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Case Studies of Radiation in the Cloud-Capped Atmospheric Boundary Layer [and Discussion]

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Case studies of radiation in the cloud-capped atmospheric boundary layer

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This review presents observations of marine stratocumulus obtained by the three research aircraft that participated in the Joint Air–Sea Interaction Project (JASIN). Detailed measurements were made of the thermodynamic, cloud physics and radiation fields for a uniform cloud sheet on 8 August 1978. These show a well mixed boundary layer with cloud liquid water contents close to their adiabatic values. The longwave and shortwave radiative components of the cloud layer energy budget were measured and good agreement was obtained between the observations and several radiation schemes. In particular, the measured cloud shortwave absorption was close to the theoretical values. Observations of shortwave fluxes made from the Falcon aircraft beneath broken stratocumulus are also shown and compared with calculations made by using a Monte Carlo model. It is concluded that the radiative cloud–cloud interactions do not play a dominant role in the bulk radiative properties of cloud fields. These are mainly determined by cloud amount and the vertical and horizontal optical depths of the clouds within the field.

Introduction

Radiative processes are important in the formation and maintenance of clouds in the atmospheric boundary layer. In stratiform clouds such as stratus and stratocumulus, the radiative contribution to the energy budget of a cloud layer may be larger than the individual contributions from the vertical transports of sensible and latent heat and from entrainment. While this may not be true for convective cloud, the cloud cover is an important factor determining the net radiative heating of the surface and hence the surface temperature, which itself largely determines the degree of convective activity. In both cases the radiative properties of the clouds therefore play an important role in the development of the boundary layer. This paper reviews measurements of these properties made by instrumented aircraft during the JASIN experiment

Stratiform clouds often mark the top of the atmospheric boundary layer, being capped by an inversion in which potential temperature increases and the water vapour mixing ratio decreases with altitude. This cloud is thermally destabilized by the vertical distribution of radiative divergence, which promotes convection and entrainment of the inversion air into the cloud. Recent model studies by Schaller & Kraus (1981 *a*, *b*) and Fravalo *et al.* (1981) demonstrate the sensitivity of the simulations to the treatment of radiation. The extent to which the radiative divergence is partitioned between the boundary layer and inversion as a result of variations in the height of the cloud top has also been discussed by Kahn & Businger (1979), Deardorff & Businger (1980) and Randall (1980). Observational studies of stratocumulus have been made by Lenschow (1973) and comparisons of the observed and theoretical radiative properties by Stephens *et al.* (1978). Roach *et al.* (1982) made a detailed study of stratocumulus over land including both radiative and microphysical observations (Slingo *et al.* 1982*a*). Comprehensive measurements of stratocumulus were made during JASIN by three instrumented aircraft. The uniform and almost unchanging nature of the cloud studied allowed a detailed comparison with several radiative transfer models. The work is described in more detail by Schmetz *et al.* (1981) and Slingo *et al.* (1982*b*). De Vault & Katsaros (1982) have used the cloud physics measurements and measurements with pyranometers equipped with coloured filters to test a model for the remote determination of the liquid water path. The model makes use of the fact that absorption by water droplets occurs only in the infrared bands.

Table 1. Estimated accuracies of aircraft instruments

instrument	absolute accuracy in level flight	approximate response time/s
Eppley pyranometer	± 10 W m^{-2}†	1
Eppley pyrgeometer	± 10 W m^{-2}†	2
Johnson–Williams probe	± 5–10%‡	0.5
Teddington probe	± 10%	1
radiation thermometers	± 0.3	0.5

† Out of cloud. ‡ For drops smaller than 30 μm in radius.

While the theoretical treatment of extended water clouds is well advanced and comparison with measurements shows that the theory is adequate, we still know little of the radiative properties of broken cloud fields. Model studies have shown that there is a significant difference in the solar bulk radiative properties (transmittance, reflectance) of finite and infinitely extended clouds (see, for example, McKee & Cox 1974; Welch *et al.* 1980). This is primarily due to the radiative energy leaking through the cloud sides and being scattered predominantly in the lower hemisphere. The three-dimensional models mostly adopt a rectangular cloud shape and therefore their results can only be interpreted qualitatively. Experimental studies are necessary for a quantitative assessment of the radiative properties of finite clouds.

Results of flights under a broken stratocumulus layer are presented and these results and a comparison with a Monte Carlo model cast some light on the radiative properties of broken cloud fields.

2. Aircraft instrumentation

Three aircraft participated in the JASIN experiment: MRF C-130, NCAR Electra and DFVLR Falcon. Identical pyranometers (Eppley model PSP) were installed in upward- and downward-facing positions on each aircraft to measure the broadband shortwave (0.3–3 μm) flux densities. The downward flux has been corrected for the non-horizontal orientation during the processing of the data. Eppley pyrgeometers were mounted on two aircraft to measure the infrared irradiance, and all aircraft had downward-looking narrow-beam radiometers and a hot-wire liquid water content probe. In addition, the C-130 was also fitted with a Knollenberg axially scattering spectrometer probe (ASSP), which measures the size distribution of cloud droplets.

The estimated accuracy and response time of the instruments are listed in table 1, where the radiation values pertain to level runs in clear air. The results of many intercomparison flights between the three aircraft show consistent agreement within the limits quoted in table 1 (Nicholls & Cockroft 1982).

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3. Extended stratocumulus

On 8 August 1978 a ridge of high pressure was located over the JASIN area and the regular radiosonde ascents made from the participating ships show a well mixed, cloud-capped boundary layer, extending from the surface to a strong inversion at about 914 mbar (91.4 kPa). The inversion strength was about 5 K and the cloud top coincided with the inversion base without penetrating significantly into the inversion layer. The stratocumulus cloud was uniform and horizontally homogeneous over the experimental area, although on a larger scale the cloud was more broken. Satellite images (see Slingo *et al.* 1982*b*) reveal that there was some upper-level cloud to the south of the experimental area.

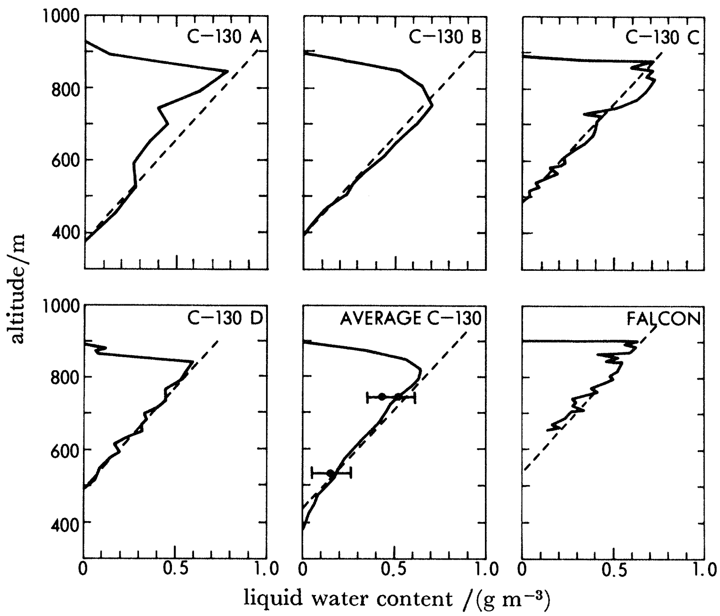


Figure 1. Profiles of liquid water content from the Johnson–Williams probe on the C-130 (A–D), the mean profile and leg-averaged values (⊢●⊣), and a profile from the Teddington probe on the Falcon. The dashed line is the adiabatic liquid water content.

3.1. *Cloud structure*

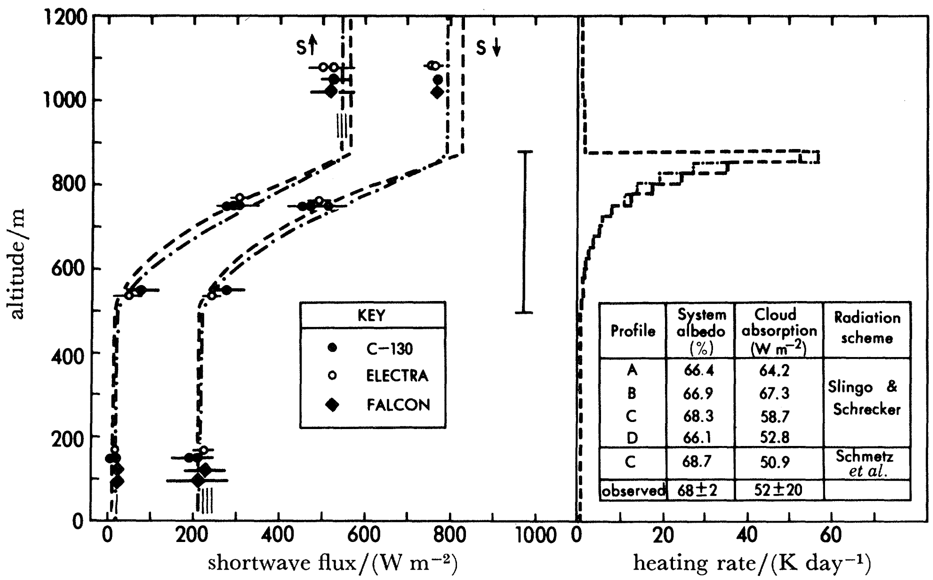
Figure 1 shows four profiles of liquid water content from the C-130, the average profile together with the leg-averaged values from three in-cloud horizontal runs, and a single profile from the Falcon. The profiles are close to adiabatic over the entire cloud depth, which suggests that there was little entrainment of dry air from above the inversion into the mixed layer. The C-130 profiles are used for the radiative transfer calculations presented in figures 2 and 3.

Cloud droplet spectra from the Knollenberg probe mounted on the C-130 were recorded at 1 s intervals throughout the flight. For the C-130 profiles C and D (figure 1) the increase of liquid water content with height is associated with a systematic increase of mode radius from about 5 μm at cloud base to 11 μm at cloud top. For the deeper profiles A and B the mode radius at cloud top is 13 μm.

3.2. *Radiation fields*

The observations and meteorological conditions on 8 August 1978 provide an excellent data set to be used for verification of one-dimensional radiative transfer schemes. The aircraft measurements of thermodynamic and cloud physics variables together with data from the radiosonde ascents are used as input to the radiation models, and the computed profiles of radiative flux densities are compared with the measured profiles. The longwave models of Roach & Slingo (1979) and Schmetz & Raschke (1981) are used. The shortwave schemes used are that of Slingo & Schrecker (1982) and that described briefly in Schmetz *et al.* (1981), which is based on the two-stream method of Kerschgens *et al.* (1978).

Figure 2 shows the shortwave fluxes measured by the three aircraft during level runs above,



Profile	System albedo (%)	Cloud absorption (W m^{-2})	Radiation scheme
A	66.4	64.2	Slingo & Schrecker
B	66.9	67.3	
C	68.3	58.7	
D	66.1	52.8	
C	68.7	50.9	Schmetz *et al.*
observed	68±2	52±20	

FIGURE 2. Comparison of the observed shortwave (S) fluxes from the horizontal legs flown by all from three aircraft, corrected to a solar zenith angle of 43.7°, with the theoretical fluxes from the two shortwave schemes: ---, Slingo & Schrecker (1982); -··-·-, Schmetz *et al.* (1981). The heating rate profiles for profile C (see figure 1) are also compared in the right-hand diagram. The groups of three vertical lines in the left-hand diagram represent the theoretical fluxes from the Slingo & Schrecker (1982) scheme for the other three C-130 profiles. The inset table summarizes the radiative properties of the cloud derived from the observations and the theoretical schemes.

within and below horizontally homogeneous parts of the cloud. The average value for each leg is shown together with the standard deviation. The observed values have all been adjusted to a solar zenith angle of 43.7° (corresponding to midday), which implies only small changes as the measurements were made close to this zenith angle.

The data from level runs give a more representative picture of the bulk radiative properties of the cloud than data obtained on aircraft profiles because the latter are obtained during a slow ascent or descent, so that entry and exit points are more than 10 km apart. The remarkable uniformity of the cloud layer on this occasion also allowed a direct comparison of measured and calculated profiles (see Schmetz *et al.* 1981; Slingo *et al.* 1982*b*). The radiative fluxes from the two models, for profile C from figure 1, are also shown in figure 2. Both models are in excellent agreement with the observations although they slightly overestimate the fluxes at cloud top, which might be due to the presence of thin high level cloud.

The Slingo & Schrecker scheme (1982) was also run for the other three C-130 profiles shown in figure 1 and these profiles give similar fluxes. The inset table in figure 2 compares the system albedo and cloud absorption determined from the observations and from the models. Despite

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the large uncertainty in the measured absorptions one can state that there is no evidence for 'anomalously high absorption', as discussed by Stephens *et al.* (1978) and Reynolds *et al.* (1975). The theoretical heating rates for profile C from the two radiation models, shown in figure 2, are similar but the Slingo & Schrecker (1982) scheme predicts a larger heating rate and a slower decline of the heating with distance into the cloud than the scheme of Schmetz *et al.* (1981). The discrepancies in absorption have been traced to different model transmittances for the solar infrared radiation above cloud.

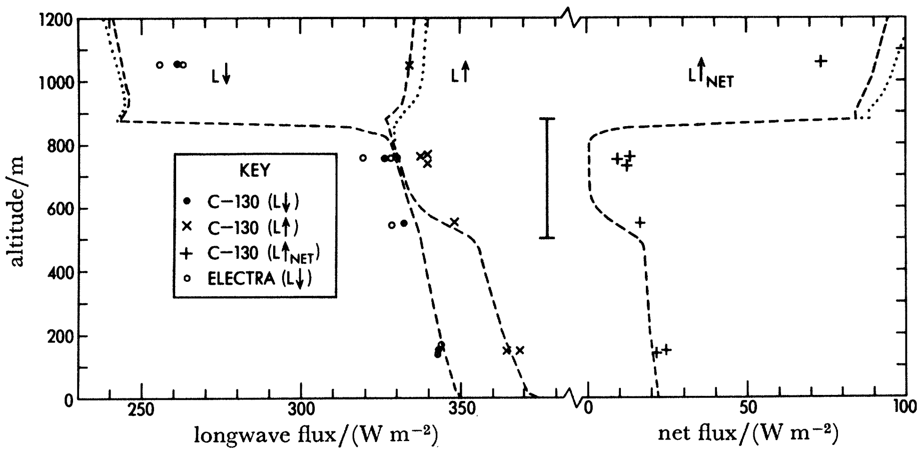

FIGURE 3. Comparison of the observed longwave (L) fluxes from the horizontal legs flown by the C-130 and the Electra with the theoretical fluxes for profile C (see figure 1) predicted from the models of Roach & Slingo (1979) (···) and Schmetz & Raschke (1981) (---).

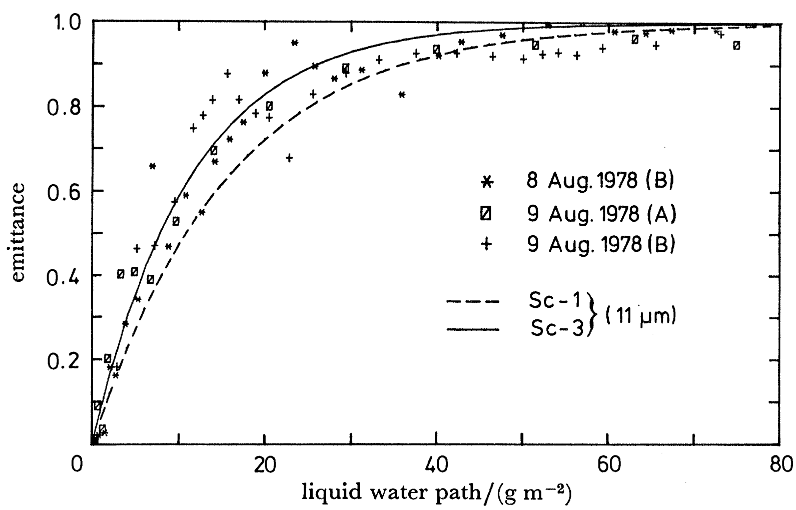

FIGURE 4. Cloud emittance (9.5–11.5 μm) measured with a narrow-beam radiometer as a function of the liquid water path. The profiles were obtained from the Falcon during descent (A)/ascent (B) through stratocumulus cloud. Curves are calculated for two cloud droplet spectra corresponding to cloud top (Sc-1) and cloud base (Sc-3).

Figure 3 shows a comparison of the longwave fluxes measured by the C-130 and the Electra during level runs with the theoretical predictions from the longwave models. While the models are in excellent agreement, the data show some systematic descrepancies. Firstly, the measured downward flux above the cloud is consistently larger than theory predicts. This again could be interpreted as the existence of thin upper-level cloud. Secondly, the net flux within the cloud does not fall to zero. This is likely to be an experimental error because pyrgeometer measurements by aircraft are known to be difficult (see, for example, Albrecht & Cox 1977) owing to the differential heating of the dome and the sink. A thorough discussion of the problems involved is given by Slingo *et al.* (1982*b*).

Evidence that the net longwave flux in figure 3 should be zero or close to zero within the cloud is given in figure 4. The vertical cloud emittance (9.5–11.5 μm) derived from the measurements with a narrow-beam radiometer on the Falcon (Schmetz *et al.* 1981) is shown as a function

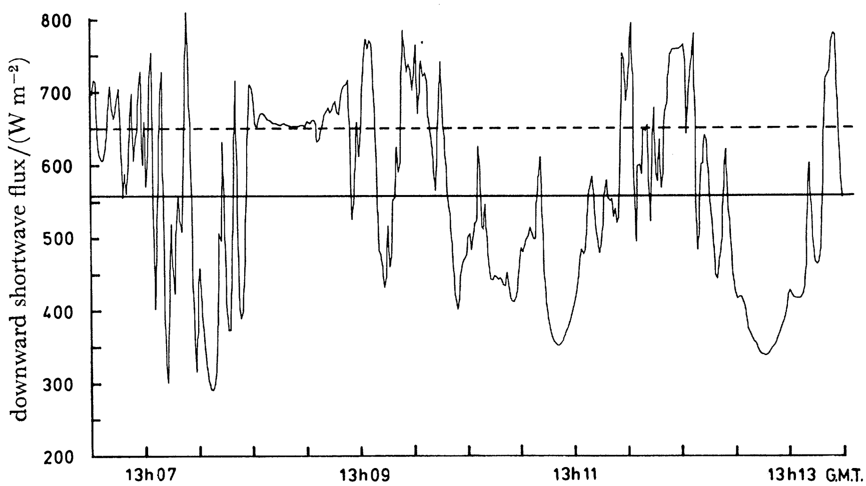

FIGURE 5. Downward shortwave flux as measured under a broken stratocumulus layer on 23 August 1978. The dashed line is the calculated clear-sky flux and the solid line the average flux.

of the liquid water path (LWP) beneath the radiometer. It can be seen that the cloud effectively becomes black as the LWP increases above 40 g m^{-2}. The measurements were performed during three profiles on 8 and 9 August 1978, the former being the day of interest. The LWP for the stratocumulus deck on 8 August was of order 110 g m^{-2} so the net flux within the cloud must be close to zero, indicating that the pyrgeometer measurements inside the cloud are questionable. Theoretical predictions for the vertical emittance at 11 μm as a function of the LWP are also shown in figure 4. Mass absorption coefficients for two drop-size distributions representative of the cloud top (Sc-1) and cloud base (Sc-2) regions were calculated from Mie theory. The theoretically derived mass absorption coefficients are 0.064 m^2 g^{-1} for the cloud top and 0.089 m^2 g^{-1} for the base, which are in good agreement with the value of 0.076 m^2 g^{-1} as measured by Platt (1976) in marine stratocumulus.

4. Cloud fields

Although uniform sheets of stratiform cloud present the best opportunities for testing radiation schemes, it is of course well known that scattered or broken cloud fields are more common. The radiation field associated with these cloud patterns is far from being horizontally homogeneous. Figure 5 shows clearly this variability: the solar radiative flux as measured during a flight leg under a broken stratoculumus layer is plotted as a function of time. The geometrical depth of the cloud was of the order of 200–400 m with tops around 1000 m. A 1 min interval corresponds to a flight distance of 6 km. The dashed horizontal line is the calculated clear-sky irradiance with an estimated error of ± 30 W m^{-2}. The measured flux can exceed the calculated clear-sky flux considerably. This emphasizes the significant effect of the cloud edges, which act as additional sources of diffuse radiation.

The downward clear-sky flux is dominated by the direct component of radiation, so the pyranometer is very sensitive to the amount of cloud covering the sun, which can thus be fairly accurately estimated from the pyranometer record. Measured flux values below the calculated

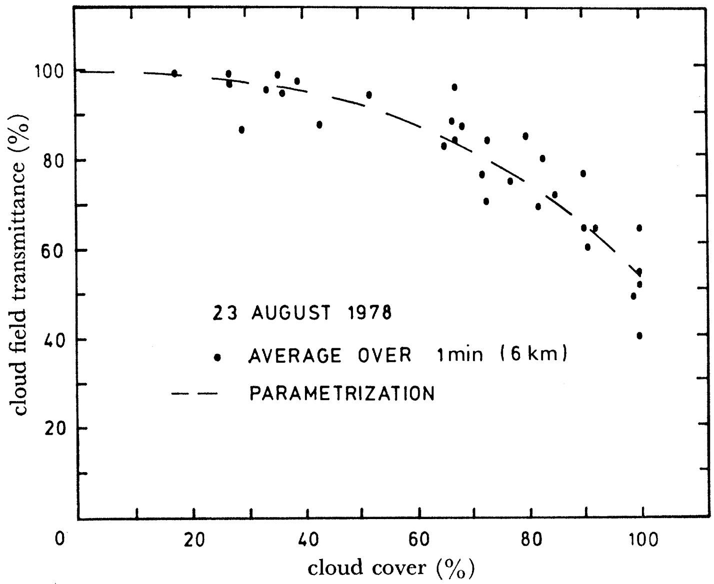

FIGURE 6. Transmission of a broken stratocumulus layer as a function of cloud amount. The parametrization corresponds to equation (1).

clear-sky values are interpreted as regions covered by cloud. The accuracy of the estimated cloud amount depends on the accuracy of the calculated clear-sky flux. Sensitivity tests show that this error is of the order of 10 % (Schmetz 1981). Furthermore, the cloud amount has to be corrected for the slant path of the sun's rays, which can be done if we know the number of cloud edges visible on the record and the cloud's geometrical depth. This procedure has been applied to four flight legs (23 August 1978) under a broken stratocumulus layer. The flux transmittance and the corresponding cloud amount are calculated for 1 min intervals (6 km flight distance) and the values are plotted in figure 6. Despite the large scatter of the values a nonlinear dependence of the bulk solar transmittance of the cloud field on cloud amount is evident. There are two reasons for this. First, it is well known that the average cloud size (height and width) of a cumulus population increases with cloud amount (Plank 1969). This in turn gives rise to the observed nonlinearity. Secondly, the cloud interaction, i.e. mutual shading and multiple reflexion between the sides, increases with increasing cloud amount. This must also increase the cloud albedo because the probability of a photon being scattered into the lower hemisphere will be reduced.

To estimate the effects of cloud–cloud interaction on the solar radiative bulk properties of cloud fields a Monte Carlo model, which includes the interaction, has been used to calculate the albedo of a field of equally sized cubic clouds with an optical depth $\delta = 10$. Deirmendjian's

(1969) C.1 phase function for a wavelength $\lambda = 450$ nm has been used. Cloud–cloud interaction is considered between a central cloud and its four neighbours. While Aida (1977) investigated only the effects of four neighbour clouds on the radiative characteristics of the centre cloud, we assume the cloud field to be infinitely extended. Thus our model is able to simulate any cloud amount and it reproduces the albedo of a plane-parallel layer as the cloud distance D is reduced to zero. The chosen wavelength $\lambda = 450$ nm is considered to be fairly representative for the visible part of the solar spectrum where the cloud–cloud interaction is most efficient.

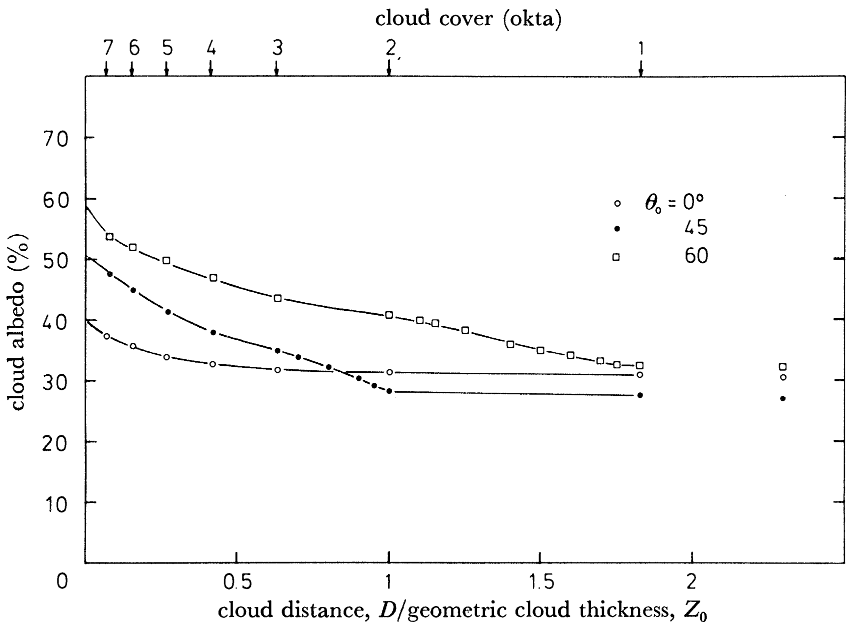

FIGURE 7. Cloud albedo of a single cloud within a field of equally sized cubic clouds for three values of solar zenith angle θ_0 calculated by a Monte Carlo simulation, which includes the cloud–cloud interaction, with an optical depth $\delta = 10$. Deirmendjian's (1969) C.1 phase function with $\lambda = 450$ nm has been used. The values on the far right of the graph correspond to a cloud not affected by neighbour clouds.

In figure 7 the albedo of a single cloud within the field is shown as a function of D/Z_0, where Z_0 is the cloud's vertical thickness. At the top of figure 7 the cloud amount is indicated. It can be seen that for all solar zenith angles the single-cloud albedo increases with cloud amount. The increase is due to mutual shading, and for large cloud amount (i.e. small distances) the albedo increases rapidly owing to multiple reflexions.

Although this albedo increase is quite significant for the single cloud, the resulting bulk reflectance, which includes weighting with cloud amount, is still much closer to a linear dependence on cloud amount than has been measured (see figure 6). Thus one can conclude that the effect of increasing cloud size is dominating the bulk solar radiative properties of cloud fields.

One aim of the investigation of the radiative properties of cloud fields is to provide a simple parametrization for use in climate models. The following equation has been found to fit the observations (figure 6) reasonably well:

$$T(N) = T_\infty N + (1-N) + g(N)\,\Delta T(N) \tag{1}$$

where

T is the solar bulk transmittance,

N is the cloud amount, $0 \leqslant N \leqslant 1$,

T_∞ is the transmittance of the plane-parallel cloud layer,

$g(N) = 4\,(N-N^2)$ accounts for the effects of cloud eges having a maximum at $N = 0.5$,

and

$\Delta T(N) = \xi(1+N)$ adjusts equation (1) to the observations ($\xi = 0.1$ for the JASIN observations on 23 August 1978).

Model calculations of the three-dimensional radiative transfer assume highly simplified cloud geometries. Therefore, further measurements are needed to establish an adequate parametrization of the radiative characteristics of cloud fields.

In more elaborate parametrizations of the bulk radiative properties of cloud fields as a function of cloud amount and of the liquid water content one should distinguish between convective and stratiform clouds, but it must be kept in mind that the cloud cover is the dominant parameter in determining the radiative characteristics of cloud fields. Thus, more elaborate parametrizations are only worth pursuing if the cloud amount and type can be specified accurately.

5. Concluding remarks

The detailed measurements made by aircraft of the cloud properties and radiation fields on 8 August 1978 provide an excellent opportunity for the verification of one-dimensional radiative transfer schemes. The theoretical treatment of extended water clouds with approximate radiative transfer models seems to be adequate.

The vertical distribution of solar radiative heating and infrared radiative cooling/heating implies that they have a strong influence on the turbulent characteristics of the cloud-capped boundary layer. Generally the radiation tends to destabilize the cloud. The diurnal variation of the solar heating is expected to lead to considerable variation of the radiative energy budget within the cloud and hence its development. The JASIN measurements present no evidence for an anomalously high absorption of solar radiation as discussed by Stephens *et al.* (1978) and Reynolds *et al.* (1975). It seems likely that the high absorptions measured within tropical clouds are caused by the neglect of solar energy exciting the towering clouds through the sides (Twomey 1978; Newiger & Bähnke 1981).

The measured longwave fluxes were in reasonable agreement with the fluxes predicted from two longwave models, but it is evident that the use of pyrgeometers on aircraft needs further investigation to allow for situations when the instrument is not at a uniform temperature (see for example Albrecht & Cox 1977).

Measurements of the solar flux under broken stratocumulus show that the solar transmittance varies nonlinearly with cloud amount, i.e. the depletion becomes more effective with increasing cloud amount. A comparison with a Monte Carlo model including the cloud–cloud interaction suggests that the radiation field is mainly determined by cloud amount and cloud size, i.e. the cloud's vertical and horizontal optical and geometrical thicknesses. Cloud–cloud interaction can become significant for towering clouds shading each other, but in general it has second-order influence on the fluxes. To establish an adequate parametrization of the bulk radiative properties of cloud fields further measurements are required.

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Discussion

S. A. Thorpe (*Institute of Oceanographic Sciences, Brooks Road, Wormley, Godalming, Surrey GU8 5UB, U.K.*). Although no direct measurements of turbulence were made, the radiation observations imply that the cloud top was destabilized by longwave radiation and that convection occurred within the cloud sheet. The observed droplet spectrum is intriguing. Is it likely that the observed spectrum represents an equilibrium state and what can be learnt about the turbulence within the clouds from the droplet spectrum?

A. Slingo. The droplet spectrum is discussed in more detail in Slingo *et al.* (1982*b*). The shape of the spectrum is a balance between the essentially adiabatic forcing of the liquid water content and the roughly uniform number of drops. The latter may reflect a uniform supply of condensation nuclei in the well mixed cloud and sub-cloud layers. There is evidence from a study of the spectra near cloud top of the inhomogeneous mixing mechanism, as proposed by J. Latham and his coworkers (Latham & Reed 1977).

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1. Dr Slingo indicated that there was little entrainment of dry air from above the inversion on 8 August. I suggest that this was because on that day the dry air above the inversion was not very dry and the equivalent potential temperature, θ_e, increased with height at the inversion. More usually during JASIN a decrease of θ_e was observed (Taylor *et al.* this symposium) and greater entrainment would be expected.

2. Concerning the observation of very dry air just above the inversion on a number of days during JASIN, several explanations have been advanced. From studying the JASIN radiosonde ascents I believe that the limited vertical extent of this dry layer is caused by the advection of moister air at upper levels. At least one such case, 25 August, has been explained by the presence of an advancing warm front (Taylor & Guymer this symposium) and we are currently studying other cases.

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1. The fact that the measured liquid water content agrees so well with the adiabatic liquid water content suggests that very little entrainment occurs at the cloud top, and that the turbulent mixing inside the cloud is rather weak. Although the top layer cools and the rest of the cloud layer warms up owing to radiation, only a shallow layer near the top is destabilized. The resulting turbulence may not be strong enough to cause significant entrainment into the much warmer air above the cloud. The night-time situation may be quite different when the strong cooling at the top and the warming at the bottom both destabilize the entire cloud layer.

2. The dry layer that is often observed just above the stratus deck appears somewhat of a mystery in that it suggests a violation of the second law of thermodynamics. A possible mechanism for drying the layer just above the cloud was considered to be radiation. When relatively large droplets detrain into the air above the cloud, the radiative cooling of the drop may be such that its temperature stays below the dewpoint. This mechanism can explain a dewpoint temperature at most 4 K lower than the cloud-top temperature. The actually observed dewpoint

temperatures are often much lower than can be explained in this way. Also scavenging of water vapour by cold droplets in the relatively dry air would cool the inversion layer.

On the other hand, for 25 August, Peter Taylor told me that his trajectory analysis is consistent with the dry layer, just above the stratus deck. So, possibly, the phenomenon is not as strange as it looks at first sight.

3. The cooling of the droplets at the cloud top enhances the droplet growth significantly, especially that of the larger droplets. They may grow relatively quickly to sufficient size to start the coalescence process. This mechanism may help explain the frequent occurrence of drizzle from rather shallow stratus clouds.

A. Slingo

Reply to Taylor (point 1) *and Businger (point* 1). The agreement between the observed and adiabatic liquid water contents shows that entrainment makes a small contribution to the mixed-layer water budget. It does not necessarily mean that turbulent mixing is weak within the cloud, merely that the turbulence levels are too low to result in significant entrainment of the very stable inversion air. If the inversion were weaker, the same turbulence levels could lead to a greater entrainment rate.

Figure 16 of Slingo *et al.* (1982*b*) shows that radiation destabilizes the cloud layer in both the day-time and night-time. The overall shortwave heating of the cloud at midday is as large as the longwave cooling, so this should certainly lead to a diurnal variation in the mixed-layer properties. However, the entrainment rate may be more sensitive to the turbulence generated by the longwave cooling maximum of the cloud top, and since this is reduced by only about a quarter by the shortwave heating, the entrainment may not vary by as much as Professor Businger suggests. At lower latitudes, however, the shortwave warming will be greater, so the diurnal contrast may be more pronounced.

Reply to Taylor (point 2) *and Businger (point* 2). The dry zone is a most intriguing feature, but I would be surprised if it could always be accounted for by differential advection. Our observations show very little shear across the cloud top, so the inversion air has probably followed a similar track to the mixed-layer air beneath it. The dry zone is often seen as a thin layer of enhanced visibility immediately above the cloud top, and some radiosonde ascents show it to be extraordinarily dry and thin. This seems to argue in favour of a local mechanism, although Businger has shown that the detrainment of large drops is probably not the cause.

Reply to Businger (point 3). Both Roach (1976) and Barkstrom (1978) have shown how the longwave cooling maximum may enhance the growth of droplets of condensation at the top of cloud or fog. Roach (1979) has added further comments on both papers. Growth rates were increased considerably by including radiation, but to demonstrate that this could allow drops to grow to the point where coalescence can take over requires a more detailed treatment of both turbulent transport and entrainment.

References

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