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The Effects of Rain on Longwave Radiation

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Abstract This article describes a simple parameterization of the effects of rain on longwave radiation.

1 Introduction

Most radiation parameterization schemes, including the unified model radiation scheme (Ingrams 1993), ignore the effects of rain. Since rain drops are bigger than cloud droplets, for the same water content, the total surface area of rain drops is less than for cloud droplets. Therefore rain will not absorb longwave (LW) radiation as strongly as clouds. However LW absorption by rain is likely to be important outside cloudy areas (*ie* below cloud base) since absorption by rain is of similiar or greater magnitude than absorption by atmospheric gases.

2 Absorption by rain

Here I follow the approach given in section 3 of Stephens (1984) for the absorption of LW radiation by cloud droplets. The absorption by rain of radiation with wavelength λ travelling through a path (z, z') inclined at an angle $\theta(= \cos^{-1}\mu)$ is given by;

$$A_\lambda(z, z', \mu) = 1 - \exp\left[-\delta_\lambda(z, z', \mu)\right], \tag{1}$$

where δ_λ is the absorption optical thickness

$$\delta_\lambda(z, z', \mu) = \frac{1}{\mu}\int_z^{z'} \kappa_\lambda(\tilde{z})\, d\tilde{z}. \tag{2}$$

The above formulation is correct when horizontal variations can be neglected as is assumed by the two stream approximation, which is used almost universally. κ_λ is the volume absorption coefficient for rain and is given by the following equation, *ie* the absorption due to the rain at $\tilde{z}$ is given by the sum of the absorption by the individual rain drops. Thus

$$\kappa_\lambda(\tilde{z}) = \pi\int_0^\infty n(r, \tilde{z}) r^2 Q_{abs}(\lambda, r)\, dr\,, \tag{3}$$

where r is the radius of a rain drop, and $Q_{abs}(\lambda, r)$ is the absorption efficiency of a drop with radius r for radiation with wavelength λ. $n(r, \tilde{z})$ is the size spectra of rain drops defined such that $n(r, \tilde{z})dr$ is the number of rain drops per unit volume in the radius interval $(r, r + dr)$.

For spherical drops Q_{abs} is obtained from Mie theory (Van de Hulst 1957, Liou 1980). However in the limit that $r \gg \lambda$ we can make use of the approximation that $Q_{abs} = 1$ (see figure 11 of Stephens 1984). This approximation is reasonable since rain drops have radii much larger than $50\,\mu m$ while the LW radiation of most significance is in the 'window' region where $\lambda \simeq 10\,\mu m$. Note that for cloud droplets, the droplet radius is much smaller than the wavelength and the absorption efficiency is assumed to vary linearly with droplet size.

Sustituting $Q_{abs} = 1$ into (3) gives us the following equation for the volume absorption coefficient due to rain

$$\kappa(\tilde{z}) = \pi \int_0^\infty n(r,\tilde{z}) r^2 \, dr \,, \tag{4}$$

Note that our approximation for Q_{abs} has removed the dependence of the volume absorption coefficient on wavelength, consequently the subscript λ is dropped. It is usual in radiation parameterization schemes to write κ in terms of water content (mass of water per unit volume) and effective radius (which will be definied shortly). We can write the rain water content as

$$w(\tilde{z}) = \rho_w \frac{4}{3} \pi \int_0^\infty n(r,\tilde{z}) r^3 \, dr \tag{5}$$

where ρ_w is the density of water. Using (4) and (5) we then obtain

$$\kappa(\tilde{z}) = \frac{3}{4} \frac{w(\tilde{z})}{\rho_w r_e(\tilde{z})} \tag{6}$$

where r_e is the rain drop effective radius defined by

$$r_e(\tilde{z}) = \frac{\int_0^\infty n(r,\tilde{z}) r^3 \, dr}{\int_0^\infty n(r,\tilde{z}) r^2 \, dr}. \tag{7}$$

3 Effective rain drop radius

Most general circulation models or cloud models do not give us any information about the rain drop size distribution from which an effective radius may be calculated. We could just assume a fixed effective radius (as is often done for the scattering of short-wave radiation by cloud droplets), however better results may be obtained by using the empirical relationship of Marshall and Palmer (Cotton and Anthes 1989)

$$n(r,\tilde{z}) = N_0 \exp\left[-\Lambda(\tilde{z})r\right] . \tag{8}$$

For Kessler microphysics N_0 has a fixed value of $8 \times 10^6\, m^{-4}$ and Λ is a function of rain water content;

$$\Lambda(\tilde{z}) = \left(\frac{\pi \rho_w N_0}{w(\tilde{z})}\right)^{1/4} . \tag{9}$$

Putting (8) and (9) into (7) and integrating by parts we find that

$$r_e(\tilde{z}) = \frac{3}{\Lambda(\tilde{z})}, \tag{10}$$

thus we can now write κ in terms of the rain water content only

$$\kappa(\tilde{z}) = 17.7 \times \left(\frac{w(\tilde{z})}{\rho_w}\right)^{3/4} \tag{11}$$

The above equation is correct for *mks* units which are used throughout this article.

4 Diffuse broadband flux transmissivity

For the problem of radiative transfer, the quantity of interest is the diffuse broadband flux transmissivity $\mathcal{T}_{\bar{\lambda}}^f$. This contains the effect of the atmospheric gases, clouds and rain. However it is possible to consider the effect of these components in isolation since

$$\mathcal{T}_{\bar{\lambda},total}^f = \mathcal{T}_{\bar{\lambda},gas}^f \times \mathcal{T}_{\bar{\lambda},cloud}^f \times \mathcal{T}_{\bar{\lambda},rain}^f \tag{12}$$

where the subscript gas, cloud or rain indicates that only the effect of that element is considered. $\mathcal{T}_{\bar{\lambda},rain}^f$ is obtained by a suitiably weighted average of the transmissivity $\exp[-\delta_\lambda(z,z',\mu)]$ over a directional hemisphere and over a frequency (wavelength) band. For rain κ is independent of wavelength and consequently only the averaging over a directional hemisphere needs to be performed. This is approximated by the introduction of a diffusivity factor $\beta = 1.66$. This then gives

$$\mathcal{T}_{\bar{\lambda},rain}^f(z,z') = \exp\left[-17.7 \times \beta \int_z^{z'} \left(\frac{w(\tilde{z})}{\rho_w}\right)^{3/4} d\tilde{z}\right] . \tag{13}$$

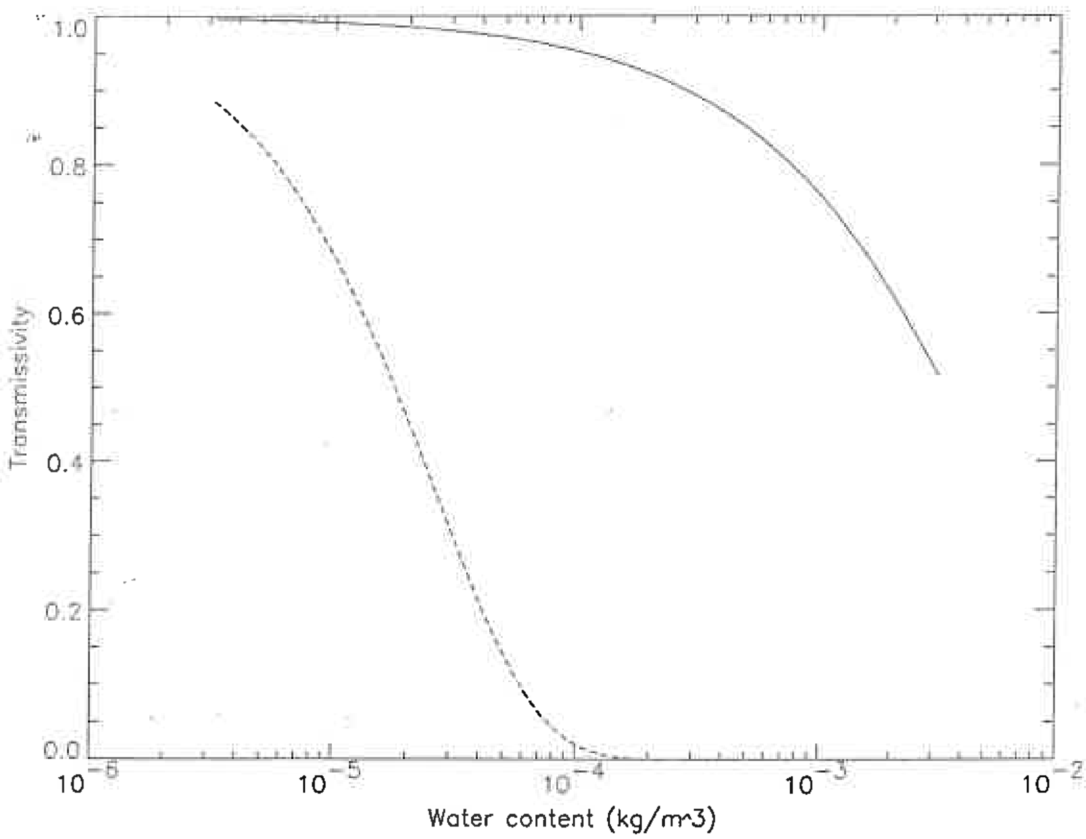
Figure 1 shows a comparison of $\mathcal{T}^f_{\bar{\lambda},rain}$ and $\mathcal{T}^f_{\bar{\lambda},cloud}$ for a 300m wide slab, *ie* $z - z' = 300m$. This value is typical for the vertical resoloution of our cloud model. In this example the water content is kept constant within the slab. For clouds, the result given by Stephens (1984) is used

$$\mathcal{T}^f_{\bar{\lambda},cloud}(z, z') = \exp\left[-k_{cloud}\int_z^{z'} w(\tilde{z})\, dz\right], \tag{14}$$

and as in the unified model LW radiation scheme $k_{cloud} = 130\, m^2\, kg^{-1}$. From figure 1 it is clear that absorption by cloud is significantly greater than absorption by rain. Therefore it is inappropriate to treat rain water in the same manner as cloud water. However, absorption by rain is still significant compared with absorption by atmospheric gases. For water vapour line absorption through a 300m wide slab with a water vapour concentration of $10^{-2}\, kg\, m^{-3}$, the transmissivity is greater than 0.95 in the window region. Preliminary results from a tropical squall line simulation show that including the effects of rain on the LW radiation spreads the cloud base warming down into the rain and reduces the magnitude of the warming.

5 Figure captions

Figure 1. Comparison of transmissivity of a $300m$ wide slab for absorption by rain (solid curve) and cloud (broken curve) as a function of water content.



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