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Short-wave optical properties of rain

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ABSTRACT

The optical properties of rain were derived from Mie theory for the short-wave region 0.25–5 μm, using lognormal rain-drop size distributions. The optical depth of rain follows the large-drop approximation closely. The asymmetry parameter is slightly larger than that for typical clouds, especially at around 1.5 μm. The quite variable coalbedo was parameterized for 4 spectral bands as a function of the rain intensity. For a cloudlayer with rain, the suggested flexible parameterizations may be combined in a simple fashion with existing cloud-drop optics, e.g. in GCM radiation schemes.

1. Introduction

The effects of rain on the cloud optics are presently neglected in weather forecast and general circulation models (GCM), although an estimate of the rain intensity R is available in these models. The optical properties needed for radiative flux calculations are the optical depth τ, the single scattering albedo ω, and the asymmetry parameter g. These were derived for precipitating and nonprecipitating waterclouds in Savijärvi et al. (1997, SAR in what follows) in the solar range $\lambda =$ 0.25–5 μm, by using Mie theory and integrating over several cloud-drop plus rain-drop size distributions. A parameterization scheme for the cloud optics including the large-drop part was also developed in SAR, by utilizing R. It was shown, for instance, that extra absorption of solar radiation in clouds (up to several tens of W m^{-2}) may take place due to the existence of the large drops (i.e. rain).

In this short note, Mie theory results for the optical properties of raindrops alone are presented, using rain-drop size distributions without cloud drops. As an alternative to SAR, a simple but relatively accurate four-spectral-band parameterization is developed for the rain optics in the shortwave region as a function of the rainfall rate. The rain optics (τ_r, ω_r, g_r) can then be combined with any cloud-drop optics (τ_c, ω_c, g_c), already in use, e.g., in a GCM radiation scheme, through:

$$\tau = \tau_c + \tau_r \,, \tag{1}$$

$$\omega = (\tau_c \omega_c + \tau_r \omega_r)/\tau \,, \tag{2}$$

$$g = (\tau_c \omega_c g_c + \tau_r \omega_r g_r)/\tau\omega \,, \tag{3}$$

which is valid assuming that raindrops are randomly distributed inside a cloud layer containing both cloud and rain. The cloud-drop optics might be parameterized, for instance, as in Slingo (1989), or as given in SAR. Eqs. (1)–(3) can then be fed into any multiple-scattering scheme calculations. Eqs. (1)–(3) have been used by, e.g., Rockel et al. (1991) when combining ice particle and water-drop optics of a mixed cloud.

The rain optics can also be utilized in a layer without cloud drops, i.e., below a precipitating cloud. Although this should have only a minor effect in a GCM framework, rains occurring normally for short periods of time only, case studies and some signal propagation applications (e.g.,

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visibility estimates) might find use of the following results and parameterizations.

2. Calculations and results

The rain-drop size distribution $n(r)$ used in the calculations is the lognormal distribution (Feingold and Levin 1986) as this was recommended by Sauvageot and Lacaux (1995) both for frontal and convective rain, based on surface observations on several latitudes. Fig. 1 shows the lognormal $n(r)$ for 3 rain intensities R. For comparison, a typical stratus-type cloud-drop distribution (the LOWTRAN-7 stratus of 250 drops/cm^3 with cloudwater content of 0.29 g m^{-3} and effective radius r_e of 8.3 μm), is also shown in Fig. 1. The rainwater content RWC is related to R in the lognormal $n(r)$ through

$$\mathrm{RWC} = 0.06R^{0.9}, \tag{4}$$

where RWC is in (g m^{-3}) and R in (mm/h). When the effective drop radius r_e is calculated from the lognormal rain-drop size distributions and plotted versus R, Fig. 2 is obtained, which shows that to a good accuracy

$$r_e = 500R^{0.23}, \tag{5}$$

where r_e is in (μm) and R in (mm/h). The relevant numerical details of these and the following Mie theory calculations may be found in SAR with the

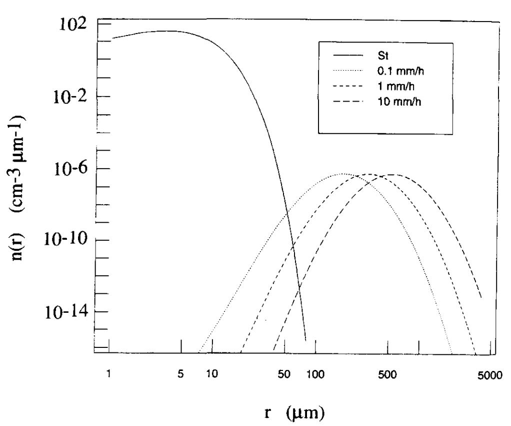

Fig. 1. Lognormal drop-size distributions $n(r)$ for rain with intensities $R = 0.1$, 1, 10 mm/h, and for a typical stratus cloud. r is in μm and $n(r)$ in cm^{-3} μm^{-1}. Note the logarithmic scales.

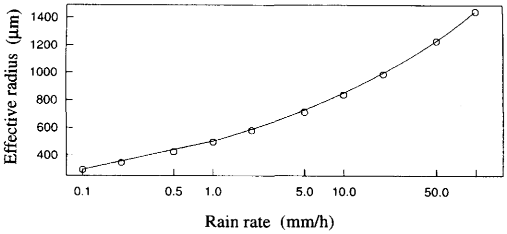

Fig. 2. Effective drop radius r_e (μm) versus rain rate R (mm/h) in the lognormal rain-drop size distribution (circles). The curve is eq. (5).

difference that the cloud-drop part is absent in the present application. The Mie calculations are based on the (slightly improved) code of Bohren and Huffman (1983), and on the refractive index of water from Hale and Querry (1973).

The volume extinction coefficient β_{ext}, coalbedo $1-\omega$ and asymmetry parameter g of rain are shown in Fig. 3 as a function of wavelength λ from 0.3 to 5 μm, for 3 rain intensities $R = 1$, 10 and 100 mm/h, corresponding to light, moderate and heavy rain, respectively. The coalbedo and asymmetry parameter of the nonprecipitating stratus cloud of Fig. 1 are also plotted in Fig. 3 for comparison. It can be seen that β_{ext} (top panel) is nearly independent of wavelength in the solar range. β_{ext} of rain is rather small in general, ≈ 1 km^{-1}, in concert with the common observation that visibility is not drastically reduced in rain unless the rain is heavy. For comparison, β_{ext} of the stratus cloud of Fig. 1 is much larger, 54 km^{-1}. The strongly varying single scattering coalbedo $1-\omega$ of rain (middle panel) is at its smallest in the visible range and depends distinctly on the rain rate mainly in the interval 0.3–2 μm. The coalbedo of rain is 1–2 orders of magnitude larger than that of the typical cloud, except at around 3 μm. The asymmetry parameter g of rain (bottom panel) is about 0.88 in the range 0.3–1.2 μm, and about 0.97 between 2.5–5.0 μm. It depends on R in the 1.2–2.5 μm interval where it is also clearly larger than the asymmetry parameter of the typical cloud.

The spectral data of Fig. 3 is available from the author on request.

3. Parameterizations for the rain optics

3.1. *Optical depth* τ_r

The optical depth of a vertically homogeneous rainlayer is $\tau = \beta_{ext}\Delta z$, while the rainwater amount,

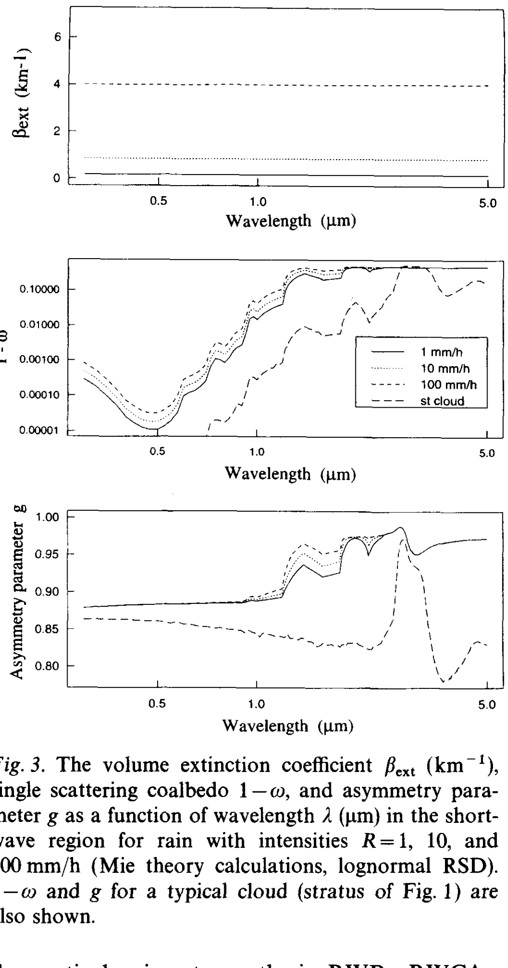

Fig. 3. The volume extinction coefficient β_{ext} (km^{-1}), single scattering coalbedo $1-\omega$, and asymmetry parameter g as a function of wavelength λ (μm) in the short-wave region for rain with intensities $R=1$, 10, and 100 mm/h (Mie theory calculations, lognormal RSD). $1-\omega$ and g for a typical cloud (stratus of Fig. 1) are also shown.

the vertical rainwater path, is $RWP = RWC\Delta z$. Thus $\tau/RWP = \beta_{ext}/RWC$. If β_{ext} of Fig. 3 is now plotted against RWC/r_e, practically the same linear curve is obtained for all wavelengths. The lines are close to the large-drop approximation, according to which $\beta_{ext} = 3RWC/(2\rho_w r_e)$, where ρ_w is the density of rainwater ($1\ g\,cm^{-3}$). The large-drop approximation is, of course, well obeyed by raindrops, which are much larger than the solar wavelengths. Thus one can write

$$\tau_r = sRWP/r_e\,, \tag{6}$$

where the slope s in the solar range is $1.505\ m^2\ g^{-1}\ \mu m$.

In some applications, (e.g., in some GCMs) the rainwater mass mixing ratio q_r and rain rate R might be available but not r_e of rain; then RWP is $\int q_r\ \Delta p/g$ where g is gravity. The optical depth of rain is in this case, using (5),

$$\tau_r = RWP{\cdot}0.003{\cdot}R^{-0.23}\,, \tag{7}$$

where R is in (mm/h) and RWP in ($g\,m^{-2}$). Alternatively, if only R is available in the host model, the relation (4) between RWC and R of the lognormal distribution can be utilized. This gives

$$\tau_r = 0.00018R^{0.67}\Delta z\,, \tag{8}$$

where R is again in (mm/h) and the depth of the homogeneous rainlayer Δz is in (m). A rainlayer 1 km thick with intensity of 1 mm/h thus produces an optical depth of 0.18.

Eqs. (6)–(8) are nearly independent of wavelength and are thus the same in any spectral band in the short-wave region. They are also valid for any nearly homogeneous path, not necessarily in the vertical. In fact it should be possible to validate (8) from horizontal visibility observations during rain of a known intensity.

3.2. *Single scattering albedo* ω_r

The quite variable single scattering coalbedo $1-\omega(\lambda)$ of rain was averaged over the 4 spectral intervals, which are used in the well-known cloud-drop optics parameterization of Slingo (1989), by weighing each wavelength by the fractional solar energy. The results are shown in Fig. 4, where $1-\omega$ is plotted versus R in each band. From the values in Fig. 4, one can deduce the following practical and simple parameterization for $1-\omega_r$ as a function of R in (mm/h):

$$\begin{aligned}
&\text{band 1 (0.25–0.69 μm): } 1-\omega = 0.00008R^{0.23}\,,\\
&\text{band 2 (0.69–1.19 μm): } 1-\omega = 0.0105R^{0.22}\,,\\
&\text{band 3 (1.19–2.38 μm): } 1-\omega = 0.264R^{0.09}\,,\\
&\text{band 4 (2.38–4.00 μm): } 1-\omega = 0.465R^{0.001}\,.
\end{aligned} \tag{9}$$

Should r_e be the preferred microphysical variable, $1-\omega$ can easily be deduced as a function of r_e by inverting (5) to $R=(r_e/500)^{-0.23}$ and substituting it in (9). For the first 2 bands, this obviously leads into linear growth of $1-\omega$ with r_e of rain. This is to be expected on the basis of the geometric optics approximation in these two spectral regions, where wavelengths are small (compared to the dropsize), and where absorption is weak (Twomey and

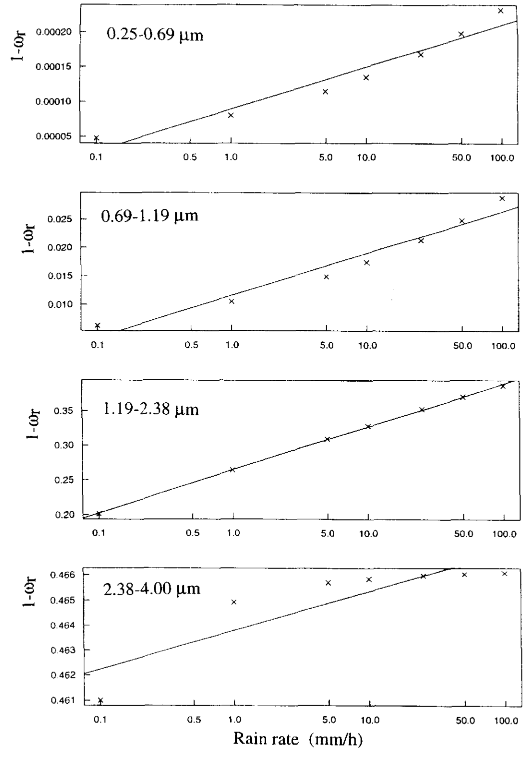

Fig. 4. $1-\omega_r$ averaged over 4 spectral bands as a function of rain intensity R (mm/h). Bands from top: 1: 0.25–0.69 µm, 2: 0.69–1.19 µm, 3: 1.19–2.38 µm, 4: 2.38–4.00 µm.

Bohren 1980). In bands 3 and 4, where the absorption is stronger, one obtains $1-\omega \approx (r_e)^p$ with $p<1$, in accordance with the anomalous diffraction theory (Ackerman and Stephens 1987).

Some GCM solar schemes make use of only two spectral bands; the visible and infrared. Band 1 of (9) is valid for the visible range. For the broad infrared band, the following fit is obtained from our results:

$$\text{IR: } (0.69\text{–}4.00\ \mu\text{m}):\quad 1-\omega = 0.118R^{0.08}\,. \qquad (10)$$

The two-band version may be inaccurate, however, when combined with the rapidly varying water vapor and/or cloud-drop absorption spectra. At least 4 bands were recommended by Slingo (1989) for cloud drops.

The coalbedo of typical clouds is smaller than that of rain, especially in bands 1 and 2. The importance of large drops for absorption of solar radiation in a rainy cloudlayer is, however, reduced by their small optical depth τ_r, which is the relative weight for the combined ω in (2). A cloud with lots of large drops near the cloudtop, e.g., a developing cu or cb, may, however, absorb considerably more solar radiation than a similar cloud consisting of small drops only, as was shown in SAR.

3.3. Asymmetry parameter g_r

The values of $g(\lambda)$ for rain, shown in Fig. 3, are not too far from those of g for typical clouds, g_c, although they are slightly larger. Furthermore, eq. (3) suggests that g_c will dominate in a cloudlayer with rain, as the relative weight of g_r is smaller than the weight of g_c, due to smallness of τ_r versus τ_c. This was in fact shown in SAR by Mie calculations over the whole droplet spectrum (cloud + rain). Thus for a cloudlayer with or without rain, it is suggested that $g = g_c$. For a layer with rain but no clouddrops, suitable g-values may be estimated from Fig. 3. Thus $g_r \approx 0.88$ in band 1, 0.89 in band 2, 0.94 in band 3 and 0.97 in band 4. Since the typical two-stream multiple scattering schemes are not too sensitive to the exact values of g when there is absorption (which is the case for raindrops), this should be accurate enough for any practical purpose.

3. Conclusions

Mie theory results for the optics of lognormal rain-drop size distributions were presented in the solar range and a simple parameterization scheme was presented as a function of rain rate (or, alternatively, of the effective drop radius r_e of rain). Rain-drop size distributions may not be exactly lognormal in all cases, but it is felt that the results are not sensitive to the details of the drop-size distribution. The optical depth of rain followed the large-drop approximation quite well while the asymmetry parameter of rain was slightly larger than that of clouds. The coalbedo of rain was larger than that of clouds, especially in the visible wavelengths. Its dependence on the rain rate R and on wavelength was quite strong. The coalbedo was parameterized in 2 and 4 spectral bands as a power function of R or r_e.

The suggested parameterizations can be used for layers with rain only. They can also be combined in a simple fashion with existing cloud-drop optics for layers containing both cloud and rain. The validity of the latter technique (eqs. (1)–(3)) has been checked against the results from the direct integrations through the whole droplet spectrum 0.5–5000 μm of SAR.

5. Acknowledgements

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