The radiative properties of inhomogeneous boundary layer cloud: Observations and modelling

By P. HIGNETT* and J. P. TAYLOR
Meteorological Office, UK

(Received 13 October 1995; revised 26 February 1996)

SUMMARY

The importance of internal inhomogeneities in the microphysical structure of stratocumulus in relation to the radiative properties of various cloud fields is studied using aircraft measurements and a 3-D Monte Carlo model. This study is unique in that in situ microphysical data and observations of cloud thickness have been used in the initialization of a Monte Carlo model, and the resulting model predictions of reflectance and albedo have been compared with in situ aircraft radiometric observations of the same cloud. The model predicts a reduction in reflectance and albedo for the 3-D cloud field compared to a homogeneous cloud layer with the same average microphysical properties. The in situ observations confirm these simulations. The Monte Carlo model predicts that internal inhomogeneities lead to a reduction in cloud absorbance and an increase in cloud transmittance. A further study of the importance of the distribution of clouds within a domain was carried out using a Monte Carlo model where the cloud fraction is kept constant while the separation of the cloud elements is varied. These results reveal a large sensitivity of the radiative properties to the distribution of the cloud, and that this sensitivity increases as the separation of the cloud elements decreases.

KEYWORDS: Airborne observations Albedo Inhomogeneous cloud Microphysical modelling Radiative sensitivity Stratocumulus Monte Carlo modelling

1. INTRODUCTION

It is now well established that clouds play an important part in the earth’s radiation budget. Of considerable interest are the extensive layers of boundary-layer cloud which persist in several parts of the world. It is apparent from both satellite imagery (Coakley 1991; Cahalan and Snider 1989) and in situ aircraft observations (e.g. Nicholls and Leighton 1986; Rawlins 1989; Korolev and Mazin 1993) that even cloud sheets that appear visually uniform can exhibit considerable horizontal and vertical internal inhomogeneity. This raises the question of what impact the neglect of these inhomogeneities can have when modelling the radiative transfer through a plane-parallel cloud constructed from some average of the observed cloud properties. An analogous problem is that of quantifying the uncertainty in the cloud radiative properties derived in a numerical model parametrization based on the average liquid-water path within a grid box (a typical droplet-size having been assumed). Even if an estimate of the cloud fraction is available there remains the effect of the distribution of cloud, given a constant cloud fraction.

The difficulty of the parametrization of subgrid radiative transfer processes was discussed by Harshvardhan and Randall (1985) and Stephens (1985), wherein Stephens emphasized that the mean albedo of a cloud layer was not a function of liquid-water content alone, but depended on the spatial distribution. Further, Stephens (1986) demonstrated that the albedo of a horizontally non-uniform cloud was less than that which would be calculated for a plane-parallel cloud with equivalent averaged optical properties. Stephens (1988a, b) also developed semi-analytic solutions in an attempt to provide a general formalism to account for the effects of spatial inhomogeneity.

A number of modelling studies, often based on Monte Carlo simulations, have addressed this problem. Cahalan (1989) and Cahalan et al. (1994a, b) used a fractal model

* Corresponding author: Meteorological Research Flight, Meteorological Office, Y46 Building, DRA, Farnborough, Hampshire GU14 6TD, UK.
to reproduce the wavenumber spectrum and probability distribution of the liquid-water path and found the area-averaged albedo of the inhomogeneous cloud field to be less than that of a uniform cloud with the same microphysical parameters and the same total liquid water. The bias in the albedo, relative to the plane-parallel case, was more sensitive to the within-cloud variance of liquid water than to the mean, and the importance of this within-cloud variance increased as the cloud fraction increased. Li et al. (1994) included the effects of only vertical inhomogeneity in a Monte Carlo model and concluded that, in this case for a complete cloud cover, the differences from the plane-parallel cloud were small.

Barker (1992) extended the Monte Carlo technique to incorporate values of extinction coefficient calculated from cloud microphysical measurements made from aircraft. On the assumption that the internal three-dimensional variability of the extinction coefficient was isotropic the calculated results showed a reduction of albedo for inhomogeneous clouds relative to the homogeneous case. A principal aim of this paper is to examine the effects of cloud inhomogeneities by adopting an approach similar to Barker’s. The extinction coefficient is calculated directly from aircraft microphysical measurements, vertical variability of the cloud is also incorporated in terms of both changes in the extinction coefficient and changes in the physical depth of the cloud, and hence of the total optical depth. The results of these Monte Carlo simulations are then compared with aircraft observations of the cloud albedo, which is an intrinsically more reliable quantity to measure than the absorbance or transmittance because the upwelling and downwelling irradiances are measured simultaneously. Stephens and Tsay (1990) identified what they referred to as ‘anomalous cloud darkening’, relative to a plane-parallel cloud, in analogy with the problem of anomalous absorption which has been the subject of debate for many years. The effects that follow from internal inhomogeneity or cloud edges are a possible explanation of this anomalous behaviour.

2. THE STRUCTURE OF INHOMOGENEOUS BOUNDARY-LAYER CLOUDS

Several studies have contributed information about the scale and nature of internal inhomogeneities in boundary-layer cloud. Korolev and Mazin (1993) gave observational evidence of zones within stratiform clouds of increased or decreased droplet concentration, with significant fluctuations over scales of tens of metres. Their calculations suggested that vertical velocity fluctuations could produce inhomogeneities like those observed. Cahalan and Snider (1989) showed that the brightness variations of Californian stratocumulus (as detected by the Landsat thematic mapper) varied as $k^{-5/3}$ (where $k$ is the horizontal wavenumber) on scales larger than the cloud thickness, but changed to $k^{-3}$ at smaller scales. Data from a surface-based microwave sounder in the same region (located on San Nicolas Island) also showed a $k^{-5/3}$ dependence of the integrated liquid-water path. Cahalan and Snider hypothesized that the liquid-water content in stratocumulus could, to some extent, be regarded as a passive scalar, reflecting vertical-velocity variations.

In another satellite study Coakley (1991) analysed AVHRR data (1 km resolution) from the 1987 FIRE marine stratocumulus project and concluded that the reflectance at 0.63 μm was less for broken clouds than for uniform clouds and did not depend on the viewing angle; at 3.7 μm the reverse was generally true. Coakley suggested that the cloud structure could be in the form of core regions of high liquid-water content and large drop-size with surrounding edges where the liquid-water content and drop size were smaller. This is consistent with the aircraft observations of Nicholls and Leighton (1986), who showed that active updraughts exist in stratocumulus, surrounded by regions of subsidence, and with Nicholls (1989), who concluded that a hexagonal cellular structure was consistent
with his data. Jonas (1994) continued this theme by using a Monte Carlo model based on hexagonal cells with circular cores. The thickness of the cells and the ratio of liquid-water path between the central core and cell perimeter were varied to study the effects of horizontal inhomogeneities, with the conclusion that clouds with horizontal inhomogeneities had lower reflectances than plane-parallel clouds of similar optical depth.

This paper uses radiative and microphysical observations made by the UK Meteorological Office Hercules aircraft during ASTEX (the Atlantic Stratocumulus Transition Experiment), conducted over the North Atlantic in the vicinity of the Azores during June 1992 (Albrecht et al. 1995). Figure 1 (upper panel) shows the broad-band albedo measured whilst flying approximately 120 m above the top of an extensive stratuscumulus layer (for a description of the operation and calibration of the pyranometers on the Hercules see Saunders et al. 1992). Although a pyranometer has a hemispheric field of view, when viewing a Lambertian surface, 75% of the signal is derived from a cone of half-angle 60° centred on the normal to the instrument (e.g. Hignett 1987). This implies that in Fig. 1 (upper panel) variations in albedo, which range from around 0.4 to 0.65, are seen on length scales down to approximately 0.5 km. The extinction coefficient, $\beta_{\text{ext}}$, has been calculated from the relation

$$\beta_{\text{ext}} \approx \frac{3LWC}{2r_e}$$

$LWC$ is the liquid-water content measured by a Johnson–Williams meter (Rogers et al. 1995) and $r_e$ is the effective radius of the droplet distribution calculated from measurements by a forward scattering spectrometer probe (FSSP) (Martin et al. 1994) as

$$r_e = \frac{\sum_{n=1}^{M} r_n^2 N_n}{\sum_{n=1}^{M} r_n^2 N_n},$$

where $M$ is the number of size bins resolved by the FSSP ($M = 15$), $r_n$ is the radius for the middle of the $n$th size bin and $N_n$ is the concentration of droplets in that size bin. Figure 1
Figure 2. Profile of extinction coefficient through a sheet of stratocumulus studied during ASTEX flight A209 on 12 June 1992. The dashed lines show the levels at which runs were flown within the cloud.

(lower panel) shows $\beta_{\text{ext}}$, as calculated from a run near cloud top, varying by more than a factor of two over the same path as that shown in Fig. 1 (upper panel). Because of the variation in time between these two runs one would not expect to see perfect correlation. Although in this case cloud cover was complete there is a substantial horizontal variability in the optical properties.

Typically, within stratocumulus, there are significant vertical gradients of liquid-water content and effective radius, with maximum values reached near cloud top. This broad vertical structure can be seen in Fig. 2, which shows $\beta_{\text{ext}}$ plotted against height for an aircraft profile through a stratocumulus layer. Because the aircraft path is at a very shallow angle to the horizontal (approximately 1.5°) much of the variability superimposed on the basic vertical gradient arises from horizontal variation in the structure. A more comprehensive impression of the variability within a stratocumulus layer can be gained from Fig. 3, which shows time series of $\beta_{\text{ext}}$ at three levels within cloud. Apart from the change with height in the mean value the distribution of $\beta_{\text{ext}}$ is distinctly skewed, with a tail of low values at all heights. This is particularly noticeable near cloud top and is reminiscent of the negatively skewed vertical velocity structure found by Nicholls and Leighton (1986), which is indicative of narrow descending motions related to entrainment events.

To show the scale of horizontal variation, and the similarity of these data to other observations, a composite power spectrum of $\beta_{\text{ext}}$ from five runs in stratocumulus has been produced by combining the power spectra from the individual runs and averaging the power spectral density, $S_{\beta\beta}$, normalized by the variance of the $\beta_{\text{ext}}$ time series $\sigma_{\beta}^2$, as a function of wavenumber $k$, here $k = 2\pi/\lambda$, and $\lambda = U/n$, where $U$ is the true airspeed and $n$ the natural frequency of the measurement. The composite power spectrum is shown in Fig. 4, where the data are averaged into ten bins per decade; this spectrum shows a $k^{-5/3}$ dependence of $\beta_{\text{ext}}$ for scales greater than or equal to 200 m ($k \leq 0.03$), which is similar to that of Cahalan and Snider (1989) who found that relationship for scales exceeding 500 m. The vertical bars are the standard deviations of the mean values from the five individual spectra and the dashed line represents a $k^{-5/3}$ slope for reference.
Figure 3. Time series of $\beta_{\text{ext}}$ for several runs within the cloud of 12 June 1992. The level at which the runs were flown are shown as dashed lines in Fig. 2. Also plotted are the distribution of the extinction coefficient values (x-axis: $\beta_{\text{ext}}$, y-axis: number of occurrences).

Figure 4. A composite power spectrum of $\beta_{\text{ext}}$ from five runs in stratocumulus clouds. The vertical lines are the standard deviations of the five individual runs and the dashed line is that of the $k^{-5/3}$ slope.
3. Monte Carlo model

This study has used a Monte Carlo modelling technique similar to that of Barker (1992), who represented the inhomogeneity of a cloud field by calculating a one-dimensional time series of the extinction coefficient, \( \beta_{\text{ext}} \), from aircraft FSSP measurements, and extended the process further to the three-dimensional case on the assumption of isotropic variability. The particular Monte Carlo model used here is a development of that described by Kite (1983, 1987). As each photon group enters the cloud it collides with a water droplet, which has a value of \( \beta_{\text{ext}} \) determined from a random entry into the observed time series of \( \beta_{\text{ext}} \). The \( \beta_{\text{ext}} \) time series are taken from flight legs flown approximately across wind. We are therefore assuming that these are representative of the horizontal variation in the cloud and that we would not anticipate different results from flight legs flown, for example, along wind. On each subsequent collision the value of \( \beta_{\text{ext}} \) is determined from the next value in the time series. The time series is given cyclical boundary conditions so that any photon group reaching the end will jump back to the beginning. Each photon group is monitored until it leaves the cloud or its weight is reduced from 1 to below \( 10^{-5} \). Each value of \( \beta_{\text{ext}} \) in the time series has an associated value of \( r_c \), which is used to determine the Mie scattering properties, carried out using the code of Wiscombe (1979). Four C1 droplet distributions (Deirmendjian 1969) with effective radii of 2, 6, 12 and 16 \( \mu \text{m} \) were used. The Mie parameters for intermediate \( r_c \) are determined by interpolation from tables of the four explicitly computed values.

There is often observed to be considerable variability in the cloud-top structure of stratocumulus (e.g. Nicholls and Leighton 1986). At any given level within the cloud the total optical depth above will vary according to changes in cloud-top height. To represent the vertical variation of both \( \beta_{\text{ext}} \) and \( r_c \), the value obtained from the time series is scaled with height according to the gradients observed from aircraft profiles of \( \beta_{\text{ext}} \) and \( r_c \) in the same cloud field. To generate a realistic time series of the vertical variability of the cloud field from aircraft measurements at a single height it has been assumed that regions of higher liquid-water path, and hence greater cloud depth, are well correlated with updraughts. Conversely, downdraughts are associated with evaporation of cloud droplets and mixing of entrained air from above cloud, leading to a local reduction in cloud depth and lower liquid-water path. Large-eddy simulations of stratocumulus show evidence of this behaviour (e.g. MacVean and Nicholls 1988). Because of this strong vertical coherence in the cloud it would be inappropriate to use several \( \beta_{\text{ext}} \) time series at different heights as these would have been measured at different times and therefore would not be correlated. The vertical distribution of \( \beta_{\text{ext}} \) is taken to be represented by what it is at a single level with its magnitude scaled by the vertical gradient.

The detrended vertical-velocity time series measured by the aircraft is used to serve as an indicator of the local cloud thickness; an updraught is taken to indicate the maximum cloud thickness and a downdraught the minimum. For each separate case studied the overall cloud thickness was determined from profiles and horizontal runs. To define the maximum and minimum thicknesses the time series of the downwelling long-wave irradiance, \( F \downarrow \), (4–50 \( \mu \text{m} \)) from a run in cloud measured with an upward-looking pyrgeometer (Foot 1986), is combined with the mean temperature of the cloud layer above the flight level, \( T \), to determine an emissivity, \( \varepsilon \), of the cloud layer above the aircraft using the relation

\[
F \downarrow = \varepsilon \sigma T^4
\]

(3)

where \( \sigma \) is the Stefan–Boltzmann constant. A time series of liquid-water path, \( LW P \), above the flight level is then generated using the relation

\[
\varepsilon = 1 - \exp (-k LW P)
\]

(4)
where \( k \), the mass absorption coefficient, is 0.130 \( \text{m}^2\text{g}^{-1} \). This value of \( k \) is taken from the paper by Stephens (1984) and represents the average of the observed values presented in his Table 3; it is also the value used in the UK Meteorological Office Unified Model (Ingram 1990). This \( LWP \) time series was used, with a knowledge of the gradient of liquid-water content and the measured liquid-water content along a run, to determine the maximum and minimum thickness of cloud above the aircraft; these were added to the height of the run above cloud base to give the maximum and minimum total cloud thicknesses.

As a photon group moves along the time series of \( \beta_{\text{ext}}, r_e \) and vertical velocity it will experience thick and thin regions of cloud. The level of cloud base is fixed, so the level of cloud top will vary with the sign of the vertical velocity. Representation of the vertical variability of the cloud has therefore been simplified to switching between the two estimated extremes. These transitions are illustrated in Fig. 5 where a range of photon groups is identified with an arrow indicating their direction of travel.
At each time step the position of a photon group, relative to the cloud, is treated according to the direction in which it is travelling. First, consider a photon moving from a downdraught to an updraught, i.e. from a thin region of cloud to a thicker region of cloud, this movement is shown in the upper section of Fig. 5. In this figure the thickness of the cloud is given in arbitrary units: 4 for the thin cloud and 6 for the thick cloud, both measured from the top. It can be seen that all photons, whatever their direction of travel, when passing from a thin to a thick cloud have their vertical position increased by the difference in thickness between the two clouds (e.g. 2 units) so as to maintain the same distance from cloud base. The direction of motion of the photon groups remains unchanged.

The lower section of Fig. 5 shows how photons are treated on passing from an updraught to a downdraught (i.e. from a thick to a thin cloud). On passing from a thick cloud to a thin cloud the vertical position of the photons is reduced by the difference in thickness between the two clouds (2 units in Fig. 5) thus maintaining the same distance above cloud base as before. This vertical translation of photon groups will result in some photon groups being moved to a position above the new cloud top, effectively leaving a thick cloud region to be above the top of a thin cloud region at the next step. This is equivalent to a photon in a real cloud leaving the side of an elevated region of cloud into clear skies. If such a photon group is travelling in an upward direction then it is deemed to have left the cloud layer permanently and so to contribute to the cloud albedo. This is shown as a photon group enclosed by a dashed-line box in Fig. 5. Photon groups with a downwards direction of travel are immediately moved vertically to the new cloud top. This is the case of a photon leaving the side of an elevated region of cloud and re-entering the cloud below.

The results presented are both for specific wavelengths of 0.55 μm (non-absorbing) and 2.26 μm (liquid and water vapour absorption) and also broad band 0.25–4.0 μm. The two specific wavelengths match the central wavelengths of two channels of the multi-channel radiometer (MCR) flown on the Hercules; the MCR is a sixteen-channel filter-wheel radiometer with a 1.5° field of view. For a description of the measurement of cloud reflectances using the MCR see Rawlins and Foot (1990). The broad-band results cover the wavelength range of pyranometers fitted to the top and bottom of the Hercules; the calibration and operation of the pyranometers are described by Saunders et al. (1992). Model results are shown in terms of nadir reflectances and hemispheric albedos, which permit direct comparison with the in situ observations. Due to computational limitations the bi-directional reflectance characteristics of the cloud are not calculated.

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength interval (μm)</th>
<th>Central wavelength (μm)</th>
<th>Bands of 24bd. scheme</th>
<th>Weighted ref. indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Real</td>
</tr>
<tr>
<td>1</td>
<td>0.25–0.69</td>
<td>0.47</td>
<td>1–10</td>
<td>1.3419 5.7099E–09</td>
</tr>
<tr>
<td>2</td>
<td>0.69–1.19</td>
<td>0.94</td>
<td>11–16</td>
<td>1.3238 1.5991E–06</td>
</tr>
<tr>
<td>3</td>
<td>1.19–2.38</td>
<td>1.79</td>
<td>17–21</td>
<td>1.3074 3.5619E–04</td>
</tr>
<tr>
<td>4</td>
<td>2.38–4.00</td>
<td>3.19</td>
<td>22–24</td>
<td>1.3066 3.7139E–02</td>
</tr>
</tbody>
</table>

When the model is run at a specific wavelength, water vapour absorption is included in the Monte Carlo calculations using the absorption data from LOWTRAN 3B (Selby et al. 1976). This is done by computing the transmittance over the photon path length
RADIATIVE PROPERTIES OF CLOUD FIELDS

TABLE 2. COMPARISON OF THE MONTE CARLO AND SLINGO–SCHRECKER MODELS FOR AN OVERHEAD SUN. THE SLINGO–SCHRECKER RESULTS ARE GIVEN IN PARENTHESES

<table>
<thead>
<tr>
<th>Band</th>
<th>Input (W m⁻²)</th>
<th>Up at cloud top (W m⁻²)</th>
<th>Down at cloud base (W m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25–0.69 µm</td>
<td>577.790</td>
<td>245.4</td>
<td>(339.006)</td>
</tr>
<tr>
<td>0.69–1.19 µm</td>
<td>430.411</td>
<td>189.4</td>
<td>239.8</td>
</tr>
<tr>
<td>1.19–2.38 µm</td>
<td>228.606</td>
<td>86.83</td>
<td>95.24</td>
</tr>
<tr>
<td>2.38–4.00 µm</td>
<td>45.3764</td>
<td>0.513</td>
<td>2.827</td>
</tr>
</tbody>
</table>

TABLE 3. SUMMARY OF THE COMPARISON BETWEEN THE MONTE CARLO AND SLINGO–SCHRECKER MODELS

<table>
<thead>
<tr>
<th>Monte Carlo</th>
<th>Slingo–Schrecker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo</td>
<td>0.404</td>
</tr>
<tr>
<td>Trans</td>
<td>0.519</td>
</tr>
<tr>
<td>Absorp</td>
<td>0.077</td>
</tr>
</tbody>
</table>

between each collision. The gaseous transmission is represented by exponential sum-fitting of transmissivities (ESFTs) with a knowledge of the average temperature, pressure and water vapour density within the cloud. The LOWTRAN 3B ESFTs were used to maintain direct comparability with the results of the widely used Slingo–Schrecker scheme (Slingo and Schrecker 1982). The broad-band irradiances were computed by running the Monte Carlo model four times, once for each of the four bands in the code of Slingo (1989). The wavelength intervals of the four bands of the Slingo code and the number of bands of the 24-band Slingo–Schrecker scheme which was combined to produce them are given in Table 1 along with the weighted refractive indices used in the Mie calculations. The weighted refractive indices were computed by taking the real and imaginary parts of the refractive indices for the central wavelength of each of the 24 bands of the Slingo–Schrecker model, and then using the relative weights given by Slingo (1989) to find the refractive indices, aₙ, for the 4 bands using the relation

\[ a_n = \frac{\sum_{i=j}^k a_i w_i}{\sum_{i=j}^k w_i} \]  

where j and k are the limits of the bands in the 24-band scheme which were combined for each of the 4 bands in the Slingo model, aᵢ is the component of the refractive index (real or imaginary) and wᵢ is the weight for each of those bands. The refractive indices, computed in this manner are, as before, the input to the Mie code of Wiscombe (1979).

For each cloud case studied the full 24-band version of the Slingo–Schrecker code was run using a profile of temperature and humidity from the aircraft at the mean solar zenith angle for the aircraft run above cloud. The irradiances for each of the 24 bands were used to calculate the irradiance at cloud top in the four bands of the Monte Carlo model (e.g. for band 1 of the 4-band scheme the irradiances from bands 1 to 10 of the 24-band scheme are summed). All the irradiance input to the Monte Carlo model is assumed to
be along the solar beam, the direct component, diffuse illumination of the cloud field is excluded in the simulation. This is a reasonable assumption for the cases considered where there were always cloudless skies above the boundary-layer cloud field.

For validation the Monte Carlo model was run using the two test cases of Lenoble (1985). The model was run as a simple single-layer cloud with a C1 droplet distribution at a wavelength of 0.7 μm in both radiance and flux mode, as detailed by Lenoble. Good agreement between this Monte Carlo model and the other models discussed by Lenoble was observed (1% for the non-absorbing case, 5% for the absorbing case). In a later stage of the paper the results of the Monte Carlo simulation of observed cloud fields are compared to the in situ reflectances and albedos. To test the broad-band irradiances a comparison was made against the Slingo–Schrecker 24-band model, with the irradiances produced by this model summed to give the irradiances in the four bands described by Slingo (1989). A simple one-layer cloud with droplets of $r_e = 6 \mu m$ and an optical depth of 10 was used. The input irradiance to the Monte Carlo model was as described above. Tables 2 and 3 show the results of this intercomparison. Water vapour absorption was not included in either model.

4. **Monte Carlo simulations of observed cloud fields**

The three cases that are presented in this section are all boundary-layer cloud fields observed during the ASTEX campaign. In each case the in situ observations of cloud microphysics, vertical velocity and cloud thickness variability have been incorporated into the Monte Carlo model using the technique described above. The in situ $\beta_{ext}$ time series for each of the three cases is shown in Fig. 6. For each individual case the results of the simulations using the Monte Carlo code running with a fully 3-D cloud with a solar zenith angle of zero are used to construct an equivalent plane parallel cloud layer. The thickness of
TABLE 4. THE STATISTICAL PROPERTIES OF THE MONTE CARLO SIMULATIONS FOR CASE 1 WITH A SOLAR ZENITH ANGLE OF 30°

<table>
<thead>
<tr>
<th>Case</th>
<th>Avg. optical depth</th>
<th>Avg. extinction coefficient</th>
<th>No. of collisions</th>
<th>Droplet ( r_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab</td>
<td>18.29</td>
<td>69.55</td>
<td>41.35</td>
<td>5.52</td>
</tr>
<tr>
<td>3-D</td>
<td>17.80</td>
<td>68.13</td>
<td>28.11</td>
<td>5.65</td>
</tr>
</tbody>
</table>

Figure 7. The reflectance of the cloud sheet of case 1 on 16 June 1992. Top panel is at a wavelength of 0.55 \( \mu \text{m} \); bottom panel at 2.26 \( \mu \text{m} \). The Monte Carlo results for the slab cloud are shown as a solid line and for the 3-D cloud as a dashed line. The squares are the measurements from above the cloud with the standard deviation shown as a vertical line.

the plane parallel cloud layer is set to the mean cloud geometric thickness experienced by the photons in the 3-D cloud, and the extinction coefficient and effective radius are also set equal to the mean value encountered by the photons in the 3-D simulation. In this manner a homogeneous cloud field is constructed which has an optical depth equivalent to the mean optical depth that the photons encountered in the 3-D simulation. In the description that follows the term ‘3-D’ is used to describe the inhomogeneous cloud, and the homogeneous cloud is termed the ‘slab’ case. It is important to note that this ‘slab’ cloud is constructed only once for each case from one realization of the model running with a zero solar zenith angle; at other solar zenith angles the ‘slab’ cloud characteristics may differ slightly from the mean characteristics of the 3-D simulation owing to changes in the incident solar zenith angle. Such differences are small, as shown in Table 4 presented later. This representation of the ‘slab’ cloud is an objective definition and is chosen because it maintains the same average \( \beta_{\text{ext}} \), optical depth and effective radius as has the ‘3-D’ cloud.

(a) Case 1: 16 June 1992

This flight took place in a continental stratocumulus cloud sheet to the east of the Azores. The in situ \( \beta_{\text{ext}} \) time series from a run near the top of this cloud sheet is shown in Fig. 6 (upper panel). Figure 7 shows the computed reflectance of the slab and 3-D cloud runs for a variety of solar zenith angles at wavelengths of 0.55 \( \mu \text{m} \) and 2.26 \( \mu \text{m} \). The in situ observations of reflectance, from the nadir viewing MCR, at the two wavelengths, are shown as squares with the standard deviation of the observations shown as a vertical line.
The reflectance is defined as

\[ R = \frac{\pi L_R}{I} \] (6)

where \( L_R \) is the reflected radiance measured by the MCR viewing at nadir, and \( I \) is the irradiance on a horizontal surface at cloud top. The average solar zenith angle during the run in which the observations were made was 38.8°, which means that the MCR was viewing backscatter at an angle of approximately 142° relative to the forward direction of the solar beam. The small, rapid change in reflectance around the angle of the observation is due to the rainbow. At both 0.55 \( \mu m \) and 2.26 \( \mu m \) the measured reflectance is close to that of the 3-D cloud; in both observations the standard deviation of the observations was around 0.1 despite no visible breaks. At the solar zenith of the observations (38.8°) the inclusion of the 3-D nature of the cloud field reduced the reflectance by 20% at both 0.55 \( \mu m \) and 2.26 \( \mu m \).

The hemispheric albedo, transmittance and absorptance have also been computed at 0.55 \( \mu m \) and 2.26 \( \mu m \); these results are shown in Fig. 8. At 0.55 \( \mu m \) there are large changes in albedo and transmittance with the solar zenith angle, and also between the 3-D and slab cases. The albedo increases with solar zenith angle and there is a compensating decrease in transmittance; the absorption, by definition, is zero at this wavelength. The albedo of the 3-D cloud is systematically lower than that of the slab cloud; the reduction increases from 4.9% at a solar zenith angle of 60° to 7.9% at angle zero. Correspondingly the transmittance at 0.55 \( \mu m \) increases in the 3-D case with respect to the slab case; these results suggest that regions within the cloud of low \( \beta_{ext} \) are more important than regions of high \( \beta_{ext} \) because the albedo did not rise but dropped in the 3-D case. Table 4 shows the statistics of the photon groups for the Monte Carlo runs at a zenith angle of 30°. The average
optical depth quoted is the mean of the products of the instantaneous extinction coefficient and the cloud thickness for each collision; the average properties are very similar for both the 3-D and the slab case. This shows that the differences in the radiative properties of the two clouds are a function of the distribution of the extinction coefficient within the cloud. It should also be noted that the average number of collisions a photon group incurred before leaving the cloud was reduced from 41.35 in the slab case to 28.11 in the 3-D case. Figure 9 shows histograms of the average optical depth (as defined for Table 4), average extinction coefficient, number of collisions and the droplet $r_e$. In the 3-D case the photons experienced a wide range of optical depths from 8 to 34 and as a result the number of collisions that each photon group incurred has been much reduced. The regions of low optical depth within this solid deck of cloud have funnelled the photons through the cloud layer, so increasing the transmittance and reducing the albedo.

The results at a wavelength of 2.26 $\mu m$ (Fig. 8, bottom panel) also show the albedo increasing with solar zenith angle but there is little difference between the 3-D and the slab cases. The transmittance decreases with increasing solar zenith angle and is increased by 45% at angle zero, from the slab to the 3-D case. The absorptance of the cloud layer is also clearly affected by the internal structure of the cloud, and is lower for the 3-D than from the slab case. It is of interest that the albedo at 2.26 $\mu m$ does not change between the 3-D and slab cases. It is important to note that there were no holes in the cloud and that, at this wavelength, there is considerable absorption by liquid water; also the reflectance is very dependent on the droplet size in the top portion of the cloud layer. In this region the droplet size is larger than deeper down in the cloud, and the influence of the regions of low $\beta_{\text{ext}}$ is small, as all the droplets even those associated with low $\beta_{\text{ext}}$ are of a size where
they are good absorbers. The albedo therefore shows little change at this wavelength. The difference arises, however, when photons pass this highly absorbing large droplet regime into the depths of the cloud where the regions of low $r_c$ associated with low $\beta_{\text{ext}}$ reduce the absorptance and lead to a higher transmittance. Thus changes in absorptance are accompanied by compensating changes in transmittance.

The Monte Carlo model has also been run to compute the broad-band (0.3–4.0 $\mu$m) radiative properties of the slab and 3-D cloud fields; the results are shown in Fig. 10. The standard deviation of the measured albedo is shown as an indication of the variability observed along the run, the absolute accuracy of the measured albedo is estimated to be approximately 4%. In common with the results at the two discrete wavelengths there is an increase in albedo with solar zenith angle and a decrease in the 3-D cloud relative to that of the slab cloud. There is a 6% reduction in the albedo of the 3-D case at zero solar zenith angle, which reduces slightly to 4.4% at 60°. Although small, these changes translate to differences in irradiance, at zero solar zenith angle, of 40 W m$^{-2}$ decrease in upwelling at cloud top and 56.3 W m$^{-2}$ increase in downwelling at cloud base, when going from a slab to a 3-D cloud. Also of note is that this case was for an unbroken cloud sheet. Although the absolute magnitudes of the absorptances are low, at around 0.06, there is an 18% reduction in the absorption within the cloud in the 3-D case relative to the slab case. In common with the results at the two discrete wavelengths the transmittance is increased in the 3-D case. The observed albedo is lower than both Monte Carlo simulations but in the 3-D case the simulation is closer to the observations than in the slab case.

(b) Case 2: 20 June 1992

This flight took place over a broken stratocumulus cloud field to the south of the Azores. This cloud field differed from case 1 in that there were definite breaks in the cloud; these breaks were less than 1 km in width (the mean width of the breaks being 280 m). The proportional cloud cover, computed by determining the number of points in the time series for which $\beta_{\text{ext}}$ was greater than 0.5 km$^{-1}$, was 0.86. Figure 6 (middle panel)
shows a time series of the extinction coefficient, $\beta_{\text{ext}}$, from a run near the middle of the cloud layer; the variation is very large, ranging from 0 to 95 km$^{-1}$.

Reflectances from Monte Carlo runs at 0.55 $\mu$m and 2.26 $\mu$m are shown in Fig. 11 for the 3-D and slab clouds. In these cases the difference between the reflectance for the 3-D and slab simulations is very large; at 0.55 $\mu$m (upper panel) the reflectance is reduced by approximately 35% in the 3-D run; at 2.26 $\mu$m (lower panel) the reflectance is reduced by 43%. The MCR reflectances also are shown in Fig. 11; the standard deviations over this cloud field are larger than those of case 1 on account of the breaks observed. At 0.55 $\mu$m the in situ reflectance measurement lies between these predicted using the slab and 3-D Monte Carlo model runs. Both model simulations however are within the standard deviation of the observations. At 2.26 $\mu$m the observed and modelled reflectances are in very good agreement (0.149 and 0.134, respectively). In the 3-D run the inclusion of regions of low $\beta_{\text{ext}}$ significantly decreases the number of photons that are reflected from the cloud layer.

Figure 12 (upper panel) shows the transmittance and albedo at 0.55 $\mu$m. The albedo of the 3-D cloud is consistently lower than that of the slab cloud and the transmittance is systematically higher. The difference in albedo amounts to a 23% reduction for an overhead sun increasing to a 28% reduction at a solar zenith angle of 69° (this was the mean zenith angle at the time of the in situ observations described later). Of note here is the fact that the difference in the reflectance and albedo between the 3-D and slab clouds increases with solar zenith angle as opposed to the decrease observed in case 1. In case 1 the cloud was continuous, there were no breaks; however, in case 2 breaks were observed and the results from the 3-D run, which included these holes in the clouds, does not show as great an increase in albedo with increasing solar zenith angle as the slab cloud does. As a result the difference between the 3-D and slab clouds increases. Figure 12 (lower panel) shows the albedo, transmissance and absorbance of the cloud at 2.26 $\mu$m. A similar pattern in the change of albedo and transmissance with solar zenith angle is observed. A decrease in albedo (15.5% at zero solar zenith angle, 24% at 60°) is predicted, in contrast to the little change in albedo observed at 2.26 $\mu$m in case 1. The internal inhomogeneity of the cloud field has also led to a significant decrease of around 40% in the cloud absorbance; there is little change in the magnitude of this decrease with solar zenith angle.
The broad-band radiative properties computed from the Monte Carlo model, along with the in situ measurement of albedo, are shown in Fig. 13. The trends of the albedo and transmittance with solar zenith angle are similar to those observed at the two discrete wavelengths with a reduction in albedo of 22% at zero solar zenith angle increasing to 26% at 69°. The in situ observation of the albedo is in very good agreement with the model prediction using the full inhomogeneity of the cloud in the 3-D case (0.435 and 0.438, respectively). The standard deviation of the observation is quite large (0.12) but does not cover the albedo predicted using the slab cloud. In common with the computation at the single wavelength of 2.26 μm, the broad-band absorptance in the 3-D cloud is reduced relative to the slab cloud.

(c) Case 3: 4 June 1992

The data presented here are for a well-broken stratocumulus sheet. A time series of $\beta_{\text{ext}}$ is shown in Fig. 6 (lower panel). The structure of the cloud observed on this day was very different from that observed in the other two cases presented. Although the cloud fraction during this run was extensive, greater than 0.9, the cloud was very thin in parts. The cloud sheet had the appearance of cumulus penetrating a thin stratocumulus deck. The reflectances at 0.55 μm and 2.26 μm are shown in Fig. 14 for both the 3-D and slab clouds representative of this case. In common with the other two cases there is a decrease in the reflectance in the 3-D run compared with the slab run. The MCR reflectances at both 0.55 μm and 2.26 μm lie between the slab and 3-D values at the solar zenith angle of the observations, 16.7°. The broken nature of this cloud field makes the comparison with in situ observations more problematical. There are two distinct regions of maxima in $\beta_{\text{ext}}$ in the in-cloud run, although, owing to the cyclical boundary conditions employed in the
Figure 13. The Monte Carlo model broad-band (0.3–4.0 μm) albedo (solid line), transmittance (dotted line) and absorptance (dashed line) for the 3-D case (diamonds) and the slab case (triangles) for case 2 on 20 June 1992. The in situ measurement of albedo is shown as a square with a bar showing the standard deviation of the observations.

Figure 14. The reflectance of the cloud sheet of case 3 on 4 June 1992. Top panel is at a wavelength of 0.55 μm; bottom panel at 2.26 μm. The Monte Carlo results for the slab cloud are shown as a solid line and those for the 3-D cloud as a dashed line. The squares are the measurements from above the cloud with the standard deviation shown as a vertical line.

model, this cloud structure is assumed to continue in all directions. The in situ reflectances and albedo, presented later, are taken from a run above cloud of the same length as the one in cloud. The average value of the reflectance or albedo measured will be strongly dependent on how many of these cloud maxima are overflown, and on their width relative to the breaks. Because the two runs are separated in time there is no guarantee that the two cloud fields observed in and above the cloud are identical. Ideally a much longer run should be made above cloud, measuring the radiative properties, to enable a more statistically significant measurement to be made.
The albedo, transmittance and absorptance at 0.55 \( \mu m \) and 2.26 \( \mu m \) are shown in Fig. 15. In these model runs the effect of inclusion of the inhomogeneity of the cloud field is, not surprisingly, very large. The albedo in the 3-D case is reduced by around 33% relative to the slab case at 0.55 \( \mu m \), and by approximately 31% at 2.26 \( \mu m \). At 2.26 \( \mu m \) the absorption in the 3-D case is again reduced relative to the slab case, this time by 32%.

The broad-band radiative properties are shown in Fig. 16 along with the observation of albedo made at a solar zenith angle of 16.7°. The albedo of the cloud sheet in the 3-D case is about 34% lower than in the slab case, and this reduction varies only slightly with solar zenith angle. The absorption of the cloud layer is low at around 0.03 and there is a small increase in absorption in the 3-D results. Despite the poor sampling of the above-cloud run the results show that the 3-D cloud simulation is in better agreement with the observations than the slab run. Of interest in this case is the increase in cloud absorption in the 3-D case relative to the slab case; in the other two cases the absorption in cloud in the 3-D case was reduced. This can be explained by reference to Fig. 17 which shows contour plots of the average \( r_e \) of each photon group versus the number of collisions that each photon group experienced before either leaving the cloud or being absorbed. The cumulative percentages of the number of photons bounded by each contour are shown. The data come from the Monte Carlo model running the 3-D simulation for the wavelength region of band 3 of the Slingo–Schrecker model, with zero solar zenith angle for case 3, upper panel, and case 1, lower panel. The horizontal solid lines, plotted on each panel, represent the average \( r_e \) of the single-layer slab cloud for each case. In the 3-D simulation for case 3 the \( r_e \) at which there are the most collisions is higher than the average \( r_e \) used in the slab simulation. In this case absorption is dominated by droplets substantially larger than are represented in the equivalent slab case, and which therefore have a smaller single-scatter albedo. The result
Figure 16. The Monte Carlo model broad-band (0.3 - 4.0 μm) albedo (solid line), transmittance (dotted line) and absorptance (dashed line) for the 3-D case (diamonds) and the slab case (triangles) for case 3 on 4 June 1992. The in situ measurement of albedo is shown as a square with a bar showing the standard deviation of the observations.

Figure 17. Contour plots of the average $r_e$ versus the number of collisions for each photon group for the Monte Carlo model runs at band 3 of the Slingo-Schrecker model with a zero solar zenith angle for case 3 upper panel, and case 1, lower panel. The solid line represents the value of $r_e$ in the equivalent single layer slab cloud for each case. The shades represent the cumulative percentage of the number of photons bounded by each contour interval.
is an overall increase of absorption, relative to the slab cloud, presumably resulting from the tall cumulus present on this day. In case 1, by comparison, the \( r_c \) at which there are most collisions is smaller than the average \( r_c \) used in the slab case (Fig. 17, lower panel). As a result of this, for case 1, the absorption in the 3-D case is lower than for the slab case. Therefore the distribution of \( r_c \) within a cloud and the vertical extent of the cloud are paramount in the determination of whether the 3-D representation enhances or reduces the absorption, relative to the equivalent slab cloud.

5. DISCUSSION

The three cases presented from the ASTEX campaign represent three different types of cloud distribution. In case 1 the cloud cover was total, in case 2 the cloud fraction was 0.86 but the breaks were narrow. In case 3 the cloud fraction was almost total at 0.96 but the cloud optical depth varied considerably; this is evident from the changes in \( \beta_{\text{ext}} \) from under 10 to over 150 km\(^{-1}\). The three cases showed similarities in that the albedo, both at discrete wavelengths and over the entire solar spectrum, increased with increasing solar zenith angle for both the slab and 3-D clouds. In all the broad-band simulations the albedo of the inhomogeneous 3-D cloud was lower than that of the slab cloud. The regions of lower than average \( \beta_{\text{ext}} \) in the 3-D clouds have acted to reduce the cloud albedo more efficiently than the regions of higher than average \( \beta_{\text{ext}} \) have acted to increase it. This is true even for case 3 where there are regions of very high \( \beta_{\text{ext}} \); this is due to the nonlinear asymptotic nature of the relationship between albedo and liquid water path (LWP). As the LWP increases the amount of change in LWP required to produce a specified change in albedo increases until eventually an asymptote is reached and the albedo cannot be increased further by increases in LWP. The simulations showed that the reduced albedo in the inhomogeneous cloud was accompanied by an increase in the transmittance and by only a small change in the absorptance. This suggests that the regions of low \( \beta_{\text{ext}} \) or holes are surrounded by regions of low \( r_c \); photons entering these regions of low \( \beta_{\text{ext}} \) are, therefore, preferentially scattered, as opposed to being absorbed, and the likelihood of their passing through the cloud, and hence increasing the transmittance, increases. Analysis of the statistics of photons travelling through the cloud has shown that the average \( \beta_{\text{ext}} \) and average \( r_c \) which a photon encounters in the cloud are positively correlated. Thus, despite the relationship in Eq. (1) which suggests that low \( r_c \) might be associated with increased \( \beta_{\text{ext}} \), there is a compensating change in the liquid water content within the regions of low \( r_c \) so that photons entering regions of low \( \beta_{\text{ext}} \) tend to collide with droplets of lower \( r_c \), and hence the transmittance is increased.

Internal inhomogeneity has been shown to be a determining factor in the radiative properties of a cloud layer. Cases 2 and 3 show that the distribution of the breaks within the cloud sheet are important. To emphasize this point the Monte Carlo model was run for a range of different cloud fields, each of which had the same fractional cloud cover of 0.66; but with differing distributions of cloud in the horizontal. The number of breaks within the cloud field range from one to twenty, but the cloud is internally homogeneous with a constant effective radius of 6 \( \mu m \) and a constant \( \beta_{\text{ext}} \) of 40 km\(^{-1}\). The albedo at 0.55 \( \mu m \) and 2.26 \( \mu m \), as a function of the cloud break width, is shown in Fig. 18, corresponding to a zenith angle of 45\(^\circ\). Also shown is the albedo at 0.55 \( \mu m \) for a zero solar zenith angle. With one break in the cloud the ratio of cloud break width to cloud fraction equals 0.5; lower values have more breaks in the clouds, i.e. the gaps are smaller. Both the albedos at 0.55 \( \mu m \) and 2.26 \( \mu m \) show a large decrease as the width of the cloud breaks decreases; there is less sensitivity to the width of the gaps as the solar zenith angle increases. The overall change is, however, still significant and the sensitivity to the width of the gaps
increases markedly as they become narrower. This implies that a cloud field with large breaks, such as cumulus, is less sensitive to their distribution, provided the fractional cloud cover is correct, than a cloud with many narrow breaks, such as the type of stratocumulus cloud present in case 2 above. The broad-band properties at solar zenith angles of zero and 45° are shown in Fig. 19. The cloud absorptance is low and shows a weaker change with solar zenith angle than does either the albedo or transmittance. Because of the narrow cloud gaps the funnelling of photons through the cloud layer is particularly efficient and results in a much increased transmittance and reduced absorptance. This effect is evident from the reduction of the reflectance at the conservative wavelength of 0.55 \( \mu \text{m} \) to less than that at the absorbing wavelength of 2.26 \( \mu \text{m} \) for small gap widths.

A summary of the aircraft radiometric measurements, and the corresponding Monte Carlo simulation results is given in Table 5. For cases 1 and 2 the observed reflectance at 0.55 \( \mu \text{m} \) lies between the Monte Carlo model predictions for a slab and for a 3-D cloud. This may be due either to a systematic error in the calibration of this channel, or more likely to a sensitivity of the reflectance at this wavelength to cloud-top inhomogeneities. At 0.55 \( \mu \text{m} \) there is no absorption by water and the reflectance is very dependent on the cloud-top structure (Taylor and English 1995). Although this Monte Carlo model has a variable cloud
thickness and an internal variability in the cloud microphysics, it nevertheless represents the cloud as a statistically realistic feature and does not represent a 3-D cloud explicitly. For this reason the intricacies of the small-scale variations in the cloud-top structure, which affect the reflectance at conservative wavelengths, may not be represented accurately enough. In case 3 the disagreement between the observed reflectances at 0.55 μm and 2.26 μm with the Monte Carlo model predictions is probably due to the limited sampling, for the radiation measurements, of this particular cloud field, which has large-scale variations in cloud optical depth. It is of importance to note that, for all the cases presented, the in situ measurements of reflectance are lower than those predicted by the Monte Carlo model for a slab cloud, which suggests that inhomogeneities do lead to a reduction in nadir reflectance as predicted by the Monte Carlo model 3-D simulations. In common with the reflectance measurements the broad-band measurements show a mean albedo that is always lower than the Monte Carlo slab cloud simulation. In all cases the broad-band in situ measurements are in better agreement with the Monte Carlo 3-D simulations and this gives some confidence in our representation of the complex 3-D microphysical structure of real clouds.

6. CONCLUSIONS

The simulations with internally homogeneous clouds, combined with those from the three real clouds presented in the previous sections, have serious implications for the modelling of the radiative properties of inhomogeneous clouds. Observational evidence suggests that no cloud is truly homogeneous and that these current results are relevant to all clouds; even case 1, which had complete cloud cover, was internally very inhomogeneous. When considering these three cases from ASTEX we have shown that the internal
inhomogeneity in the cloud microphysics, and the macrophysical structure in terms of cloud thickness, are both important in the determination of the cloud radiative properties. Confidence in the Monte Carlo simulations was given by the level of agreement between in situ measurements and model results. Significantly better sampling will be required, particularly in conditions such as those of case 3, to deal with inhomogeneous effects in a more general sense. Similarly greater spectral resolution in the broad-band Monte Carlo model will be necessary to compare with better spectrally resolved observations.

A simple study with internally homogeneous clouds has shown the importance of the distribution of the cloud within the domain. Furthermore, this sensitivity is not linear and suggests that the sensitivity increases with decreasing width between the cloud elements. Hence the occurrence of breaks, or, as shown in case 1, regions of low extinction coefficient, in an otherwise solid stratocumulus cloud field can significantly change the cloud radiative properties. These results suggest that in numerical modelling a knowledge of the liquid-water fraction within a grid box is not sufficient and that a knowledge of the distribution of this liquid water within the grid box is also a prerequisite for the determination of the radiative properties of that cloud area. It may be that simplified characteristic distributions of liquid water corresponding to different cloud types need to be sought and parametrizations developed that relate these distributions to the bulk radiative properties of the cloud field.

ACKNOWLEDGEMENTS

The authors thank Dr M. MacVeey for his 3-D large-eddy simulations of stratocumulus which gave some insight into the relationship between cloud-top structure and vertical wind. We also thank the staff and the Royal Air Force aircrew of the Meteorological Research Flight for their support in the gathering of the measurements during the ASTEX campaign.

REFERENCES


Kite, A. 1983 'A Monte Carlo model to simulate the multiple scattering of shortwave radiation'. MRF Internal Note, No. 15. Available from National Meteorological Library, Bracknell, UK


Selby, J. E. A., Shettle, E. P. and McClatchey, R. A. 1976 'Atmospheric transmittance from 0.25 to 28.5 μm: Suppl. LOWTRAN 3B'. AFGL-TR-76-0258 ADA04701


Wiscombe, W. 1979 'Mic scattering calculations; advances in technique and fast vector speed computer codes'. NCAR Tech. Note TN140+STR