A Simple Model for Cloud Radiative Properties

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1. Introduction

Clouds play a vital role in the Earth's hydrological cycle by influencing the spatial distribution of latent heat and precipitation [*Olson et al*., 2006]. Clouds can also affect the radiation budget of the climate system via absorption, reflection and scattering of shortwave and longwave radiation [*Ramanathan et al*., 1989]. Cloud particles are largely composed of liquid water or ice. The microphysical properties of clouds, such as cloud droplet size, determine precipitation efficiency [*Shen and Li*, 2011] as well as the radiative properties of clouds.

In this work we create a simple model to examine the relationship between the radiative properties of droplets with different effective radius and liquid water path. The remainder of the paper is organized as follows. Model parameterization is described in section 2 and results are presented in section 3. Conclusions are summarized in section 4.

2. Model Description

The liquid water path (W_l) is defined as the vertical integral of the liquid water mixing ratio (w_l).

$$W_l = \int_{z_b}^{z_t} \rho_a w_l \, dz \tag{1}$$

where z_b and z_t are cloud base height and cloud top height, respectively, and ρ_a is the density of air. The size parameter (x) is the ratio of the particle circumference to the wavelength.

$$x = \frac{2\pi r}{\lambda} \tag{2}$$

where r is the radius of the droplet and λ is the wavelength. For cloud droplets, the size parameter is much greater than unity in the shortwave spectrum (*Curry and Webster*, 1998).

The volume extinction coefficient (σ_{ext}) is given by

$$\sigma_{ext} = \int_0^\infty n(r)\pi r^2 Q_{ext}(x) dr \tag{3}$$

where Q_{ext} is the extinction efficiency and $n(r)$ is the drop size distribution.

The extinction optical depth (τ_{ext}) is determined from

$$\tau_{ext} = \int \sigma_{ext} \, dz \tag{4}$$

When x is much greater than 1, which is the case for cloud droplets, Q_{ext} is approximately 2. Substituting this value into (4) and we can obtain from (1)

$$\tau_{ext} = \frac{3W_l}{2\rho_l \bar{r}_e} \tag{5}$$

where ρ_l is the density of water and r_e is the effective radius of cloud droplets defined as

$$r_e = \frac{\int_0^\infty r^3 n(r)\,dr}{\int_0^\infty r^2 n(r)\,dr} \tag{6}$$

Transmittance is defined as

$$\mathrm{T} = \exp(-\tau_{ext}) \tag{7}$$

And the sum of transmittance, absorption and scattering equals 1.

$$T + A + S = 1 \tag{8}$$

Because most water clouds are both optically thick and are only weakly absorbing, multiple scattering cannot be neglected (*Petty*, 2006). However, multiple scattering cannot be computed from a simple formula. To simplify the calculation, we empirically derive a ratio between scattering and the sum of scattering and absorption, essentially the single scattering albedo (ω), and assume that ω is a constant for a given r_e (Table 1). We use this simple model to examine the variation of shortwave radiative properties as a function of W_l for four values of r_e and three different types of clouds, namely cumulus (Cu), stratocumulus (Sc) and cumulonimbus (Cb).

3. Results and Discussions

Figure 1 shows the shortwave scattering as a function of W_l for four values of the mean effective radius. Scattering is calculated using equations 5, 7, 8 and ω given in table 1. Scattering increases as r_e decreases for a given value of W_l. When W_l is 10 g m^{-2}, scattering is 55% for r_e equals 2 μm compared to 15% for r_e equals 16 μm. Scattering has strong dependence on W_l when W_l is less than 100 g m^{-2}. Such dependence is much weaker when W_l exceeds 100 g m^{-2}.

Figure 2 shows the shortwave absorption as a function of W_l for four values of the mean effective radius. The variation of absorption depends on the value of W_l. For W_l less than 20 g m^{-2}, absorption increases as r_e decreases for a given value of W_l while for W_l larger than 20 g m^{-2}, absorption increases with increasing r_e. Absorption is notably smaller than scattering at any given W_l, indicating that scattering is dominant in water clouds. For example, when W_l reaches 1000 g m^{-2}, scattering approaches 90% while absorption is less than 10% for r_e equals 2 μm. When W_l equals 10, scattering is an order of magnitude larger than absorption for r_e less than 8 μm. ω decreases with increasing r_e, indicating that scattering is more prominent when the particle is small (Table 1).

We use this simple model to examine the radiative properties of three types of clouds, namely Cu, Sc and Cb. Cu clouds are dense low-level clouds with noticeable vertical development. Sc clouds are also found at low altitude with thinner vertical structure compared to Cu clouds. Cb clouds are denser than Cu clouds and are associated with intense precipitation. The base of Cb cloud is low, but vertical structure can extend for a few kilometers.

The shortwave scattering as a function of W_l for the three clouds is exhibited in figure 1. The mean effective radius, W_l and ω of each cloud are summarized in table 2. Sc clouds scatter more radiation than Cu and Cb clouds due to the relatively small r_e. Cb clouds have much larger W_l due to a massive vertical extension and larger r_e, which facilitates water droplets collision and growth, and consequently, produce heavy precipitation. Cb clouds scatter less radiation and therefore appear to be darker compared to Cu and Sc clouds.

The shortwave absorption as a function of W_l for the three clouds is exhibited in figure 2. Cb clouds are more absorptive than Sc and Cu clouds. The magnitude of absorption for Sc and Cu clouds are around 10%, a fraction of the magnitude of scattering (70%-80%), indicating that more radiation is scattered by the clouds than being absorbed.

4. Conclusions

The radiative properties of clouds depend on the size and the number of the water droplets in the clouds. Using a simple model we find that scattering and absorption increase with increasing W_l. The dependence of scattering and absorption on W_l is weak when W_l exceeds 100 g m^{-2}. Scattering is significantly larger than absorption at all W_l and small particles scatter more radiation. Absorption increases with particle sizes when W_l exceeds 20 g m^{-2}. Among the three types of clouds, Cb clouds have the largest r_e and W_l, and as a result, scatter less and absorb more radiation compared to Sc and Cu clouds.

Reference

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Table 1. Single scattering albedo for four values of r_e.

r_e (μm)	2	4	8	16
ω	0.93	0.92	0.90	0.85

Table 2. The mean effective radius and W_l of three types of clouds.

Cloud type	Sc	Cu	Cb
$\overline{r_e}$ (μm)	10	12	18
W_l (g m^{-2})	50-250	100-300	200-1000
ω	0.888	0.875	0.828

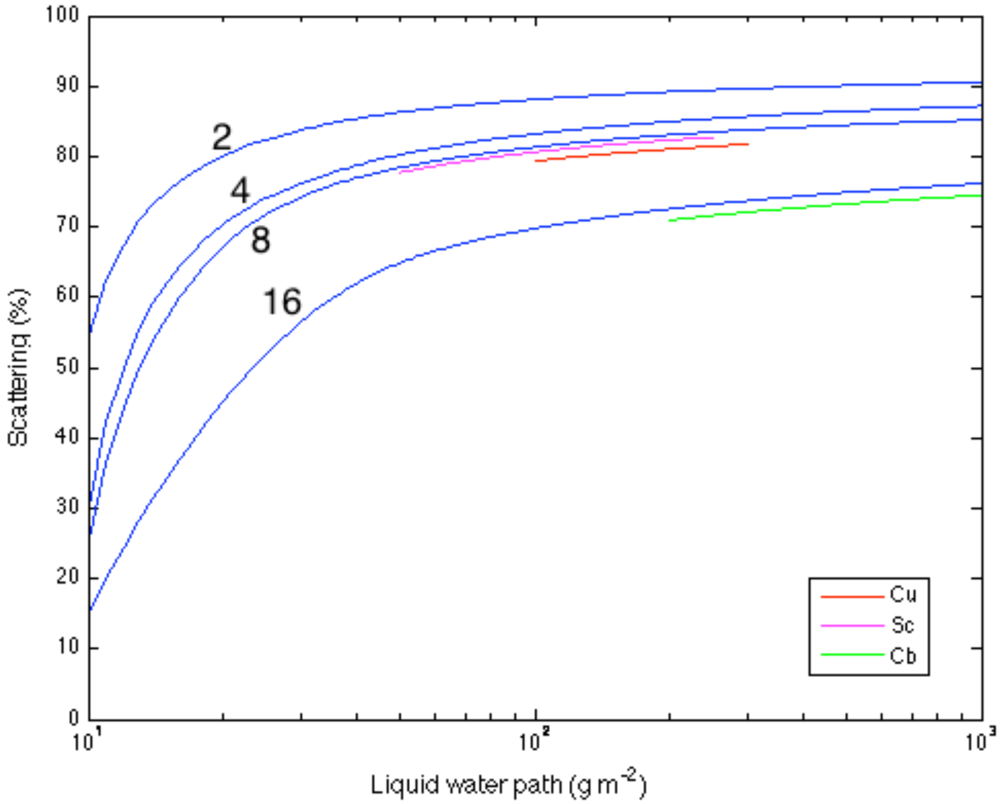

Figure 1. Shortwave scattering of water clouds as a function of the liquid water path for four values of the mean effective radius (μm). Red is cumulus. Magenta is stratocumulus and green is cumulonimbus.

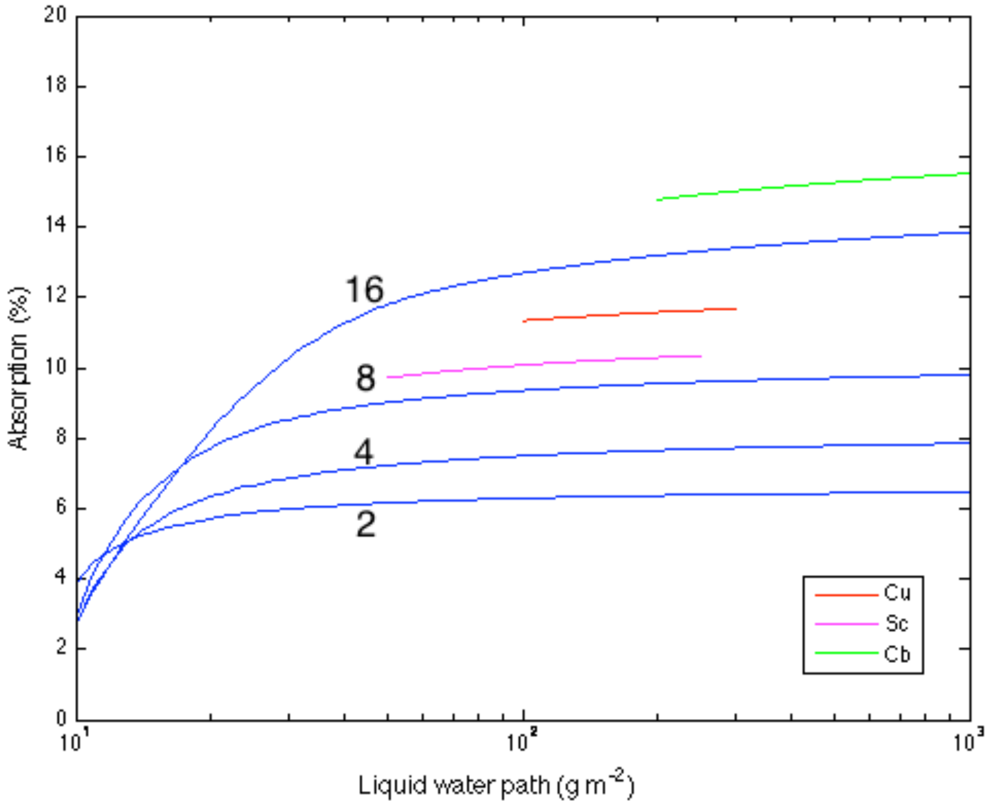

Figure 2. Shortwave absorption of water clouds as a function of the liquid water path for four values of the mean effective radius (μm). Red is cumulus. Magenta is stratocumulus and green is cumulonimbus.