RADIATION AND CLOUD PHYSICAL ASPECTS OF BOUNDARY-LAYER CLOUDS

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Introduction

Boundary-layer clouds play a significant role in the transfer of radiation through the atmosphere, thereby affecting the surface energy balance and the vertical distribution of radiative heating and cooling. These clouds are also a major factor in the water budget of the atmosphere, acting both as a reservoir for water and as a source of precipitation. Boundary-layer clouds also contribute to the vertical turbulent fluxes of heat, water and momentum, although the vertical profiles of the area-average fluxes are dependent on the cloud type and structure.

The radiative and microphysical processes in stratocumulus clouds are strongly interactive, in that the cloud development and structure depend on radiative heating and cooling which are determined by the microphysical properties of the cloud, while the evolution of the droplet spectrum depends on the dynamical structure of the cloud. This two-way interaction, which occurs often on horizontal scales of less than 1 km, makes it difficult to separate the radiative and microphysical processes in parametrization schemes for larger-scale models. The problem of parametrizing the effects of boundary-layer clouds is further complicated by the fact that the microphysical processes, which govern the development of precipitation and cloud lifetime, as well as the radiative transfer through the clouds, are dependent on the atmospheric aerosol content and chemistry, which are very variable in space and time, and are not normally predicted by atmospheric models.

The parametrization of the effects of boundary-layer clouds is therefore a complex problem; the fact that many aspects of the in-cloud processes, and their interactions, are themselves not fully understood only serves to add further complications. In this paper we briefly review our current understanding of boundary-layer cloud processes and draw attention to factors which may need to be taken into account in parametrization schemes. Although stratocumulus and boundary-layer cumulus have many features in common, and indeed evolution from one to the other often occurs, the discussion is separated in this paper as the differences are relevant to the parametrization problem.

Stratocumulus

Structure

Stratocumulus clouds are characterized by being generally well mixed in the vertical, so that the potential temperature is almost independent of height within the cloud layer and sub-cloud layer. Entrainment through the cloud top is generally rather weak since the necessary condition for cloud-top entrainment instability (MacVean and Mason, 1990) is seldom met. As a result, the liquid water content at all levels in the cloud is close to that in an air parcel lifted adiabatically from cloud base; over depths typical of most stratocumulus, the liquid water content increases linearly with height above cloud base. Typical profiles through maritime stratocumulus, obtained by Nicholls and Leighton (1986) are shown in Figure 1. These show the well mixed profile of equivalent potential temperature θ_e in the cloud and sub-cloud layer, the linear increase in liquid water content (q_l) with height, and the formation of a stable layer with reduced turbulent velocity fluctuations (u, v) below cloud base.

Due to the effects of radiative long-wave cooling at cloud top, combined with some evaporative cooling resulting from the small amount of cloud-top entrainment, stratocumulus tends to develop a horizontal cellular structure on the scale of hundreds of meters, the dominant scale being related to the depth of the cloud layer. The cloud therefore consists of active core regions of updraught and adiabatic water content surrounded by regions of subsiding air characterised by lower water content and reduced droplet *concentrations*. This structure is often visible in the structure of the top of the cloud layer and was demonstrated by Nicholls (1989) to extend through much of the depth of the cloud layer. Figure 2 shows a typical record of the vertical velocity along a level run through a stratocumulus layer, while Figure 3 shows the results of compositing suitably scaled observations which demonstrate the consistent structure of cold, dry descending regions within the cloud layer. Statistical analysis of the observations confirms that they are consistent with a structure consisting of hexagonal cells in which central core regions are surrounded by "walls" of subsiding air whose width is roughly one sixth of the diameter of the core regions.

Microphysics

Due to the relatively weak updraughts within the cloud, and the low level of entrainment at the top of the cloud layer, activation of cloud condensation nuclei at levels removed from cloud base is inhibited, so that the droplet concentrations are relatively independent of height above cloud base. Some typical profiles of the relative droplet concentration, from Nicholls and Leighton (1986), are shown in Figure 4. The droplet concentration is determined largely by the properties of the aerosol in the sub-cloud layer. However, also due to the small amount of entrainment, droplet concentrations and liquid water contents in stratocumulus tend to be much larger than those found in cumulus cloud formed at the top of boundary layers having similar aerosol loadings. This can be seen by comparing the empirical results obtained by Martin *et al.* (1993) for stratocumulus with those for cumulus presented by Raga and Jonas (1993); a summary of these results is shown in Figure 5.

Due to the almost adiabatic increase in water content with height and the almost constant droplet concentration, the mean radius of the droplets increases with height above the cloud base. The shape of the spectrum is such that the radiatively important effective radius (given by $\Sigma n_i r_i^3 / \Sigma n_i r_i^2$) is usually simply related to the mean radius and, due to the linear increase in water content with height, is readily derived from an assumed concentration and height above cloud base. From the sensitivity of the droplet concentration to the aerosol concentration, it is apparent that an order of magnitude increase in the aerosol concentration will lead, approximately, to a doubling of the droplet concentration and a reduction in the mean droplet radius of about 30%.

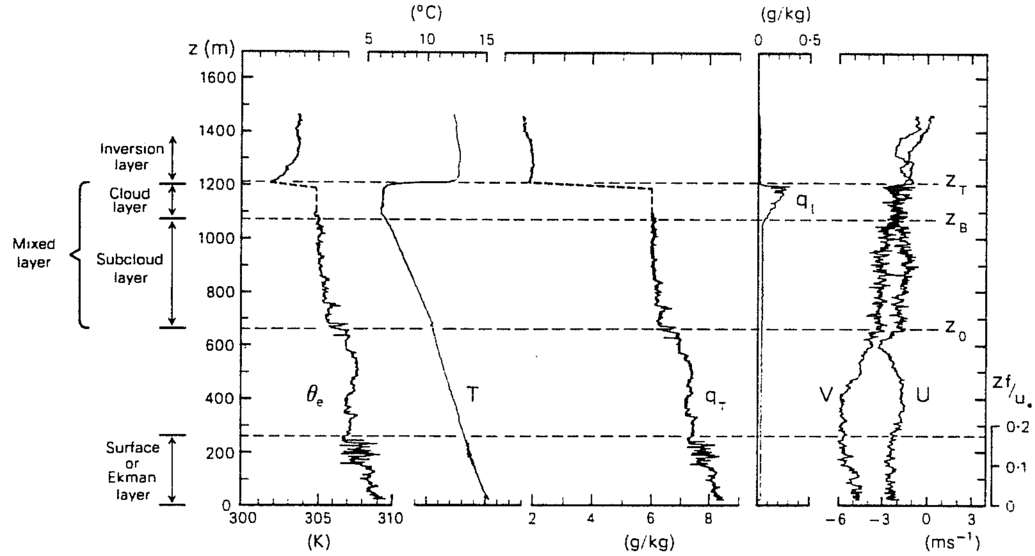

Fig 1 Profiles of equivalent potential temperature (θ_e), temperature (T), total water content (q_T), liquid water content (q_l), and horizontal velocity components (u,v) through a stratocumulus capped boundary layer. The cloud layer was approximately 150 m thick.

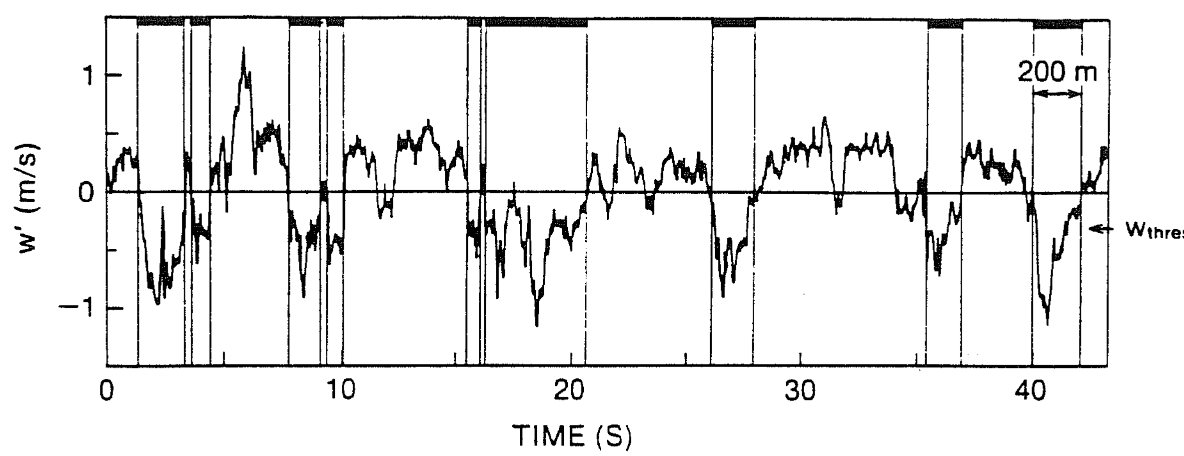

Fig 2 Record of vertical velocity measured along a horizontal path through a stratocumulus sheet, showing the presence of downdraught regions. Distinct regions of updraught and downdraught are indicated.

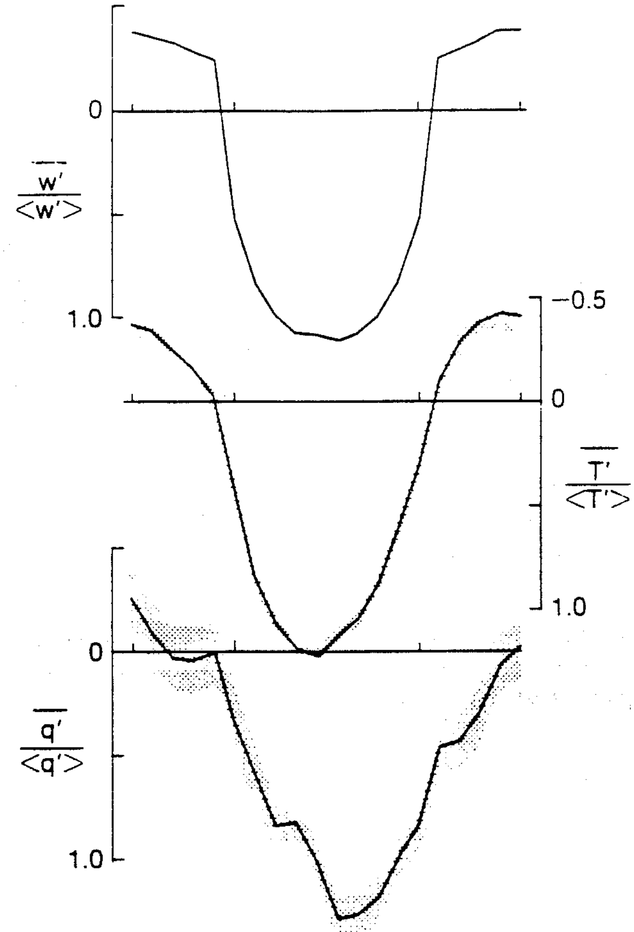

Fig 3 Composite, scaled observations showing the correlation between vertical velocity, temperature and total water in the downdraught regions in a stratocumulus layer in which the vertical velocity record shown in Fig 2 was obtained.

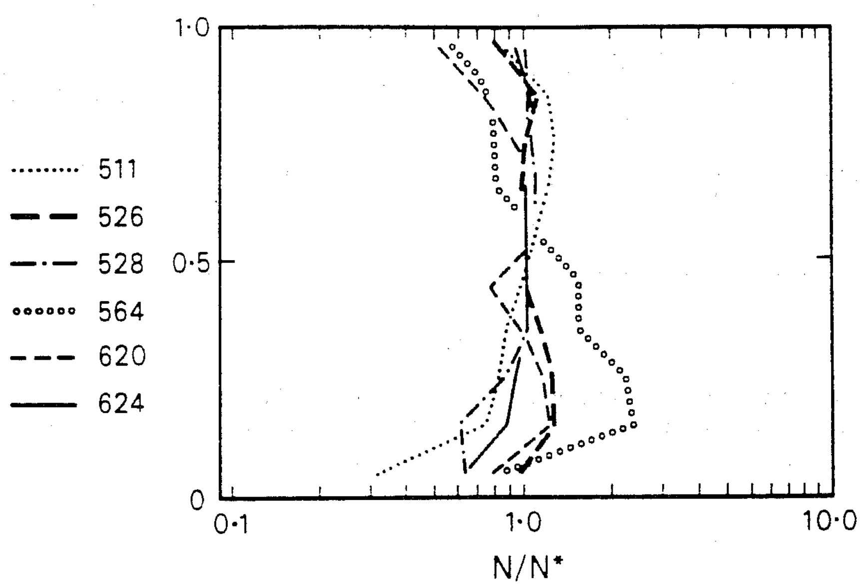

Fig 4 Profiles of the ratio of the droplet concentration, N, to the mean value in the cloud, N^*, plotted against normalized height above cloud base, for several case studies of marine stratocumulus.

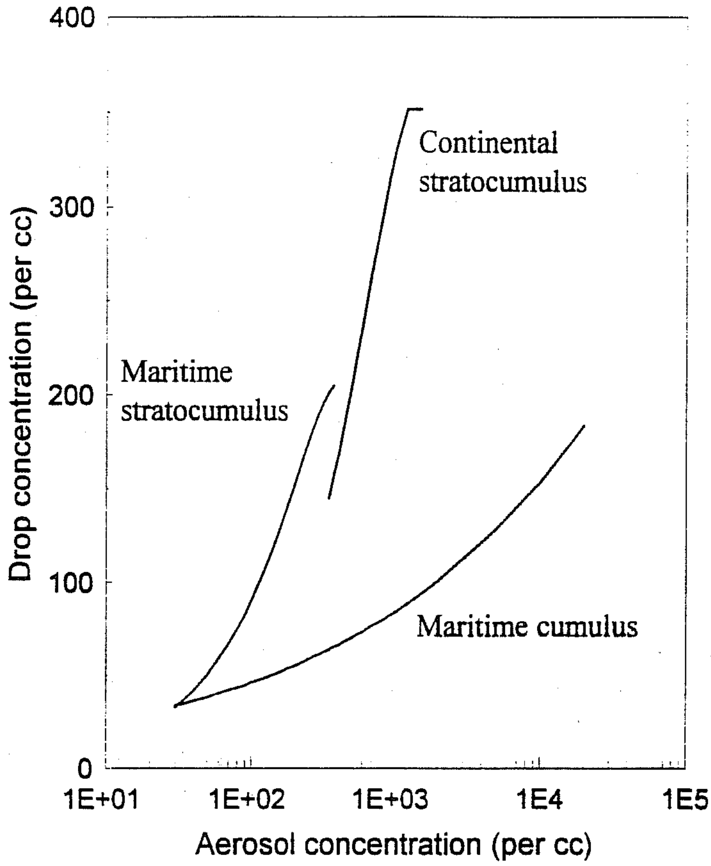

Fig 5 Empirical relations between droplet concentration, in the size range (1-24 μm), in different types of cloud and the sub-cloud aerosol concentration, in the size range 0.05-1.5 μm.

The long cloud lifetime, however, combined with the presence of significant turbulent vertical velocities, ensures that some drops remain within the cloud for sufficiently long periods to grow by condensation and coalescence to precipitation size even in cloud only a hundred meters deep or so. Many conventional cloud parametrizations of the type developed by Kessler (1969) would fail to predict the formation of precipitation under such conditions as they are designed for use in convective cloud simulations and do not account for the growth in the tail of the drop size distribution over long periods and under turbulent conditions. Turton and Nicholls (1987) showed that the vertical flux of water arising from the drizzle may be a major term in the water budget of the cloud and that it influenced the diurnal variation in the structure of the boundary layer and the vertical transport of heat and water from the surface. There is evidence that drizzle formation may be further enhanced by the presence of cumulus, with generally rather low droplet concentrations, rising into the base of stratocumulus, with a higher droplet concentration. Figure 6 shows droplet spectra and the number of large drops in the unperturbed parts of a stratocumulus layer and in regions influenced by cumulus (from Martin (personal communication)). It appears that the formation of bimodal spectra is associated with the recent influence of penetrating cumulus clouds although the mechanism by which the enhanced growth occurs is not at present fully understood.

Radiative transfer

The radiative properties of horizontally uniform stratocumulus layers may be calculated by a variety of methods. Model studies by Duynkerke (1989), Rogers and Koračin (1992), and others, have shown that solar heating is confined to a narrow region close to cloud top, while long-wave cooling is more distributed in the vertical, giving rise to localised regions of net radiative heating and cooling. It appears that the radiative budgets are a major contribution to the heat budgets of the cloud layer and, due to diurnal changes in the incoming solar flux, give rise to a diurnal variation in the structure of the cloud layer. The effect is especially significant in terms of the diurnal variations in the radiation reaching the surface. Figure 7 shows an example of the surface long- and short-wave fluxes calculated by Turton and Nicholls (1987) using a mixed-layer model of the diurnal evolution of the cloud layer. It is evident that even though the cloud layer does not completely dissipate during the day, there are substantial diurnal changes in the surface short-wave flux. The formation of a stable layer below cloud base is also predicted by this model; its evolution would not occur in the absence of the cloud layer. These stable layers are often observed (Figure 1) and need to be considered when estimating the vertical turbulent fluxes of heat and water from the surface.

However, as has been indicated earlier, stratocumulus is seldom horizontally uniform, and different techniques must be employed in order to calculate the optical properties of the non-uniform layers. Using a Monte Carlo technique, and assuming that the stratocumulus layer is composed of a series of regular hexagonal cells, Jonas (1993) showed that the amount of short wave, solar, radiation scattered by the cloud layer for small solar zenith angles is significantly less than might be expected for a uniform layer having the same horizontally averaged water content profile. Results presented in Figure 8 show the reflectance at 0.45 μm of a cloud layer in which the water content in the regions between the active cell cores is reduced to 20% of that in the cores. It can be seen that, at these non-absorbed solar wavelengths, the reflectance is reduced significantly compared with a uniform layer due to the channelling of radiation through the regions of low water content. For larger solar zenith angles, however, the effect

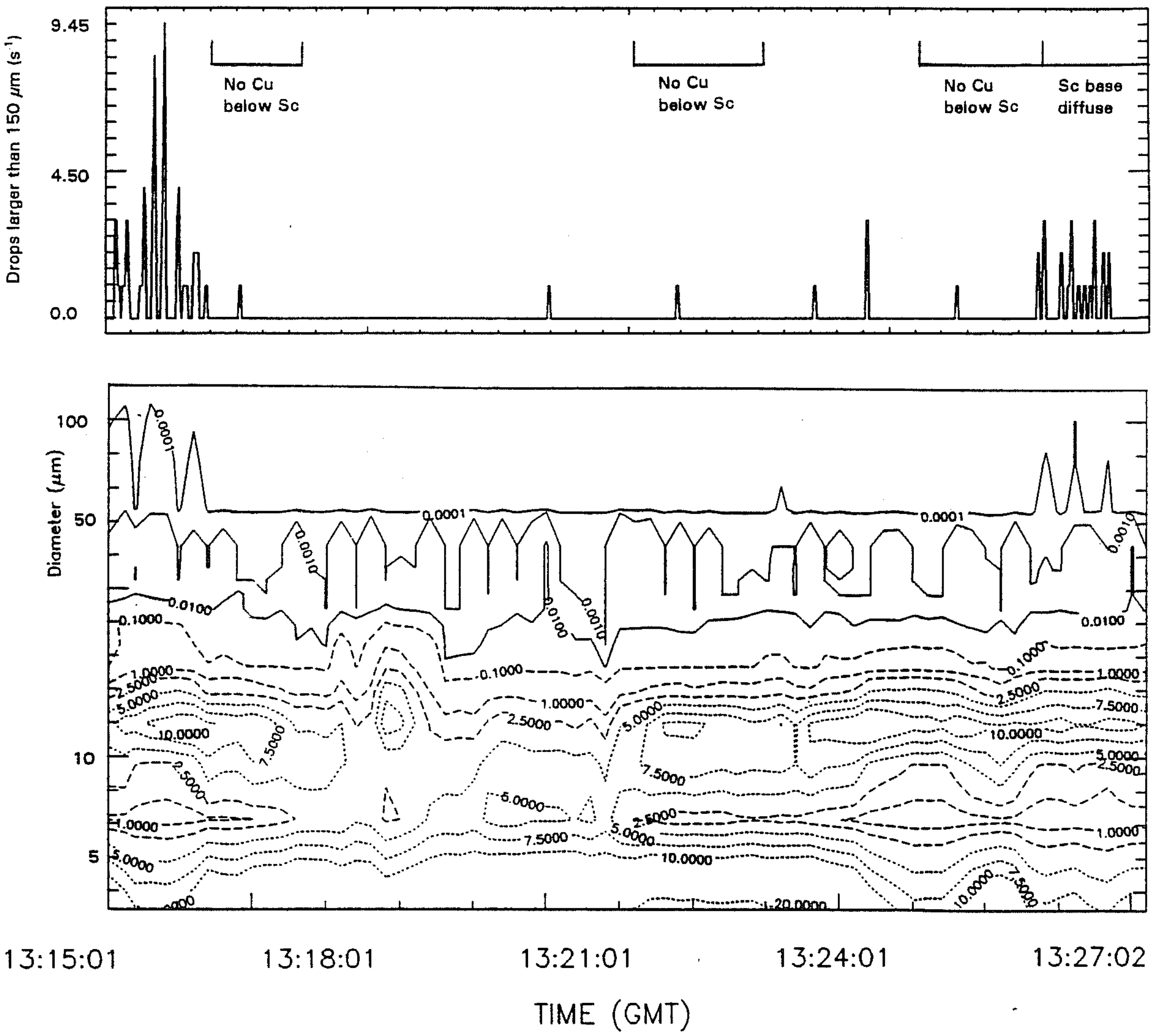

Fig 6 Droplet spectral measurements along a 12 min level flight through a stratocumulus layer. (Above), number of droplets larger than 150 μm encountered per second. (Below), contours of droplet concentration (cm^{-3}). Regions where no cumulus were observed to be penetrating the stratocumulus layer are indicated; in other regions penetrating cumulus were present below the stratocumulus base.

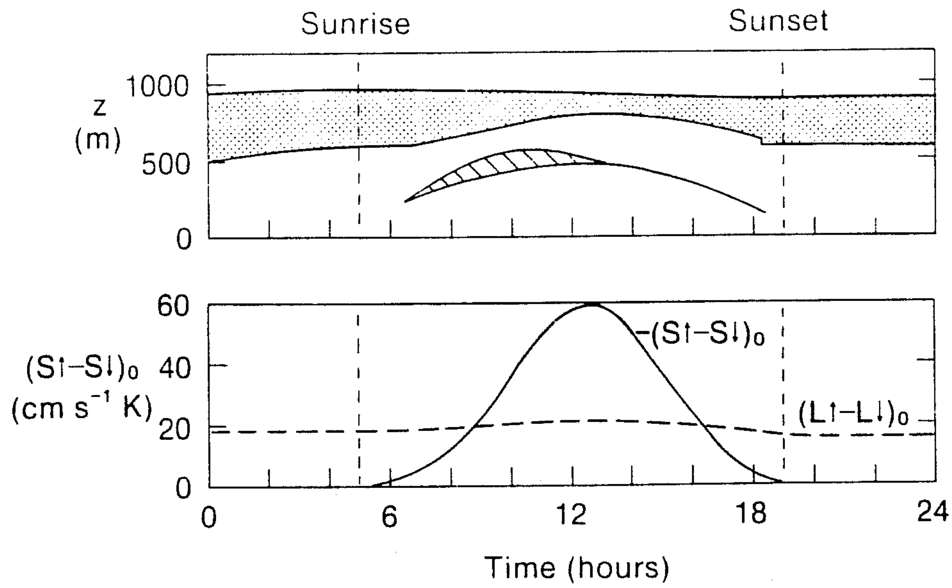

Fig 7 Calculated evolution of a stratocumulus layer (stippled), showing the formation of a stable layer below the cloud (hatched), cutting off the supply of water and heat, together with the net surface long- and short-wave fluxes. The results were obtained using a mixed layer model.

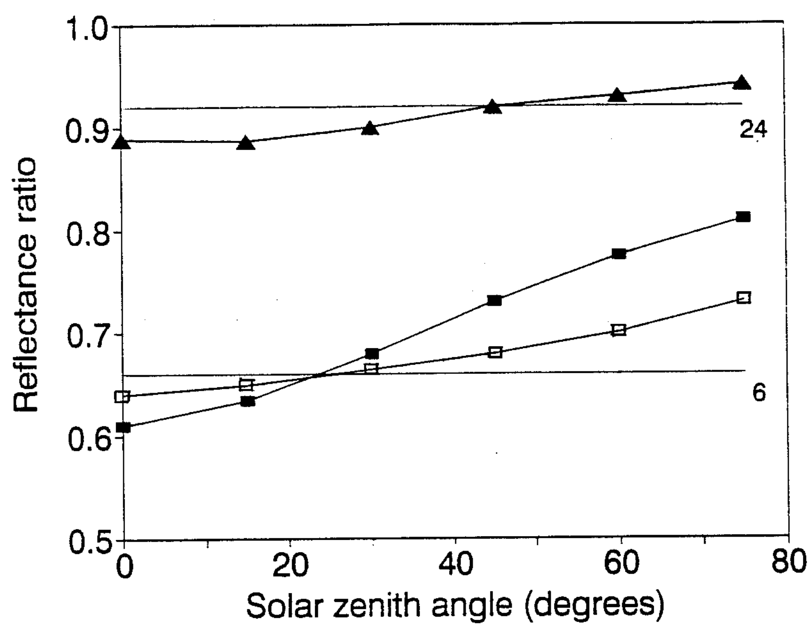

Fig 8 Ratio of the reflectance at 0.45 µm of a cellular stratocumulus cloud layer, 300 m thick, to that of a horizontally uniform layer for different cell geometries. The water content between the cells is assumed to be 20% of that in the active parts of the cells. The straight lines represent the values obtained by a weighted average of the reflectances of the high and low water content regions for the indicated ratio of the cell diameter to the wall thickness. Cell diameters and wall thicknesses are: ■, 1200 m and 200 m; □, 4800 m and 800 m; ▲, 4800 m and 200 m.

of shadowing of one core region by another outweighs the increased transmission through the regions of low water content and the reflection increases compared with the uniform layer with the weighted average reflectance of the high and low water content regions. The effects are large and for typical cloud conditions give changes in the reflection which exceed those which might result from changes in the droplet concentration and effective radius of the drops near cloud top, such as might result from changes in the aerosol concentration.

It is also of interest to note that the Monte Carlo models can predict the length of the path of photons as they pass through the cloud layer. Due to the effects of multiple scattering, the path length of photons which are eventually transmitted through the cloud layer are much greater than the cloud layer thickness, and even photons scattered upwards by the cloud layer have long paths in the cloud. These effects are demonstrated in Figure 9. Clearly, for wavelengths which are appreciably absorbed by water vapour, the increased path through saturated cloudy air will lead to enhanced absorption compared with that estimated from the direct paths. This may be a contributory factor to "anomalous absorption" which has been reported by Stephens (1978), among others. It appears likely that this effect may be further increased by inhomogeneities in the cloud structure, due to radiation channelling through low water content regions, but this effect has not been quantified.

Cumulus cloud fields

Structure

Cumulus cloud fields show considerable variability both in the dynamical organisation of the cloud field and in the microphysical properties of individual clouds. The cloud fields may be essentially random or they may exhibit organisation in the form of streets or cells. The organisation is dependent on the atmospheric structure, especially on the temperature and shear profiles. In addition, the organisation of the cloud field may reflect the nature of the underlying surface, for example, clouds may form preferentially over a region of locally raised sea surface temperature or over dark, warm, surfaces. The microphysical structure of cumulus also shows considerable variability on a wide range of scales resulting from the entrainment of air into the active cumulus. From the point of view of parametrizing the radiative effects of the clouds, variability on scales less than about 100 m is probably not important, although the variability on smaller scales is crucial to the development of precipitation. Individual clouds making up the cloud field are often very different from each other in terms of their microphysical properties, even at a similar stage in the development of the clouds, further complicating the parametrization problem.

The variability of the updraught structure and droplet spectrum observed within stratocumulus is due to instability at the top of the cloud, resulting from radiative imbalance, as described earlier. The structure of the turbulent transport processes in any cloud layer reflects the source of the turbulent kinetic energy, with turbulent kinetic energy transport from this source region. The horizontally averaged profiles of the turbulent fluxes (averaged over both the in-cloud and between-cloud regions) within cumulus capped boundary-layers may, or may not, resemble those within the stratocumulus cloud capped boundary-layer. Smith and Jonas (1993) have shown that, if the cumulus reach a strong inversion, the profiles of the turbulent kinetic energy and heat transport resemble those of the stratocumulus layer, although the magnitudes of the fluxes are rather different. This is due to the dominant source of turbulent kinetic

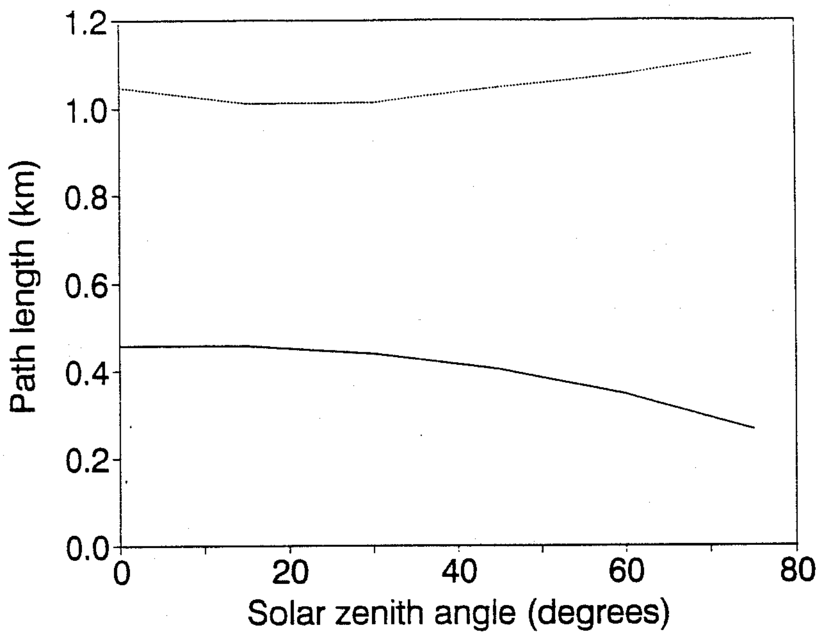

Fig 9 Average path lengths of photons passing through (dotted), and scattered upwards by (solid), a horizontally uniform cloud layer 300 m deep. The calculations were made at 0.45 μm.

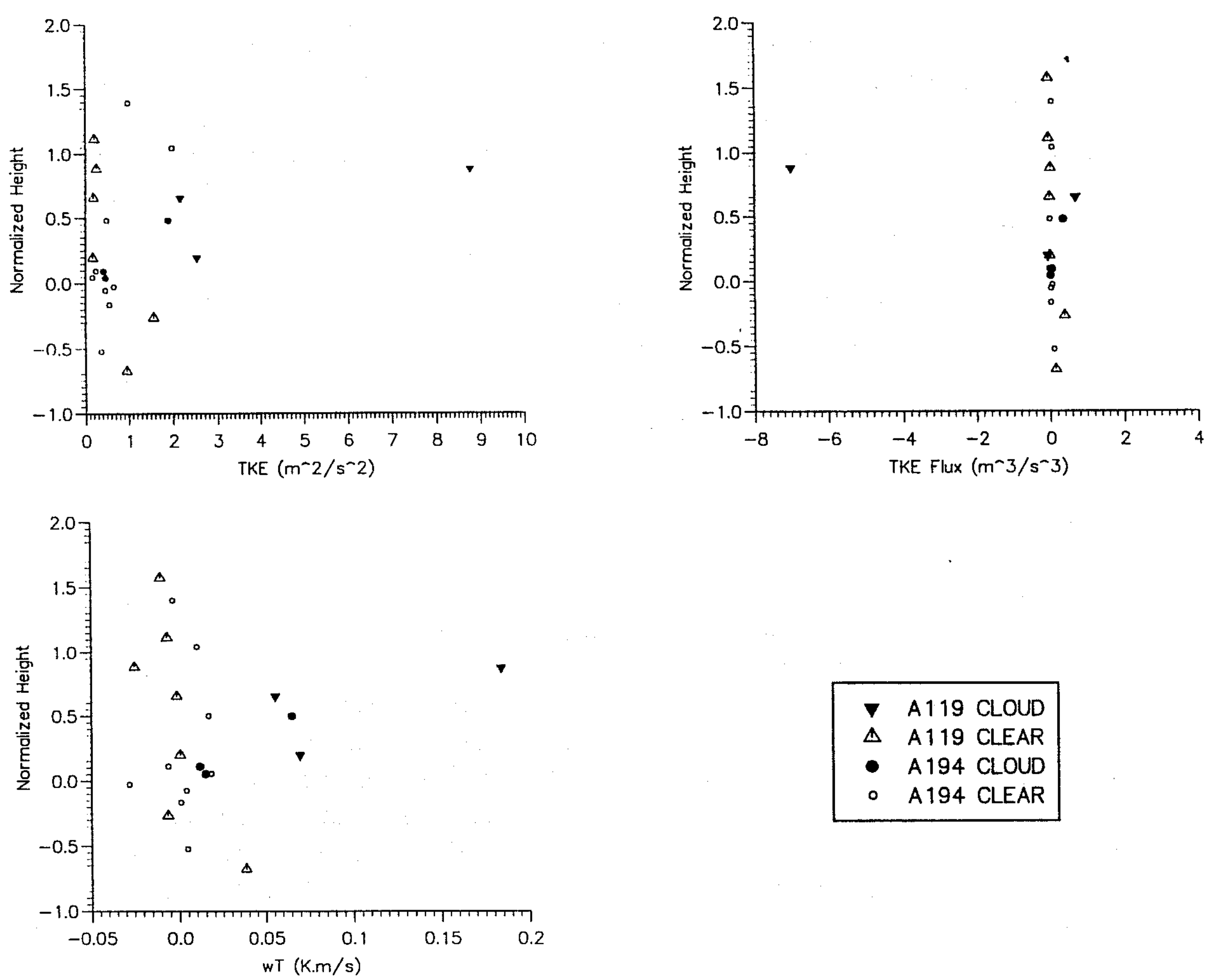

Fig 10 Profiles of the in-cloud and between-cloud turbulent kinetic energy, turbulent kinetic energy flux and sensible heat flux in cumulus layers capped by a strong inversion. Two flights were made on different occasions through cumulus formed under similar conditions.

energy in such clouds being at cloud top, where energy is released by entrainment instability (Macvean and Mason, 1990). Entrainment of dry air from above the inversion leads to evaporative cooling and the formation of downdraughts which may penetrate deep into the clouds. In these clouds, cloud top radiative cooling is generally weak due to the short life time of individual clouds and cannot generate the static instability which is converted into turbulent kinetic energy. However, the vertical development of many cumulus layers is inhibited, not by a strong inversion, but by regions of only slightly increased static stability or by the presence of thin dry layers from which evaporation following entrainment of the dry air is not sufficient to render the air negatively buoyant. In these cases, entrainment instability at cloud top does not contribute significantly to the turbulent kinetic energy budget, and the dominant source is condensational heating at relatively low levels in the cloud. The location of the turbulent kinetic energy source region has a profound effect on the vertical flux profiles both within cloud and in the horizontal average fields, as can be seen by comparing the observations presented in Figures 10 and 11. In these figures, the height above cloud base has been normalized using the depth of the cloud layer although no scaling has been applied to the magnitudes of the fluxes. the flux profiles show clear maxima near cloud top when the main source of turbulent kinetic energy is close to cloud top, while the maxima are around mid-cloud level when the energy source is lower in the cloud.

Microphysics

It has been known for many years that, within cumulus clouds, the liquid water content, averaged over horizontal distances of a few hundred meters, is much less than the water content in a parcel lifted adiabatically from cloud base; typically the water content is 20-40% of the adiabatic value (Figure 12). The observations also show that the dispersion of the droplet spectrum often exceeds 50%, especially where the effects of dilution by entrained air are largest. These observations imply that spectral broadening is influenced by entrainment and it is believed that this is crucial to the rapid development of precipitation in small, warm, cumulus clouds. However detailed observations, such as those in Figure 13, due to Stith (1992), show that on smaller scales, considerable variability exists with regions with almost adiabatic water content separated by regions containing no liquid water. In many cases, the in-cloud variability results from variability in the cloud droplet *concentration*, with the shape of the droplet size spectrum and the mean droplet radius showing less variability at one level in the cloud. The variability is believed to result from the nature of the entrainment process in which filaments of cloud-free air are engulfed into the cloud, with final homogenisation taking place only on the very smallest (< 1 cm) scales.

The droplet concentration is dependent on the aerosol concentration in the sub-cloud layer, as in the case of stratocumulus. There is however no simple relation between the two parameters since the activation of aerosol to form droplets depends on the dynamics of the cloud and on the chemical composition of the aerosol, although it is possible to fit an empirical curve to observations of these parameters, as was shown in Figure 5. The number of droplets depends largely on the number of aerosol particles which are able to act as Cloud Condensation Nuclei (CCN) at the maximum supersaturation reached near cloud base. Due to the large updraughts in many active cumulus, it is possible that fresh nuclei entrained into the cloud may be activated, and form small drops, at levels well above cloud base. For this reason, there is often no simple relation between droplet concentration and height above cloud base since the concentration is reduced by entrainment induced evaporation and dilution,

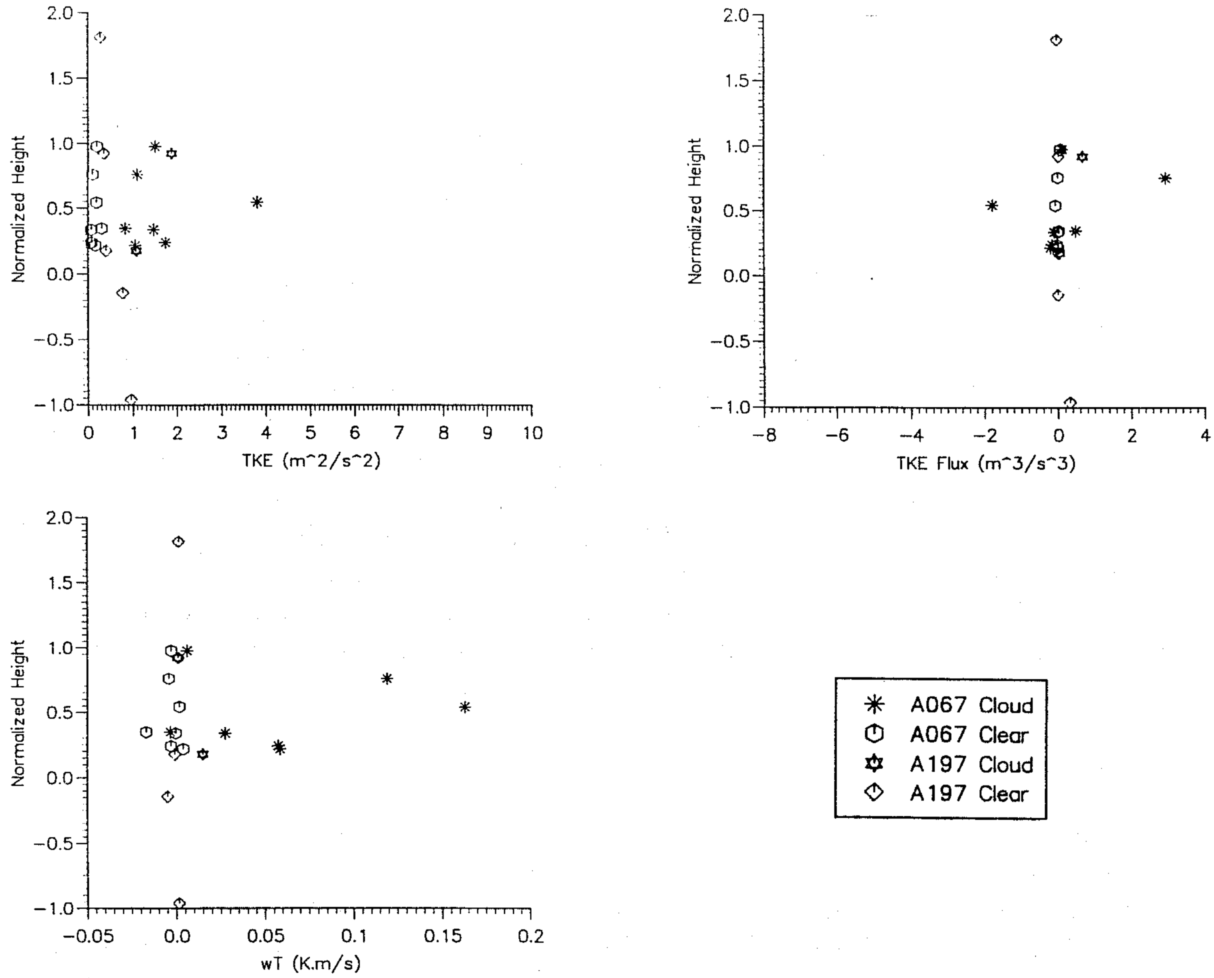

Fig 11 As Fig 10, except for cloud layers with no strong capping inversion.

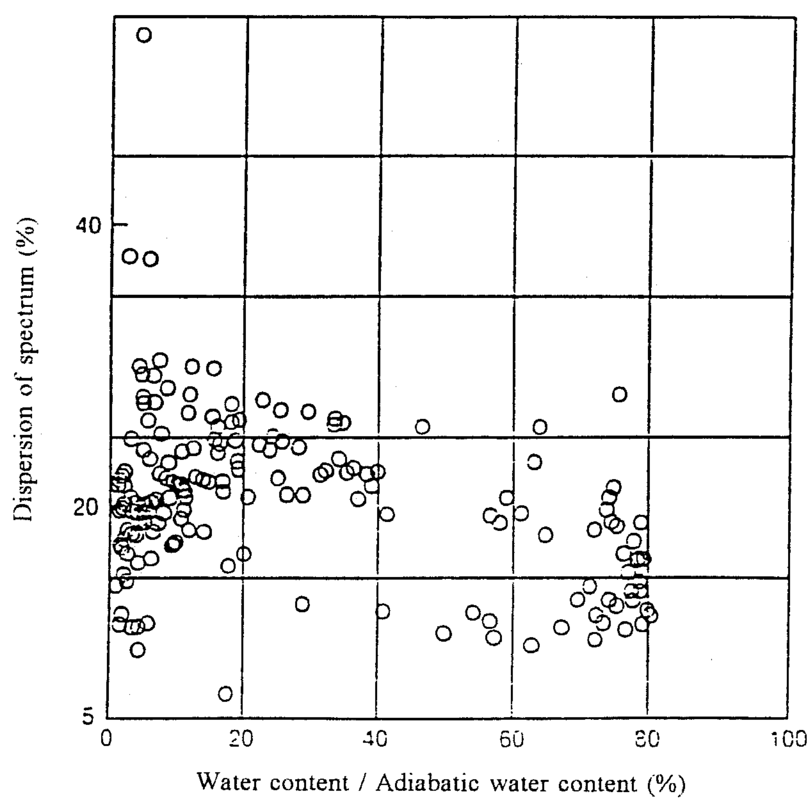

Fig 12 The dispersion of the droplet spectrum plotted against the ratio of the water content to the adiabatic water content from observations at many levels in a field of small cumulus.

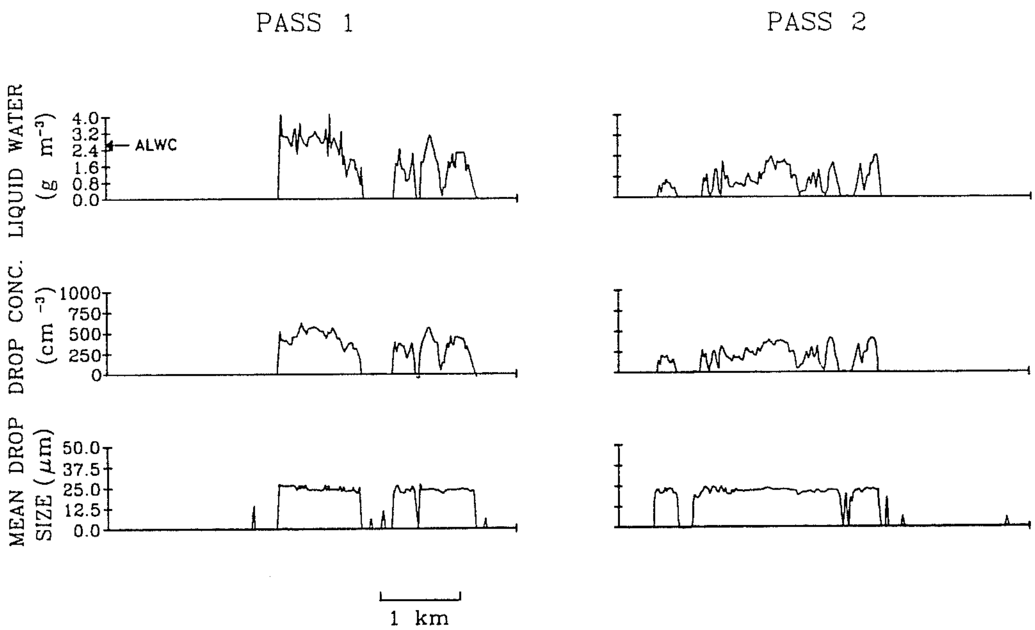

Fig 13 Liquid water content, cloud droplet concentration and mean droplet radius measured on two level flights through a moderate cumulus cloud.

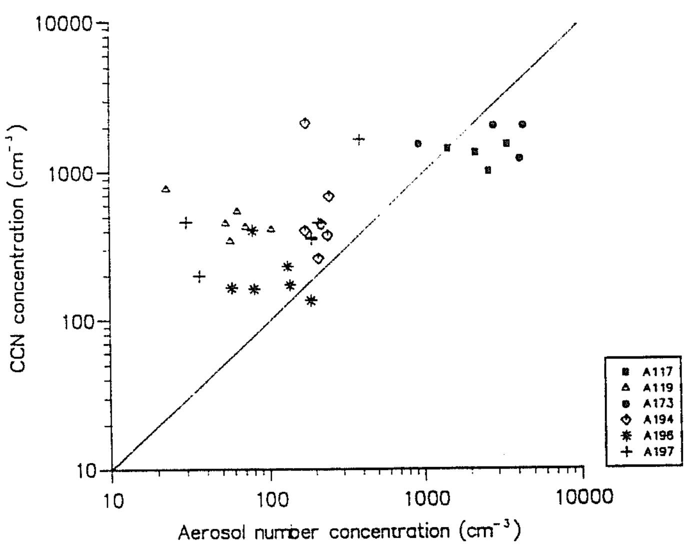

Fig 14 Observations of CCN and aerosol concentration measured in maritime airflows in the vicinity of the British Isles.

while it may be increased by fresh activation. Figure 14 shows observations of aerosol and CCN concentrations made in maritime regions in the vicinity of the British Isles. In some cases the aerosol concentration (in the radius range 0.05-1.5 μm) exceeds the CCN concentration (at 0.9% supersaturation), but in other cases it is much less. Detailed examination of the observations shows that, close to pollution sources the aerosol concentration is high, but the newly formed aerosol particles are either too small to be effective as CCN, or more probably, are coated with material which makes them hydrophobic. However, in cleaner air or in polluted air further removed from the pollution sources, CCN concentrations exceed those of the aerosol in this size range suggesting that particles larger than 1.5 μm are an important source of nuclei, or that many particles smaller than 0.05 μm could be activated at this large supersaturation. The observations also suggest that even a comparatively short air passage over land may be sufficient to increase sub-cloud aerosol concentrations significantly. The passage of air over the UK, a distance of a few hundred kilometres, is sufficient to double the aerosol concentration, with a profound effect on cloud radiative properties, almost doubling the backscatter coefficient at cloud top.

A further factor which may need to be taken into account is that glaciation of boundary layer cumulus is often more common than would be expected on the basis of the cloud temperature. Statistical expressions are often used in climate and weather prediction models to relate the extent of cloud glaciation to temperature, or to cloud top temperature. Typically these relations assume that cloud is not glaciated at temperatures warmer than about -15°C while glaciation is complete for temperatures colder than -40°C. Many observations of small maritime cumulus, with low droplet concentrations, show that the clouds may be partially glaciated even with cloud top temperatures as high as -5°C. Consequently, small short-lived clouds may produce significant amounts of drizzle through the Bergeron-Findisen mechanism, while the presence of large ice particles will affect the radiative properties of the clouds. The processes leading to this enhancement of glaciation, which appears to be confined to maritime clouds with low droplet concentrations, is not understood, but probably results from in-cloud processing of aerosol particles to form additional ice nuclei. The rapid onset of precipitation in such clouds may require modifications to be made to bulk microphysical parametrization schemes, if is is to be adequately represented in larger-scale models

Radiative transfer through cumulus layers

Radiative transfer through broken cloud layers is a complex process which has not been completely resolved. The complicating factors are those which have also been identified in the case of stratocumulus, shadowing and channelling of radiation. In addition, sub-cloud scale variability and the variety of cloud sizes and shapes may be important. Due to the complexity of the entrainment processes in cumulus, it is more difficult to develop robust parametrizations for droplet effective radius in cumulus than in stratocumulus, however, some progress has been made by Jonas (1991) using numerical simulations and by Bower and Choularton (1991) and Baker and Latham (1992) from an analysis of numerous field observations.

The importance of cloud shadowing and its influence on the radiative properties of broken cloud fields was demonstrated by Kite (1987) and Rawlins (1990). It appears that the effective cloud cover, N_e, is non-linearly related to the actual cloud cover and that modelled values of N_e can only be reconciled with observations (Figure 15) if the variability of the cloud dimensions is taken into account. Jonas (1992) showed however that the effects of random

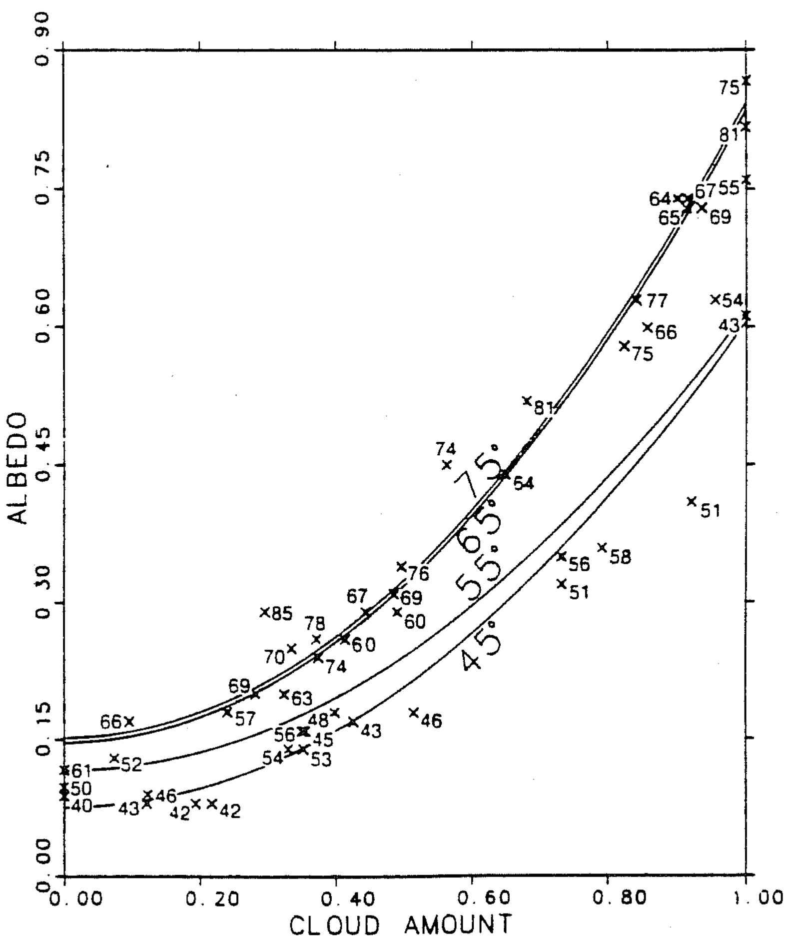

Fig 15 Observations of broad-band short-wave albedo plotted against cloud amount, showing the solar zenith angle at the time of measurement. The curves are parabolic fits to the observations including all observations within ±5° of the indicated solar zenith angle.

fluctuations in water content *within* cumulus clouds were small, although the effects of *organised* reductions in the water content close to cloud edges could alter the short wave albedo of individual clouds by around 10%. This is consistent with the results presented by Rawlins and Foot (1990) who showed that the optical properties of cloud layers were dominated by the microphysical characteristics close to the top of the cloud.

Conclusions

In this paper we have drawn attention to some of the similarities and differences between the stratocumulus and boundary-layer cumulus which have an impact on the parametrization problem.

The main conclusions are:

(i) The turbulent flux profiles in boundary layer cloud systems are sensitive to the location of the source regions of turbulent kinetic energy and differ between stratocumulus and some cumulus layers. While the source region in stratocumulus is near to cloud top, where motion is driven by radiative imbalances, in cumulus it may be close to cloud top. driven by entrainment instability, or lower in the cloud, driven by condensational heating.

(ii) The radiative properties of cloud layers are sensitive to the horizontal structure of the layer, on scales of less than 500 m, and estimates based on mean cloud properties may be significantly in error due to channelling of radiation or cloud shadowing effects.

(iii) Estimation of the effective radius of the cloud droplets is relatively straightforward for stratocumulus, where it may be determined from the water content and an assumed aerosol concentration but is more difficult for cumulus due to increased entrainment effects, although empirical parameterizations are available.

(iv) Cloud droplet concentrations, and hence the effective radius of the droplets in cloud, are sensitive to the properties of the sub-cloud aerosol. While it may be possible to obtain empirical parametrizations, the problem is complicated by the impact of cloud dynamics and the nature and age of the aerosol particles. The problem is significant one. Recent analyses of satellite observations (Han and Rossow (personal communication)) suggest that there are systematic differences between the mean effective droplet radii in clouds formed in the northern hemisphere and similar clouds in the southern hemisphere; these may be due to differences in the aerosol concentrations between the two hemispheres.

(v) Precipitation formation may be enhanced in stratocumulus by the presence of cumulus rising into the cloud layer, or in cumulus by glaciation at relatively high temperatures. The precipitation flux, even in drizzle, forms a significant component in the water budget and influences the development of cloud layers. Bulk parametrization schemes break down when applied to these situations.

Several of these problem areas are currently being studied using a combination of high resolution models, with minimum parametrization, and field studies. For example, studies have been made in which the effective optical thickness of an evolving broken cloud layer has been obtained by diagnosis from a model simulation of cloud layer development. Also, high resolution droplet spectral data are being used to determine the processes by which drizzle may be enhanced in non-uniform cloud fields. Such studies offer the chance of providing solutions to some of the more difficult parametrization problems, where the cloud process involves interactions between dynamics, microphysics and radiative transfer.

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