THE INFLUENCE OF BULK AND MICROPHYSICAL STRUCTURE ON THE RADIATIVE PROPERTIES OF WATER CLOUDS

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1. INTRODUCTION

The problem of the realistic treatment of clouds and radiation in General Circulation Models may be broken down into two main areas;

a) Prediction of cloud amount, type, vertical and horizontal distribution etc, within a grid box from the model variables and/or climatology.

b) Determination of the radiation fields for this cloud configuration.

The presentation will concentrate on the second area and will try to summarise the known radiative properties of water droplet clouds as a function of their microphysical structure (drop size distribution, liquid water content and its vertical integral - the liquid water path). Results from some recent observational studies which complement the large body of theoretical work will also be shown. Cirrus and other ice clouds will not be considered here as the study of their physical and radiative properties is still at an early stage. For recent research see Stephens (1980), Platt et al, (1980) and references therein.

2. LONGWAVE PROPERTIES

The transfer of infrared radiation in clouds is dominated by water droplet absorption. If the liquid path through a cloud is greater than about 30 gm^{-2}, which is the case for the great majority of clouds in the lower troposphere, then the cloud is optically thick, so that the fluxes emitted will be close to the Planck function fluxes at the cloud boundary temperatures. If all that is required in a model is the total cloud cooling, then a relatively simple scheme in which the cloud is treated as a black body may be used. This approach has been adopted in most GCM treatments up to now. The cloud top experiences strong radiational cooling, mainly by emission through the overlying atmosphere of radiation in the 8-12 μm atmospheric window. In the same way the cloud base is heated slightly by the warmer atmosphere and ground beneath the cloud. Both these effects increase with cloud height, due to decreasing air density, increasing transparency of the overlying air and contrast between cloud and ground temperature (e.g. Stephens 1978a). Provided that the cloud is optically thick, the total cooling is independent of the internal structure.

The partitioning of the infrared cooling, however, is strongly dependent on the liquid water content profile. As the liquid water content near cloud top is increased, the depth over which the net upward flux falls to zero is reduced, so that the cooling is progressively concentrated into a thinner layer and local cooling rates are increased. This is well shown in the top half of Fig. 1 (from

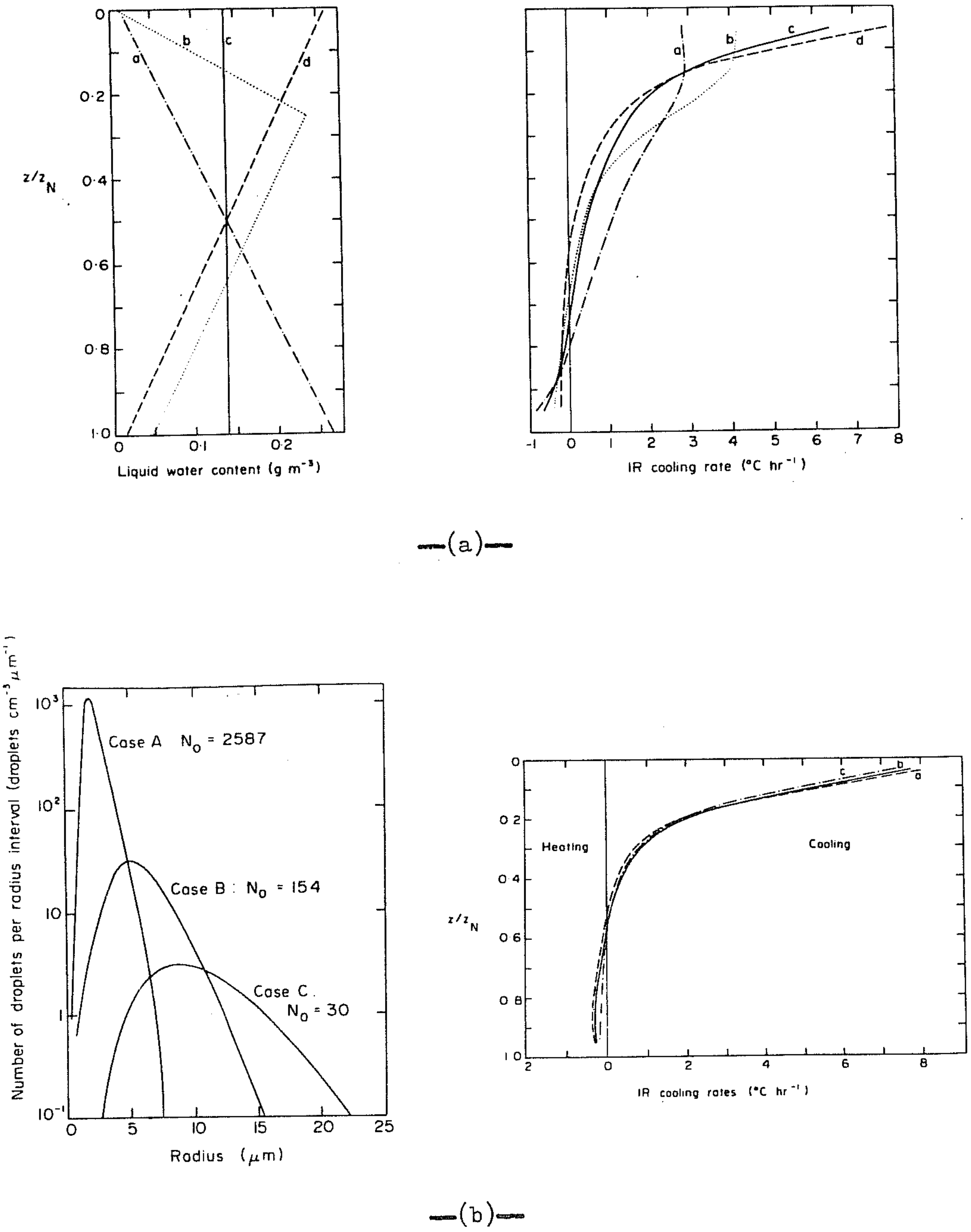


Fig. 1 (a) Comparisons of the longwave cooling rate profiles (right) in an experimentally observed cloud possessing four different liquid water content profiles (left), but with the same liquid water path ($44 gm^{-2}$). The cloud layer is 320 m thick.

(b) Comparisons of the longwave cooling rate profiles (right) for a cloud possessing three different dropsize distributions (left), but with the same liquid water content profile (profile d from above). (from Stephens 1978a).

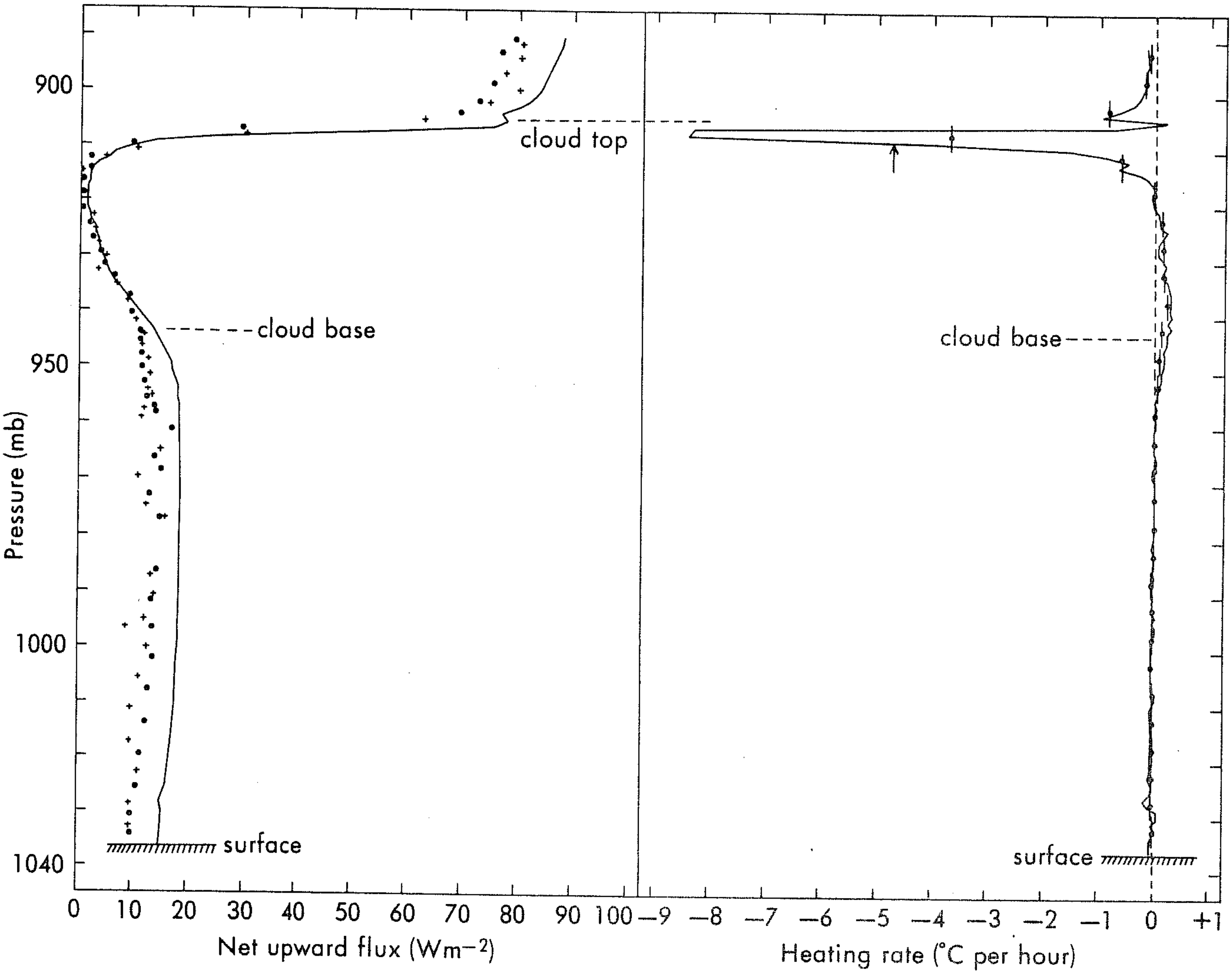


Fig. 2 Profiles of infrared net upward flux and radiative heating rate through Stratocumulus. The solid curves show the theoretical values and the points are from measurements with net radiometers. (from Slingo et al 1980).

Stephens 1978a). Note that since the cloud is optically thick (just) the total cooling (i.e. the area under each curve) is about the same in each case. The lower graphs show that the dependence of the cooling rate profile on drop size distribution is very weak. As a further example, Fig. 2 shows results from a comprehensive tethered balloon study of nocturnal stratocumulus (Roach et al, Caughey et al, Slingo et al, 1980). The points represent measurements and the solid curves are theoretical fluxes and heating rates from the infrared scheme of Roach and Slingo (1979). The liquid water content was roughly triangular in shape, close to the adiabatic profile, which results in a concentration of the radiative cooling into a layer only about 50 m deep at cloud top.

3. SHORTWAVE PROPERTIES

The shortwave properties of water clouds are dominated by droplet scattering, but there is also droplet and water vapour absorption in a number of near-infrared bands. This means that computational techniques for calculating shortwave fluxes and heating rates within clouds have to be chosen with care and several spectral bands are required. Some of the most important papers are those by Lacis and Hansen (1974), Zdunkowski and Davis (1974), Liou (1976), Twomey (1976), Welch et al, (1976), Feigel'son (1978), Kerschgens et al (1978), Stephens (1978a), Liou and Wittman (1979), Welch et al, (1980), and references within these papers. The broadband reflectivity or albedo R, transmissivity T and absorptivity A depend in a complex way on a number of parameters, but the main results of these studies can be summarised as follows:

a) As liquid water path increases:

$R^{\uparrow}$ $T^{\downarrow}$ $A^{\uparrow}$
(max $\approx$80%) (max $\approx$20%)

b) As solar zenith angle increases:

$R^{\uparrow}$ $T^{\downarrow}$ $A^{\downarrow}$
(complex dependence)

The dependence of R, T and A on liquid water path and zenith angle is illustrated in the example from Liou and Wittman (1979), shown in Fig. 3. Both these authors and Stephens (1978b) have shown that it is possible to parameterize this dependence for use by simpler radiation schemes. There are, however, obvious advantages to be gained by incorporating fast multiple scattering schemes directly into GCMs which treat liquid water path as a model variable, because R, T and A may then be computed implicitly without the need for such parameterizations.

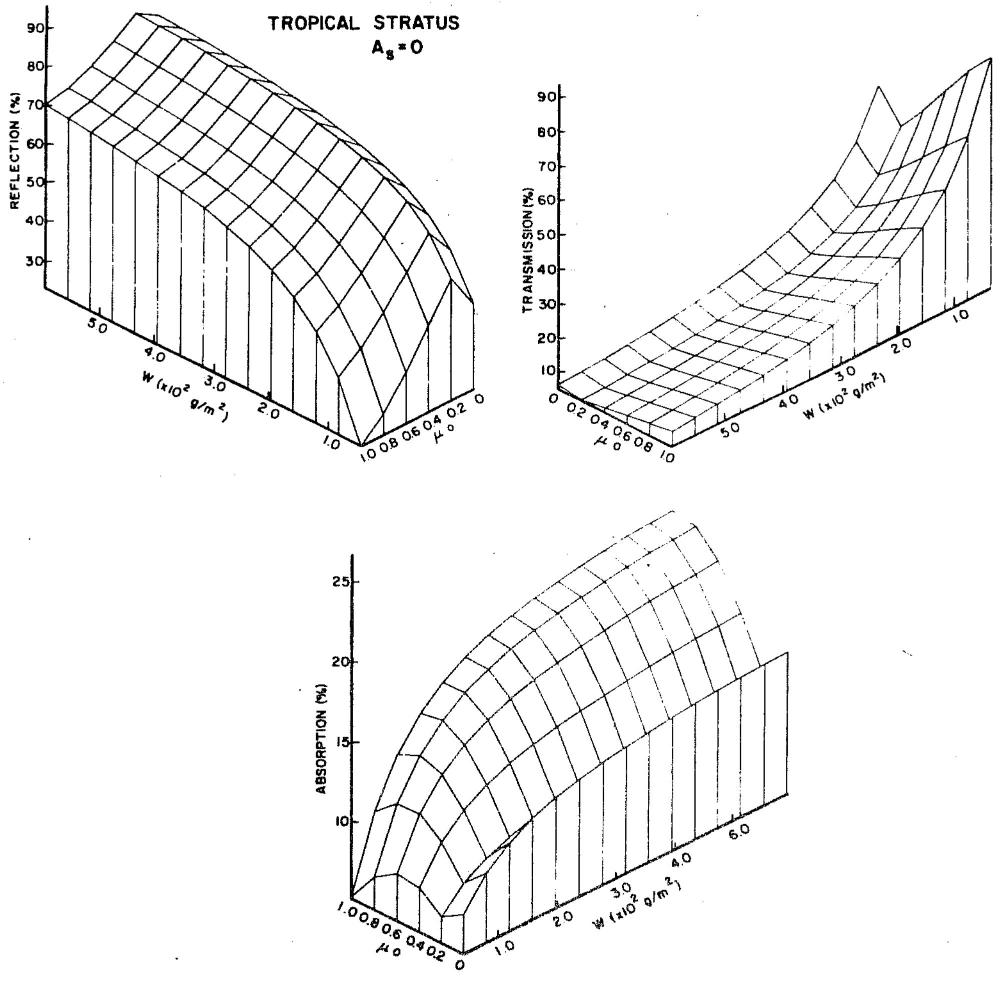


Fig. 3 Three-dimensional reflection, transmission and absorption surfaces of a Stratus cloud as functions of the vertical liquid water content W and the cosine of the solar zenith angle μ_o. (from Liou and Wittman 1979).

c) As mean drop radius increases at constant liquid water content;

$R^{\downarrow}$ $T^{\uparrow}$ $A^{\uparrow}$
(complex dependence)

The dependence on drop size distribution is such that a small increase in cloud absorption due to the larger drops is reinforced by a much larger increase in transmissivity, so that not only does the cloud absorb more but also more is transmitted to the underlying atmosphere and surface for further absorption. This provides a subtle contrast between continental and maritime clouds, although the effect may be marked by the concurrent meteorological and surface albedo changes.

As an example, Fig. 4 shows results from a theoretical study completed recently (Slingo and Schrecker 1980; in preparation). Cloud absorption and albedo have been calculated for boundary layer clouds in three atmospheres with realistic temperature and humidity structure, for a range of drop size distributions. The dependence of cloud radiative properties on the drop size distribution N(r) is determined almost uniquely by the equivalent radius r_e ;

$$r_e = \int n(r)\ r^3\ dr / \int n(r)\ r^2\ dr$$

Boundary layer clouds growing in a continental airmass with high concentrations of condensation nuclei may have $r_e \approx 5\ \mu m$, whereas the same liquid water content clouds in a much cleaner maritime airmass may have $r_e \gtrsim 10\ \mu m$ (e.g. Mason 1971, Twomey 1977). The corresponding variations in albedo on Fig. 4 are quite large and would have to be modelled by any comprehensive cloud scheme.

d) As the liquid water content is concentrated towards cloud top at constant liquid water path;

$R-$ $T^{\downarrow}$ $A^{\uparrow}$
(insensitive)

This result comes from Stephens (1978a), although Welch et al (1980) find hardly any effect at all

e) Shortwave absorption in clouds is concentrated towards cloud top but is smaller in magnitude than the infrared cooling.

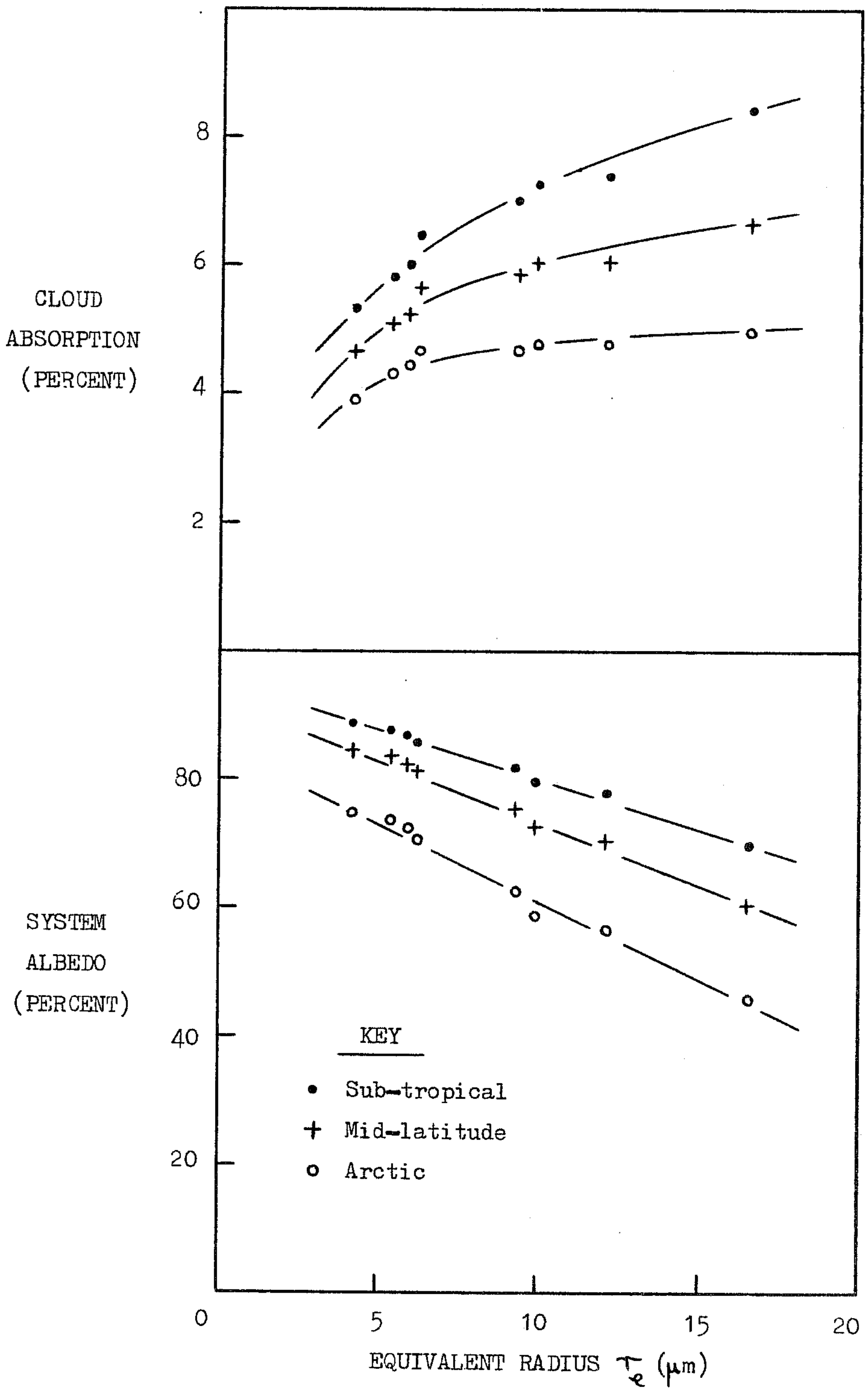


Fig. 4 Percentage cloud absorption and system albedo for boundary layer clouds in three model atmospheres, as a function of the equivalent radius of the drop size distribution. (from Slingo and Schrecker 1980).

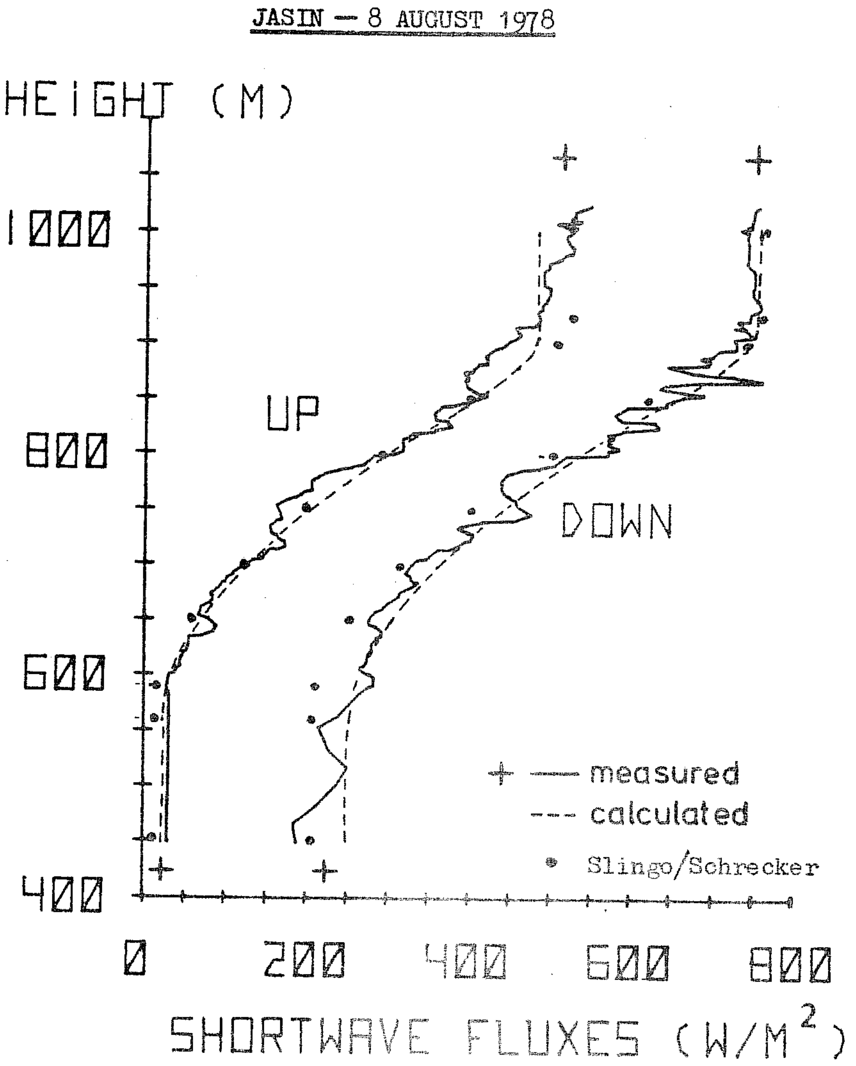
Some observational studies, especially those of Drummond and Hickey (1971) and Reynolds et al (1975) have obtained absorptions well in excess of the 20 per cent maximum value found in theoretical studies. Stephens et al (1978) also reported measured absorption in excess of theoretical values. The presence of absorbing aerosols, observational error and finite cloud geometry have all been invoked to explain this discrepancy. Welch et al (1980) suggest that the excess heating may be due to a secondary droplet population of up to precipitation size (i.e. the clouds may be close to, or actually, raining), which it is known have much higher absorption optical depths in the visible than smaller drops, for the same liquid water content.

There have been very few observational studies in which shortwave fluxes and heating rates and microphysical measurements inside clouds have been compared with theory. During the Joint Air-Sea Interaction experiment (Pollard 1978), however, good data were obtained during a multi-aircraft study of marine stratocumulus. Preliminary results are shown in Fig. 5, extended from Schmetz and Raschke (1980). The comparison is between observations from the DFVLR "Falcon" aircraft with radiation schemes developed in Professor Raschke's group and at the Meteorological Office. The agreement between fluxes and heating rates is very good indeed and gives some confidence that further studies may resolve the conflicts outlined above.

4. DISCUSSION

The theoretical work and observational studies suggest that cloud radiative properties can be predicted with sufficient accuracy for GCMs provided the liquid water path and droplet equivalent radius of the cloud are specified. Unfortunately, very few observational studies have been made in which these quantities were measured together with the radiation fields and there is certainly no climatology of cloud microphysical properties from which modellers can draw. It is only relatively recently that research aircraft have been fitted with comprehensive Cloud Physics and radiation instrumentation and to build up such a climatology will take considerable effort. No detailed theoretical models of medium and high cloud sheets have been developed which can be used to predict the liquid water path. For such clouds the use of satellite data to deduce the liquid water path and radiative properties probably represents the easiest way to build up the required information.

The theoretical treatment of bounday layer cloud, especially stratocumulus, is much more advanced and models which could be incorporated into GCMs to predict liquid water path and interact with a radiation scheme are being studied (e.g. Randall (1980) and references therein). There is still argument, however,



	Schmetz/ Raschke	Slingo/ Schrecker	Measured
Albedo (percent)	64.0	69.0	≈ 68
Absorption (Wm^{-2})	40.6	43.1	≈ 40
" (percent)	5.4	5.7	≈ 5.3

Fig. 5 An example of a comparison between the measured shortwave fluxes and the theoretical values from two radiation schemes, using data from a field study of marine Stratocumulus carried out during the JASIN international experiment. (to be published).

as to the relationship between the turbulent and radiative flux profiles (Deardorff and Businger, 1980) and it is therefore unfortunate that experimental verification of the models is made very difficult by their sensitivity to the assumed divergence and entrainment rate, both of which are extremely difficult to measure.

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