to the Advanced Very High-Resolution Radiometer (AVHRR) [4], the Moderate Resolution Imaging Spectroradiometer (MODIS) [5], the Visible Infrared Imaging Radiometer Suite (VIIRS) [6], and the Advanced Himawari Imager (AHI) [7]. On the other hand, with the advancement of polarimetric measurements of clouds, such as by the Research Scanning Polarimeter (RSP) [8], the water cloud droplet R_e can also be retrieved using multi-angle polarized radiances [9–11]. The R_e from polarimetric sensors such as the RSP is retrieved using the polarized reflectance of the cloudbow with scattering angles ranging between 137 and 165 deg. The polarized reflectance structure of the cloudbow is dominated by the single-scattering properties of cloud particles. The single-scattering properties of cloud particles are simply determined by particle shape, size distribution, refractive index, and inhomogeneity. They are affected very little by cloud 3D shape and aerosols [10]. A pre-calculated look-up table of single-scattering polarized phase functions with various R_e, ν_e (effective variance), and scattering angles is used in the polarimetric droplet-size-retrieval method. The polarimetric R_e is derived by comparing the tabulated theoretical polarized phase function with the observed polarized reflectance. The scattering angle at which the cloudbow has a maximum magnitude basically determines the water cloud R_e.

Numerous studies have been conducted to evaluate the errors in the water droplet size derived from the bi-spectral technique [12–16]. It is also found that sometimes droplet sizes retrieved by the bi-spectral method are significantly larger than those from the polarimetric method [17]. Many explanations are given for the reasons for this difference, such as 3D cloud radiation effects, aerosols, the plane parallel atmosphere assumption, etc. However, inhomogeneity of the particles due to partial melting of ice crystals in clouds, could also be a reason for this difference.

The CALIPSO mission [18] uses lidar to detect clouds and aerosols from space [19–21]. One problem that has puzzled the lidar community for about two decades is that the lidar ratios from water clouds are often measured to be much lower than those calculated using the Mie theory [22]. Since aerosols and ice cloud particles have lidar ratios that are larger than those of water clouds, their presence cannot cause the increase in the lidar backscatter and thus smaller lidar ratios. A solution for this long-standing problem is reported in Sun et al. [23] by assuming partially melting droplets exist in water clouds. This finding suggests that many water clouds have partially melting droplets which increase the lidar backscatter and thus lower the lidar ratio.

Based on Sun et al. [23], a reasonable question for the bi-spectral and polarimetric droplet size retrieval methods is as follows. Do partially melting droplets which have liquid water shells and ice cores also impact polarimetric and bi-spectral retrieval of water cloud particle sizes? The corresponding questions for the two methods are (1) Does the scattering angle of maximum polarized radiance stay the same for water droplets with ice cores? (2) Do water droplets with ice cores increase the near-IR absorption compared to pure liquid water droplets?

To answer these two questions, we use a light scattering model for layered particles to calculate the single-scattering properties of water droplets with ice cores. We study the linear polarization reflectance/polarization degree (P_{12}) of these particles. We also input these single-scattering properties into a radiative transfer model to simulate the solar spectral reflectance from the cloud with these particles. The algorithms and results are given in Section 2. The summary and conclusion are provided in Section 3.

2. Algorithms and Results

As in Sun et al. [23], we assume clouds that contain partially melting droplets. These droplets are either pure liquid water spheres or liquid water spheres with spherical ice cores, as illustrated in Figure 1. Also illustrated in Figure 1 is the complication of the light scattering process due to the inhomogeneity of the particle: Layered particles can involve more scattering or absorption of light.

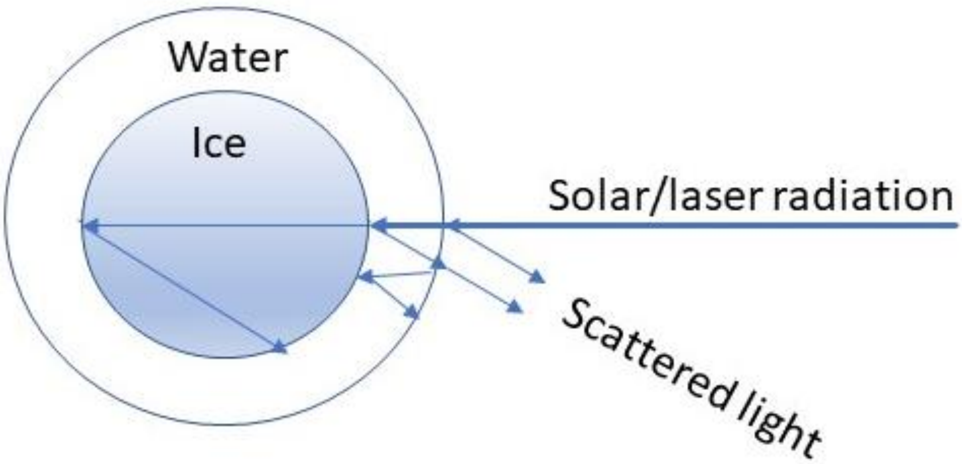

Figure 1. Illustration of the scattering and absorption process of light by a layered sphere.

We use a light scattering model for layered spheres based on the Mie theory [24,25] to calculate the single-scattering properties of these partially melting droplets. We apply the single scattering properties of these droplets to clouds with a modified Gamma distribution (MGD) of particle sizes defined by

$$dN/da = N_0 a^{\nu} exp(-\nu \frac{a}{a_0}) \tag{1}$$

where a denotes the droplet radius, a_0 is the modal radius, ν defines the shape of the distribution, and

$$N_0 = \frac{\nu^{\nu+1}}{\Gamma(\nu+1) a_0^{\nu+1}} N_{tot} \tag{2}$$

is a constant where $\Gamma(\nu+1)$ is the gamma function and N_{tot} is the total number of particles per unit volume. The commonly used C1 size distribution [26] is a specific case of the MGD with a_0 = 4 μm and ν = 6. The effective radius of particles with a MGD is

$$R_e = \frac{\int N(a) a^3 da}{\int N(a) a^2 da} = \frac{a_0}{\nu} \frac{\Gamma(\nu+4)}{\Gamma(\nu+3)} \tag{3}$$

As in Sun et al. [23], in this study we set N_0 = 0.7 and ν = 6 for all simulations. We assume that the particles represented by MGD_1 with a modal radius of a_0 = 4 μm are pure liquid water droplets, and those represented by MGD_2 with modal radii of a_0 = 4–30 μm (corresponding to effective radii R_e = 5–45 μm) are water droplets with ice cores. For particles represented by MGD_2, when their diameters are smaller than 20 μm, we still set them as pure liquid water droplets based on our assumption that small droplets should have melted completely when larger particles are partially melting. The two size distributions are summed together in calculation for the clouds' single-scattering properties. The ice core radius is randomly set by a random number function in FORTRAN between 0 and the radius of the whole droplet at each size bin. The bin size is set with a small value of 0.025 μm, so that this random core size scheme effectively produces a random core size distribution to approach a steady result. The integration of single-scattering properties of droplets for clouds is carried out over a particle diameter range from 1 to 500 μm, to include all possible sizes, including drizzle particles whose sizes are generally between 20 and 500 μm. Note that the units of N_0 and dn/da have no effect on the calculation [23].

For the effect of partially melting droplets on the polarimetric retrieval of water cloud particle size, we can simply study the cloudbow of the single-scattering matrix element P_{12} (linear polarization element) of the cloud particles. For the effect of partially melting droplets on the bi-spectral retrieval of water cloud particle size, we input the whole set of single-scattering properties of clouds into the adding-doubling radiative transfer model

(ADRTM) [27] to calculate the solar spectral reflectance to investigate the effect of ice cores in droplets on the spectral reflectance from the cloud at both VNIR and SWIR wavelengths. Through these calculations, we can evaluate the impact of partially melting droplets on the polarimetric and bi-spectral particle size retrieval methods.

Figure 2 shows the linear polarization degree (P_{12}/P_{11}) of the scattered light from water clouds calculated with the layered sphere light scattering model at a wavelength of 865 nm. At this wavelength, the refractive index of ice is 1.30378 + 2.400 $\times$ 10^{-7}, and the refractive index of water is 1.32437 + 3.546 $\times$ 10^{-7}. We assume a_0 = 10, and 16 µm, respectively, for two exemplary clouds. The clouds are either pure liquid water droplets or those with ice cores, as described previously. We can see that, when the clouds are dominated by large particles such as those with a_0 = 16 µm, the existence of partially melting droplets changes the cloudbow angle significantly, and this could cause the polarimetric method to underestimate the particle size up to ~12 µm. However, for moderate-sized particles such as those with a_0 = 10 µm, the polarimetric method should be able to retrieve accurate particle sizes no matter if the clouds consist of partially melting droplets or not.

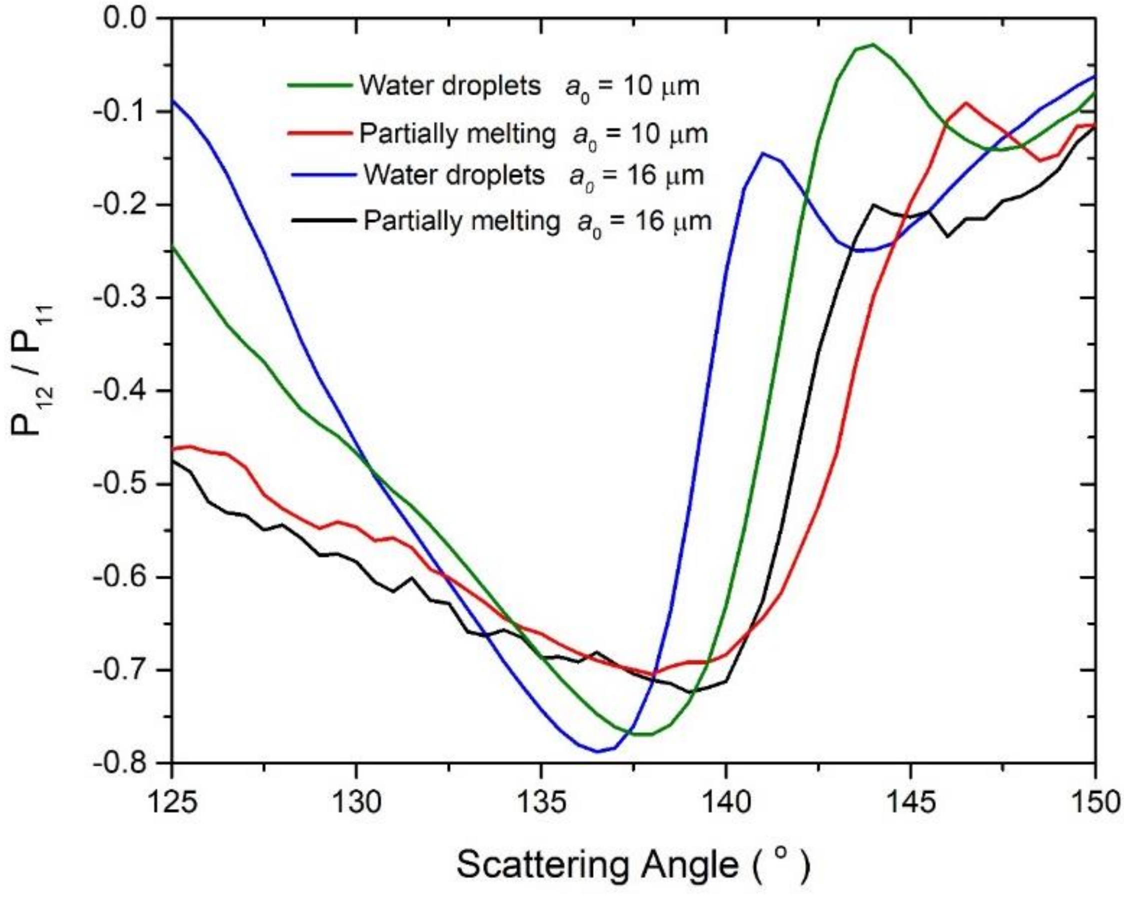

Figure 2. Linear polarization degree (P_{12}/P_{11}) of the scattered light from water clouds calculated with a layered sphere light scattering model at a wavelength of 865 nm.

We use the adding-doubling method to simulate water cloud reflectance at different solar wavelengths. We choose a solar zenith angle (SZA) of 30 deg. We assume a water cloud with an optical depth (OD) of 16 at 550 nm is located between 2 and 3 km altitude over an ocean surface with a wind speed of 7.5 m/s. The atmosphere is assumed to have a midlatitude summer profile and to contain oceanic aerosols with an aerosol optical depth (AOD) of 0.06 at 550 nm. All the modeling details including trace gas and water vapor absorption can be found in Sun and Lukashin (2013) [27].

Figure 3 shows the spectral reflectance at the nadir viewing angle from the ADRTM modeling for water clouds with a_0 = 10 µm with and without ice cores. We also calculate the reflectance of a pure liquid water cloud with a a_0 = 16 μm for comparison to the partially melting droplet case. We can see that partially melting droplets result in significantly larger absorption at the wavelength of 1.6 μm, which will cause an overestimation in the particle size using the bi-spectral method. By comparing the reflectance curve of the partially melting clouds with the precalculated look-up tables of the reflectance curves of pure water clouds, we can find the overestimated value of particles size due to partially melting droplets., e.g., at the band of 1.6 μm; the particle size of the clouds of a_0 = 10 μm could be estimated as ~14 μm if assumed partially melting droplets exist. However, at the band of 2.1 μm, the effect of partially melting droplets on the reflectance is negligible, thus having nearly no effect on particle size retrieval. This finding suggests that the retrieved droplet size difference between droplet sizes from 1.6 μm and 2.1 μm channels can be used to detect partially melting droplets.

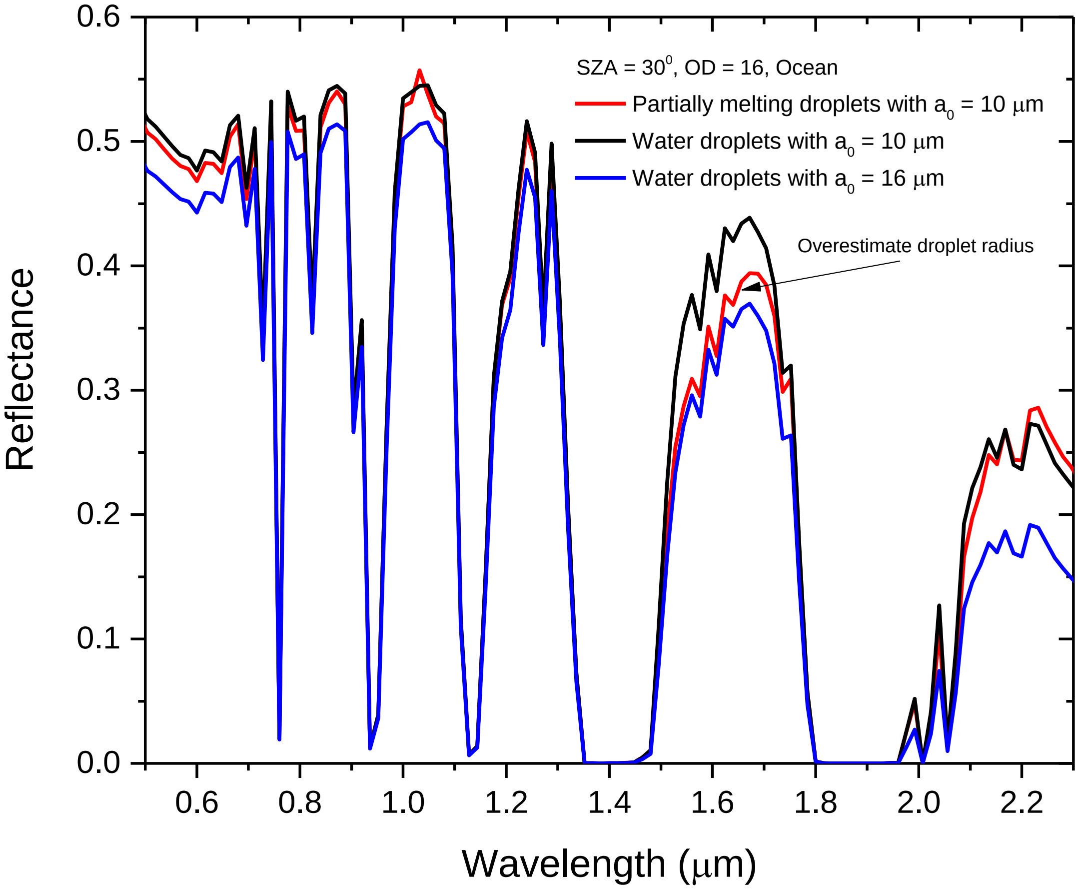

Figure 3. Solar spectral reflectance at the nadir viewing angle from the ADRTM for clouds with a_0 = 10 μm and with and without ice cores, respectively. We also calculate the water clouds without partially melting droplets but with a a_0 = 16 μm for comparison with the partially melting case. The solar zenith angle (SZA) is 30 deg. The optical depth (OD) of the cloud is 16 at the wavelength of 550 nm. The cloud layer is between 2 and 3 km altitude over an ocean surface with a wind speed of 7.5 m/s. The atmosphere is assumed to have a midlatitude summer profile and ocean background aerosols with an aerosol optical depth (AOD) of 0.06 at the wavelength of 550 nm. All the modeling details including gas/water vapor absorption can be found in Sun and Lukashin (2013) [27].

The effects of partially melting droplets on the single-scattering properties of water clouds at 1.6 and 2.1 μm wavelengths are given in Table 1. We can see that at the wavelength of 1.6 μm, ice cores significantly increase the absorption of light, and that the (*1—single scattering albedo*) of partially melting clouds with a_0 = 10 μm is very close to that of the pure liquid water clouds with a_0 = 16 μm. This enhanced absorption is the reason for the bi-spectral model's overestimation of the particle R_e by ~3 μm if considering both 1.6 and 2.1 μm channels for retrieval. Smaller single-scattering albedo due to inhomogeneity of the droplets results in overestimation of particle size by the bi-spectral method; this is valid generally for any clouds.

Table 1. Effect of partially melting droplets on single-scattering properties of water clouds at *1.6* and 2.1 μm wavelengths.

At 1.6 μm	Water a_0 = 10 μm	Water a_0 = 16 μm	Partially melting a_0 = 10 μm
Asymmetry factor: 1—Single Scattering Albedo:	0.860 1.0084×10^{-2}	0.872 1.5509×10^{-2}	0.864 1.5349×10^{-2}
At 2.1 μm	Water a_0 = 10 μm	Water a_0 = 16 μm	Partially melting a_0 = 10 μm
Asymmetry factor: 1—Single Scattering Albedo:	0.864 3.6776×10^{-2}	0.880 5.5580×10^{-2}	0.869 4.4225×10^{-2}

3. Summary and Conclusions

The water droplet size of water clouds can be retrieved either using the bi-spectral method or the polarimetric method. The retrieved droplet sizes derived from the bi-spectral method are sometimes significantly larger than those from the polarimetric method. Vertical spatial heterogeneity of the droplet size is considered as a likely cause of this difference. However, this study shows that partially melting droplets in mixed-phase clouds can be another cause of this difference. We find that, when the clouds are dominated by large particles such as those with a_0 = 16 μm, the existence of partially melting droplets could cause the polarimetric method to underestimate the particle size up to ~12 μm. For moderate-sized particles such as those with a_0 = 10 μm, the polarimetric method should be able to retrieve accurate particle size no matter if the clouds consist of partially melting droplets or not. However, the effective droplet radius of partially melting droplets from the bi-spectral method can be seriously overestimated if the infrared channel of the bi-spectral method is at the 1.6 μm wavelength, while the droplet radius retrieved from the bi-spectral method is relatively insensitive to the presence of partially melting spherical droplets when the infrared channel is at the wavelength of 2.1 μm. The retrieved droplet size difference between droplet sizes from 1.6 μm and 2.1 μm channels can be used to detect partially melting droplets.

Through this study and Sun et al. (2022) [23], we expect that partially melting cloud products can become a new product of satellite cloud observations, that can significantly improve the understanding of cloud physical processes, weather forecasting, and radiation climatology studies.

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