On the reflectance of cellular cloud layers

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SUMMARY

A Monte Carlo model is used to investigate the effects on the reflectance of low cloud layers of organized cellular structure, which is often observed in such layers. It is assumed that the cloud is composed of a series of cells each of which comprises a core region surrounded by a wall region of reduced water content. It is shown that the sensitivity of reflectance to the structure is largest for wavelengths that are not absorbed by liquid water. The reflectance of the cloud layer is reduced when the water content in the regions of low water content is less than about 30% of the water content in the remainder of the layer. The effect on the cloud-layer reflectance of organized structure in the water content is large compared with the effect of changes in the effective radius at cloud top. It is further shown that, for narrow (~100 m) regions of low water content, estimations of the layer average reflectance based on the area weighted average of the reflectance of layer clouds with high and low water contents are significantly in error. For small solar zenith angles the regions of low water content tend to permit incident radiation to pass through the cloud, reducing the reflectance, while for large solar zenith angles the reflectance is increased by the effects of cloud shadowing.

1. INTRODUCTION

The importance of the interaction between clouds and incoming solar radiation has been established by many authors through the use of numerical models of the general circulation of the atmosphere. Since the grid length employed in such models is longer than the horizontal scale of most clouds, it is necessary to parametrize many aspects of the cloud–radiation interactions. Recent work has demonstrated the sensitivity of climate simulations to these parametrizations; for example, Mitchell et al. (1989) and Smith (1990) discussed the prediction of cloud water content while Slingo (1990) demonstrated the importance of the droplet size distribution which is parametrized using an effective radius. Such is the sensitivity, that changing the parametrization may result in circulation changes similar to those resulting from doubling the concentration of carbon dioxide in the atmosphere.

Parametrization of the radiative properties of clouds usually involves the derivation of 'mean' cloud microphysical properties and the use of these in radiative-transfer calculations. Parametrizations are usually based on the assumption that the clouds within the grid volume are homogeneous, and, although they may only occupy a fraction of the volume, edge effects are neglected. It is well known that clouds are not homogeneous. The water content normally increases with height above cloud base, while even apparently uniform cloud layers exhibit considerable variability in the water content and droplet spectrum on scales ranging from less than 1 metre to more than 1 kilometre. The aim of the present note is to provide an indication of the effects of such variability on the short-wave radiative properties of low-level layer clouds. While it is not intended to develop improved parametrizations here, the results could be used in sensitivity studies to determine the degree of complexity that is required for parametrizations developed for particular applications.

In attempting to explain the reflectivity of layer clouds determined from satellite observations, Coakley (1991) suggested that the observed variation with wavelength and satellite viewing angle resulted from non-uniformities in the water content, with regions of high water content surrounded by regions of reduced water content and reduced droplet size. Nicholls and Leighton (1986), and others, have demonstrated from in situ aircraft microphysical observations that mid-latitude stratocumulus layers do indeed exhibit a cellular structure, with active updraught regions surrounded by subsiding regions in which the water content is reduced. The observations also indicated that the water content in such cloud layers roughly increases linearly with height above the cloud base. Variability in the optical thickness and effective radius of the droplet distribution in stratocumulus layers was also apparent in the radiometer measurements of Rawlins and Foot (1990).

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The short-wave properties of different types of low-level cloud have been modelled by many authors. McKee and Cox (1974) were among the first to use Monte Carlo methods to determine the variation of the reflectance of clouds as functions of cloud thickness and solar zenith angle. The results of these and other studies suggest that the reflectance varies strongly with zenith angle, and increases rapidly as the cloud depth is increased from 100 m to 1 km, but less rapidly for further increases in cloud thickness. Foot (1988) showed that the reflectance was dominated by the microphysical properties close to the top of the cloud layers, since little radiation penetrates into the interior of the cloud. The problem of broken cloud fields is much more complex than that of layer clouds, due in part to the extent to which the clouds cast shadows on each other. Hence the radiative properties depend on both the depth and spacing of the clouds. The complexity of the results was demonstrated by Kite (1987), whose results indicate that, even for the same horizontally averaged water content, the radiative properties of the cloud field are determined by the size and spacing of the clouds.

Some aspects of the effects of cloud variability on radiative transfer have been investigated by Davis et al. (1991). These authors used a fractal model to represent the cloud variability but used a simplified radiative-transfer model. Stephens (1988) considered the general problem of the effects of inhomogeneity on radiative properties, but the magnitude of the effects in clouds was not clearly established. In the present work, an idealized model of the in-cloud variability is employed, together with a detailed radiative-transfer model. Jonas (1992a) showed that microphysical variations close to the edges of localized clouds could have a significant effect on the reflectance of such clouds, and that significant effects would also result from similar, but random, variations within the clouds. From the results of the present work it is possible to demonstrate the importance to the reflectance of layer clouds of organized variability on different scales, although the importance of interactions between the different scales cannot be treated with the simplified cloud model used here.

2. The model

The model consists of two parts, a model of the structure and microphysical properties of the stratuscumulus layer, and a radiative-transfer model.

(a) Cloud structure and microphysical properties

The cloud layer is assumed to be composed of a series of identical hexagonal cells of radius \( R_{cell} \), as shown in Fig. 1. The cells consist of vertical, active core regions surrounded by wall regions of thickness \( R_{wall} \). In both regions the water content and droplet size distribution are assumed to be horizontally uniform and the water content is assumed to increase linearly with height above cloud base. Unless otherwise stated, the water content in the core regions is assumed to increase at 1 g m\(^{-3}\) km\(^{-1}\) above cloud base; this is typical of mid-latitude stratuscumulus and represents about 40–70\% of the adiabatic liquid water content in a closed parcel lifted from cloud base. In the wall regions the water content is assumed to be some fraction, \( f_{\text{wall}} \), of the value at the same level in the core region. The value of \( f_{\text{wall}} \) is independent of height, but may be varied to simulate different types of layers, ranging from horizontally uniform 'stratuscumulus' layers (\( f_{\text{wall}} = 1.0 \)) to hexagonal 'cumulus' clouds separated by clear air (\( f_{\text{wall}} = 0.0 \)). In most of the calculations the core water content was held constant, so that as \( f_{\text{wall}} \) was decreased the horizontal average water content was reduced. Some calculations were also made, however, in which the reduction in the water content in the walls was compensated by an increase in the cell water content, so that the horizontal average water content at all levels was preserved.

In order to calculate the cloud radiative properties it is assumed that the local values of the scattering coefficient and phase function are functions of the local cloud water content and wavelength alone. These were normally derived assuming a droplet concentration of 320 cm\(^{-3}\) and an effective radius, \( r_e \), for the droplet spectrum which was related to the water content, \( w_l \), by

\[
r_e^3 = 1080 w_l
\]

where \( r_e \) is in \( \mu \text{m} \), and \( w_l \) in g m\(^{-3}\). This approximation is consistent with the observational results of Bower and Choularton (1992) and the calculations of Jonas (1991). It is implicit in this approximation that the differences in the water content between the core and wall regions result from differences in the spectrum, not in the droplet concentration. However, to test the sensitivity of the results to this approximation, some of the calculations were repeated with the assumption that the reduction in the water content in the wall regions was the result of a reduction in the
droplet concentration compared with the concentration in the core, and the effective radius was the same as that in the core at the same level.

(b) **Radiative-transfer model**

The radiative-transfer model is based on the Monte Carlo model described by Jonas (1992a). The paths of large numbers of photons are traced through the cloud layer as they undergo scattering according to the local values of the phase function and scattering coefficient. In order to avoid recalculating these parameters at each point along the photon paths, they were derived by interpolation between tabulated values obtained from detailed Mie-scattering calculations for several values of the effective radius. Some simulations (see Jonas (1992b)) were also made using the radiative properties derived assuming the droplet spectra used by Deirmendjian (1969), but the results were not significantly different from those shown here. The use of the effective radius was adopted in the present work since its variability within clouds is better justified by observations than is any systematic change of droplet spectrum.

The effects of gaseous absorption are neglected in the model. However, depending on wavelength, absorption by liquid water is included by reducing the weight associated with each photon as it undergoes scattering events. Thus each photon may be considered as representing the path of a group of photons whose number is reduced by absorption in the cloud droplets. In the model it is assumed that the incident radiation is in a single direction, that is the cloud is directly illuminated. It is recognized that this approximation will give rise to errors in calculating the total upward flux of radiation, but the aim of the present work is to investigate the sensitivities of one cloud process and not to attempt to model the complete radiative budget of the cloud layer. Furthermore, the effects of emission are also neglected; these might be expected to be significant at 3.9 μm where the emission from low-level clouds is of the order of 30% of the upward-scattered radiation.

The photons are assumed to enter the top of the cloud layer at random positions and they are traced until they leave the upper or lower surface of the layer. Incident photon paths have a prescribed solar zenith angle and the azimuthal direction is assumed to be parallel to one face of the hexagonal cells, as shown in Fig. 1. Advantage was taken in the model of the fact that all cells are identical. A photon leaving the side of one cell was assumed to re-enter it on the opposite side, reducing the need to consider a cloud of large horizontal extent. The reflectance is determined from the ratio of the number, or total weight, of photons emerging from the upper surface of the cloud layer, to the incident number. (Other authors have used a variety of expressions including **integrated hemispheric reflectance** to denote the parameter denoted here simply as the reflectance.)
A statistical analysis, as well as calculations using different numbers of photon paths, suggests that the reflectances are accurate to better than 0.02. The largest uncertainty arises from the interpolation of the phase function, not from the limited number of photon paths ($\sim 10^5$) which were analysed.

3. Results

The effect of reducing the water content in the wall regions is illustrated by Fig. 2 which shows, for a particular cloud geometry, the reflectance as a function of solar zenith angle. In this example the cloud thickness is 300 m and the value of $R_{\text{cell}}$ is 600 m. In accordance with the observations of Nicholls (1989), the value of $R_{\text{wall}}$ is here chosen to be one sixth of the core size, 100 m.

When $f_{\text{wall}}$ has the value 1.0 the results are almost identical with those reported by Jonas (1992a) for horizontally uniform clouds, any discrepancies resulting from the use of the equivalent radius, rather than the detailed droplet spectrum, to calculate the local phase function. At 0.45 $\mu$m the reflectance of the cloud layer is reduced as $f_{\text{wall}}$ is reduced, but the changes are small until $f_{\text{wall}}$ is reduced below 0.3. However, at 3.90 $\mu$m the effect of the reduced water content in the wall regions is not seen until $f_{\text{wall}}$ is reduced to less than 0.2 and, even then, the changes are much

![Graph](image_url)  

**Figure 2.** Reflectance of a 300 m deep stratocumulus layer with $R_{\text{cell}} = 600$ m and $R_{\text{wall}} = 100$ m for the indicated values of $f_{\text{wall}}$ (a) at 0.45 $\mu$m, (b) at 3.90 $\mu$m. See text for the details of the dotted curves in (a).
smaller than at 0.45 μm. This is a consequence of strong absorption at the longer wavelength which reduces the sensitivity of the reflectance to changes in the properties of the cloud layer unless the layer is very thin or the walls contain very little liquid water. For horizontally uniform layers the reflectance at 0.45 μm, where there is no absorption, increases by a factor of more than two as the thickness of the layer is increased from 100 m to 1 km, as can be seen in Fig. 3. The reflectance at 3.90 μm shows little systematic dependence on cloud thickness over this range, although it decreases as the cloud thickness is increased beyond 1 km as a result of increased absorption due to the high values of the liquid water content close to the top of the deep clouds. The largest reflectance at this wavelength is found for a cloud approximately 500 m thick, although the exact value depends on the solar zenith angle.

Figure 3. Reflectance of horizontally uniform layers 100 m, 300 m and 1.0 km deep, at 0.45 μm.

Results obtained at 0.45 μm but with the low water content in the walls resulting from reduced droplet concentrations, rather than spectral changes, are also shown in Fig. 2 by the dotted lines, which are the lower of the two curves shown for values of \( f_{\text{wat}} \) of 0.1 and 0.3. The results for values of \( f_{\text{wat}} \) of 1.0 and 0.0 are, of course, identical with those obtained in the calculations described above in which the walls are characterized by smaller droplets. It can be seen that while the reflectances obtained with reduced droplet concentrations and \( f_{\text{wat}} = 0.3 \) are only slightly smaller than those where the effective radius is reduced, the reduction is much greater for \( f_{\text{wat}} = 0.1 \). This is a consequence of the greater sensitivity of the scattering coefficient to drop concentration than to effective radius. For conditions typical of cloud top, a 3% change in effective radius results in a 2% change in scattering coefficient, only one quarter of the effect of a change in droplet concentration giving the same change in water content.

The same general trend is found even when the cell radius and wall thickness are increased by a factor of four; there is little effect of the cellular structure until the wall water content is a small fraction of that in the core region, as with the smaller cells. Results obtained at 0.45 μm are shown in Fig. 4; at 3.90 μm the effects are much smaller than at 0.45 μm. The largest difference between the results at 0.45 μm, shown in Figs. 2(a) and 4, is for small values of \( f_{\text{wat}} \) and for large solar zenith angles. It is probable that this is a geometric effect due to the reduced effect of cloud shadowing as the spacing is increased while the cloud depth remains constant.

The reflectance of the layer with larger cells \( (R_{\text{cell}} = 2.4 \text{ km}) \) for \( f_{\text{wat}} = 0.0 \) varies between 64% and 73% of that for the uniform layer, as shown in Fig. 5. The reflectance obtained from a weighted average of the reflectance of cloudy areas and clear areas (the latter having zero reflectance) is 65% of that for a uniform layer with the same water content as that in the cell core. However, in the case of the smaller cellular structure \( (R_{\text{cell}} = 600 \text{ m}) \), and for small solar zenith angles, the reflectance is lower than would be expected from the weighted average, owing to interactions between adjacent cells. For this structure the interactions also lead to a reflectance in excess of the weighted average for higher zenith angles. Although the results are only presented for broken cloud fields \( (f_{\text{wat}} = 0.0) \), similar results were also found for larger values of \( f_{\text{wat}} \).
These results demonstrate the importance of two processes that influence the reflectance of broken cloud layers: channelling of radiation through narrow gaps between the clouds, and cloud shadowing. In the case of the smaller cells, channelling of the radiation through the layer results in reduced reflectances for small solar zenith angles where shadowing effects are small. As the solar zenith angle is increased, shadowing becomes more important, and this has the effect of increasing the reflectance of the layer compared with the weighted average. For the larger cells the gap is also larger, reducing the channelling effect, so that the reflectance at small solar zenith angles, where shadowing is not significant, is similar to the weighted average value. As the zenith angle is increased, shadowing effects again become important, increasing the reflectance, but by a smaller amount than for the smaller cells. An estimate of the solar zenith angle, \( \phi \), at which shadowing becomes important can be obtained using the expression \( \tan(\phi) = 2 \times R_{\text{wall}} / (\text{cloud depth}) \). This gives a value of about 35° for the small cells and 70° for the larger cells. These figures are consistent with the zenith angles at which the calculated reflectances significantly exceed the area weighted average values.
The fact that it is the absolute thickness of the wall regions, rather than their relative thickness, which is important for channelling the radiation can be seen in Fig. 5, in which the results are also shown for the larger hexagonal cell size \( R_{\text{cell}} = 2.4 \text{ km} \) but with the wall thickness reduced to 100 m. Here the weighted reflectance would be 91% of that for a uniform layer, but the calculated values for \( f_{\text{wat}} = 0.0 \) are significantly smaller than this for solar zenith angles less than 30° because of significant channelling. For larger values of the solar zenith angle the reflectance is again larger than the weighted average owing to shadowing. While narrow gaps between the clouds, or regions of low water content, tend to channel the incoming radiation through the clouds for small solar zenith angles, the cloud-shadowing effect at larger zenith angles results in more of the incoming radiation being reflected by the cloud.

Although results have only been presented here for a limited number of cloud geometries, calculations have been made for a number of different cases. It may be concluded that channelling is important when the value of \( R_{\text{wall}} \) is less than about 150 m (or the gap between the active regions is narrower than 300 m) while shadowing becomes important at large solar zenith angles determined by the ratio of the cloud depth to the wall thickness.

It should be noted that, from the point of view of the development of parametrizations of layer-cloud reflectance, it is important to know how the reflectance varies with cloud structure under the constraint of constant horizontal average water content, rather than with the constant core-water content used in the calculations described above. The effect of such a constraint is small, however, as can be seen in calculations at 0.45 \( \mu m \) shown in Fig. 6. In these calculations the water content in the core has been increased, with constant droplet concentration, as \( f_{\text{wat}} \) is reduced, to preserve the horizontal average value of the water content. The results show a similar trend to those of Fig. 2, with the increased reflectance of the core as the water content is increased failing to compensate for increased transmission through the wall regions as the water content in these regions is reduced.

![Figure 6](image)

Figure 6. As Fig. 2(a) except that the core liquid-water content was increased as \( f_{\text{wat}} \) was reduced, to preserve the horizontal average water content at any level.

4. Discussion and Conclusions

The calculations presented in this note are intended to indicate the possible importance of cloud structure on the optical properties of layer clouds with a view to assessing the potential accuracy of cloud-parametrization schemes based on assumptions of uniform layer clouds. In particular, while regions of reduced water content reduce the reflectance, especially if liquid water absorption is weak, they also serve, for small solar zenith angles, to facilitate the passage of radiation through the cloud layer. In contrast, for large solar zenith angles, interactions between the high water-content regions tend to reduce the transmission through the layer when compared with a weighted average of the regions of high and low water content.
The climatological importance of changes due to the cellular cloud structure can be judged from calculations in which the assumed droplet concentration was changed. Changes in concentration of 40% are equivalent to changes in the effective radius of the droplets at the top of a 300 m deep cloud layer of about 1 μm. The present model predicts that such an increase in the effective radius increases the reflectance of a uniform layer at 0.45 μm by about 0.02 over the whole range of solar zenith angles. Changes in the cellular structure may change the reflectance by around 0.1 and therefore have an effect on the reflectance which is larger than that of a 1 μm change in effective radius, which was shown by Slingo (1990) to be climatologically significant.

The model which has been used is highly idealized; clouds exhibit organization on a wide range of scales that has been approximated here by two length-scales, those of the active and wall regions. Furthermore, the model has retained the approximation of plane parallel surfaces to the cloud layer. As Foot (1988) showed, the effects of the shape of the upper surface of the cloud layer cannot be neglected in many situations. The climatological importance of the variability will also depend on the integrated effects on clouds illuminated from a variety of directions. In order to develop better parametrizations it will be necessary to consider all facets of the structure of the clouds. This can best be achieved by combining the Monte Carlo approach adopted here with numerical simulations of the cloud-water field that contain the entire range of variability. However, such an approach, while assisting the development of parametrizations, cannot identify the mechanisms by which variability influences the cloud optical properties in the way that has been achieved in the present work.

The effects of gaseous absorption have been neglected in the model. However, the model can be used to determine the length of the in-cloud path of each photon. Average path lengths are much larger than the depth of the cloud layer, owing to the effects of multiple scattering. For example, for normally incident radiation at 0.45 μm, photons emerging from the top of a horizontally uniform cloud layer 300 m thick have a mean path length in the layer of nearly 500 m, while those emerging through cloud base have a mean path length of around 1000 m. These results suggest that in-cloud gaseous absorption may be more important than has been suggested previously because of the long path lengths; this may explain some of the reported ‘anomalous absorption’ in clouds. These effects are currently the subject of further study.

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