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Observations of Cumulus Cloud Entrainment

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ABSTRACT

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Observations of the dynamical, thermodynamical and microphysical structure of cumulus clouds, based on aircraft penetrations of small, non precipitating, maritime clouds are presented. On the basis of thermodynamic properties it is shown that many of the clouds contain evidence of entrainment of air originating significantly above the observation level which may result from penetrative downdraughts formed by entrainment at cloud top. Entrainment of cloud top level air is more common in deeper (~4 km deep) clouds than in shallower clouds. The instability at the edges of the cloud, coupled with observations in the developing and mature phases of the cloud life cycle of a thin subsiding layer of air surrounding the cloud suggests that some of the cloud top level air may be entrained through the cloud edges.

In the later mature and decaying phases of the cloud life cycle the surrounding layer of subsiding air is absent but there is frequently observed a subsiding layer of cloudy air close to the cloud edge. This layer is observed to contain a relatively low liquid water content but contains some of the largest drops observed at the same level within the cloud. The data are consistent with the idea that the largest drops are brought down from higher levels in air parcels which are maintained close to saturation by entrainment of air from within the cloud.

RESUME

On présente des observations sur la structure dynamique, thermodynamique et microphysique des cumulus basées sur des traversées par avion de petits cumulus maritimes non précipitants. Des considérations thermodynamiques montrent que dans nombre de ces nuages il y a un entraînement d'air d'origine supérieure au niveau d'observation, ce qui peut résulter de courants descendants formés par entraînement au sommet des nuages. L'entraînement au sommet des nuages est plus fréquent dans les nuages à développement vertical important (~4 km) que dans les autres. L'observation d'une instabilité aux bords du nuage, et celle d'une mince couche de subsidence d'air autour du nuage dans sa phase de développement et de maturité, suggèrent que de l'air au niveau du sommet est entraîné à travers les bords du nuage.

Dans la phase ultérieure de maturité et dans celle de déclin du nuage, on n'observe plus de couche environnante de subsidence, mais il y a souvent une couche de subsidence d'air nuageux à proximité de la bordure du nuage. On observe que cette couche possède un contenu en eau liquide assez

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faible, mais renferme quelques-unes des plus grosses gouttes observées au même niveau dans le nuage. Ces données sont en accord avec l'idée que les plus grosses gouttes sont transportées d'en haut dans des parcelles d'air maintenues à peu près à saturation par l'entraînement d'air venant du coeur du nuage.

INTRODUCTION

It is well known from observational studies (e.g. Squires, 1958a; Warner, 1969, 1970; Paluch, 1979; Nicholls and Knight, 1984) that entrainment of environmental air during the lifetime of a growing cumulus cloud reduces the horizontal average liquid water content through a small cumulus to a value which is often less than 50% of the value expected in an unmixed cloud at the same level, the adiabatic liquid water content. Many of the observations also show evidence of penetrative downdraughts. These are regions of subsaturated descending air within the cloud which are believed to have originated from entrainment. It is thought that regions of subsaturated air engulfed into the cloud become negatively buoyant as cloud droplets mixed into these regions evaporate. However, there is still doubt as to the mechanisms giving rise to downdraught formation. The numerical studies of Klaarssen and Clark (1985) suggest that the initial engulfment or entrainment is an essentially laminar process and that although turbulent mixing and droplet evaporation may enhance downdraughts it does not cause them.

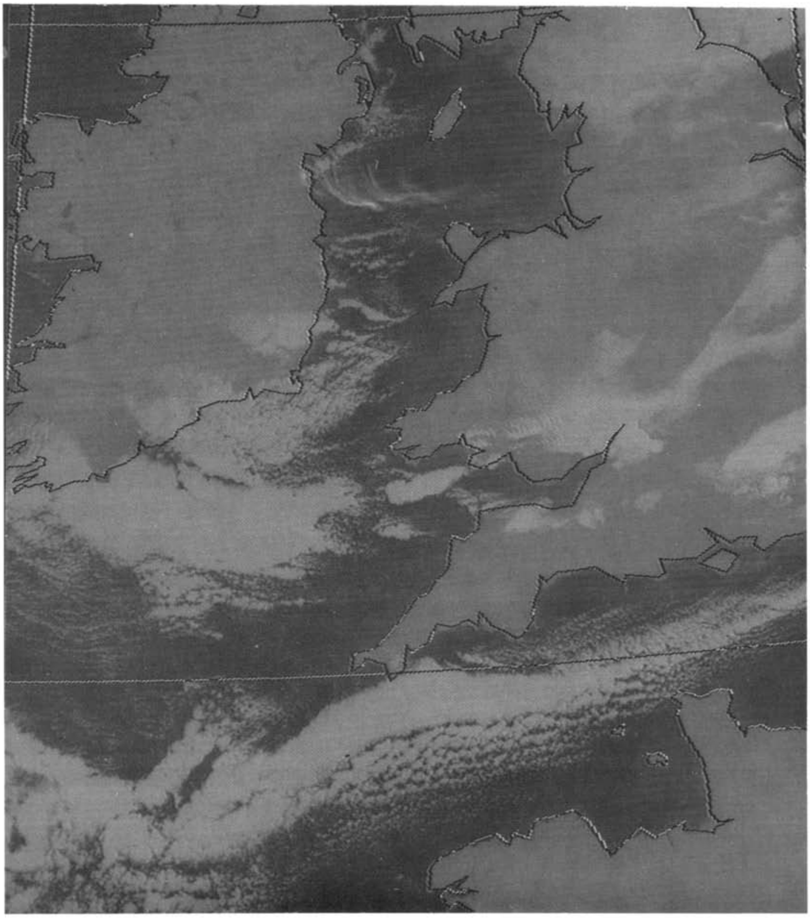
Although much of the early work on cumulus was directed to studies of the dynamical structure of the clouds and the general characteristics of the droplet spectrum, more recent work has been concerned with the detailed variation of the droplet spectrum and the relationship between this and the in-cloud turbulence. These studies have been made possible by the development of airborne instruments able to measure droplet spectra over short distances along a flight track. Baker et al. (1980) suggested that the failure to explain the observed form of the droplet spectrum using a continuous model of mixing and entrainment, was due to misrepresentation of the mixing process which, since this occurs on a short time scale, cannot be regarded as spatially uniform. These ideas were supported by the measurements in continental cumulus of Paluch (1986) who postulated that these clouds contained non-uniformities in droplet concentration on very small scales. Recently Meischner and Bogel (1988) have presented data which demonstrate that the variability was associated with the cloud structure; vigorous ascent was associated with small microphysical variability but inhomogeneity was associated with negative buoyancy. The relationship between the dynamical structure of cumulus clouds and the droplet spectrum was investigated by Jensen et al. (1985). They showed that under some conditions it was possible for the mixing process to be regarded as homogeneous although the results exhibited considerable spread.

Despite the number of observational studies it is still not clear whether dilution of the clouds (which is observed in both developing and decaying cumulus) results from entrainment at the top of the cloud and the consequent formation of penetrative downdraughts, as suggested by Squires (1958b) and modelled by Jonas and Mason (1982) or whether lateral entrainment, that is quasi-horizontal mixing of entrained air, is significant. Evidence for the importance of lateral entrainment is suggested by the absence of penetrative downdraughts in small maritime cumulus reported by Nicholls and Knight (1984) which nevertheless had substantially subadiabatic water content. Observations (e.g. Bennetts and Gloster, 1980) of significant differences in cloud microphysical structure and liquid water distribution between the upwind and downwind sides of a cloud in a strongly sheared environment also suggest that lateral entrainment may be important. In contrast, the observations of Paluch (1979) show clear evidence that in deep continental clouds entrainment of air from close to the cloud top level is very common.

It is obvious that the development of a cumulus cloud and its lifetime will depend on the nature of the entrainment process. Telford et al. (1984) showed, for example, that the entrainment process was of importance in maintaining the strength of the inversion at cloud top. Entrainment is also believed to be important for the development of the cloud droplet spectrum at least to the point where this becomes dominated by collision and coalescence. Mason and Jonas (1974) suggested that the breadth of the observed droplet spectrum could be explained by the re-entrainment of droplets from decaying regions of a cloud; entrainment of droplet-free environmental air containing unactivated condensation nuclei would increase the concentration of small droplets but would promote growth of the large droplet tail of the spectrum. On the other hand Bower and Choularton (1988) have suggested that entrainment of subsaturated air could reduce the droplet concentration by evaporation and thus increase the mean supersaturation experienced by the drops if the air was subsequently forced to rise. This could then lead to the increased growth of a few droplets which underwent repeated entrainment events followed by ascent. While evidence has been presented for the effect of entrainment in reducing droplet concentrations it is not clear that sufficient drops would experience the particularly favourable chain of events to explain the observed droplet spectra.

In the present paper a number of observations of small maritime cumulus clouds are presented. The observations are analysed to provide information on the source of the entrained air and to show how the entrainment process may be influenced by the air flow around the cloud. Microphysical data are also presented; data from cloud edges show that these regions may, while descending, contain the largest drops. It is suggested that this provides evidence for droplets being brought down from higher levels in the cloud but only in regions where downdraughts are partially mechanically forced, that is, which are driven by the motion of the rising thermal rather than by evaporative cooling following mixing of cloudy and cloud-free air.

The literature in this area refers to many different processes by the terms mixing and entrainment. In the present paper the incorporation or engulfment of a volume of air into a cloud without a significant change in its properties will be referred to as entrainment. This process may be a result of finite amplitude baroclinic instability, Kelvin Helmholtz or Rayleigh Taylor instability. Following entrainment turbulence erodes the distinction between the entrained air and its surroundings; this mixing process may result in the evaporation of droplets mixed into subsaturated air. Entrainment may occur at cloud top when it may result in penetrative downdraughts whose vigour is increased by evaporation of droplets mixed into the entrained air or at the (vertical) edges of the cloud, termed lateral entrainment.



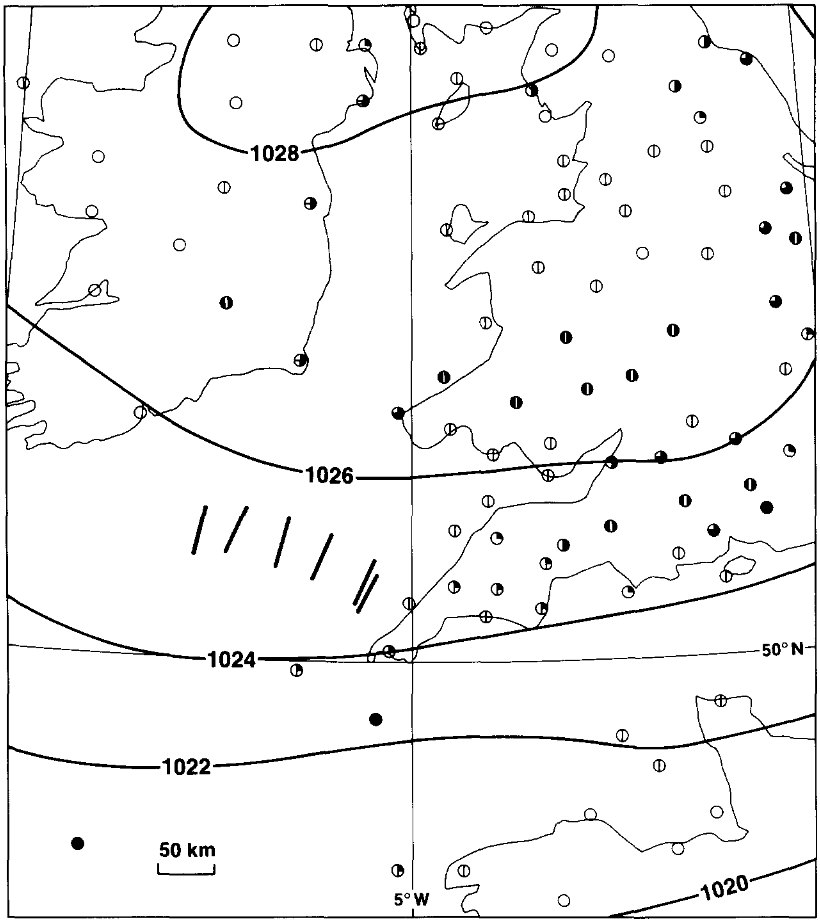


Fig. 1. Synoptic situation for 12 GMT 9 December 1987 showing isobars, cloud cover and flight legs (bold lines) together with the satellite infra red image covering the same area for 14h56 GMT.

OBSERVATIONS

The observations were made using the instrumented Hercules aircraft of the Meteorological Research Flight. Details of the instrumentation have been given by Nicholls and Readings (1979) and Readings (1984) and will not be repeated here. Of particular relevance to the present work are the in-situ observations of temperature (wet and dry bulb Rosemount thermometers), vertical velocity (intertial platform and wind vanes), humidity (cavity refractometer and dew point hygrometer), liquid water content (Johnson-Williams instrument and integrated droplet spectra) and droplet spectra (PMS Forward Scattering Spectrometer Probe and 2D cloud probe). It is known that the use of Rosemount thermometers in cloud is subject to error due to wetting. Nicholls et al.

(1988) have compared the performance of these thermometers with a radiation thermometer under conditions similar to those used for the present work. Their results suggest that temperature errors may reach 0.5 K although examination of the present high resolution time series shows only a few examples of obvious temperature/liquid water correlations. Data from the radiation thermometer were available from one of the present flights but analysis of these observations does not significantly affect the conclusions drawn using the Rosemount thermometer data.

The data were obtained during a number of flights in the vicinity of the British Isles, mostly at around 50°N 7°W. The observations were made in small, non-precipitating cumulus clouds which formed over the relatively warm sea in a cold air flow. Cloud top temperatures were chosen to be higher than −10°C so that ice crystals were not present. Non-precipitating clouds were selected so that thermodynamic analyses could be made using the assumption that total water content is conserved following the air flow. On rare occasions when evidence of ice crystals or of precipitation was present in the observations the data were excluded from the subsequent analysis. In general clouds satisfying the above criteria were between 2 and 3.5 km deep but some data were obtained in shallower or deeper clouds.

Two flight plans were used in the present study, one designed to provide detailed information on individual, isolated, clouds while the other was intended to provide data for a more statistical type of analysis in which many clouds were sampled. In the former plan, multiple straight and level penetrations were made of the individual clouds with the flights along the prevailing wind direction. The flights extended about 5 km either side of the cloud and generally three penetrations were made in cloud (near cloud base, near cloud top and at the mid level) with others above the cloud top and immediately below cloud base. In general the penetrations were made at the highest level first but this procedure was sometimes reversed. The time taken to complete each set of penetrations was typically 15 min. The statistical flights consisted of straight and level runs about 50–80 km in length oriented across the prevailing wind direction again at several levels within, above and below the cloud layer. Reciprocal flights were made along the same ground track with no attempt to sample the same clouds as in earlier runs. These runs sampled approximately five to ten clouds. In some flights it was possible to make several statistical runs in clouds of different depths by sampling at different distances downwind from the coast as the clouds became more vigorous due to increased effects of surface heat and moisture fluxes. An example of such a flight plan is shown in Fig. 1.

In addition to the level runs, ascending or descending profile flights were made between levels about 1.5 km above the general cloud top to about 15 m above the sea surface. These flights were intended to provide the out of cloud

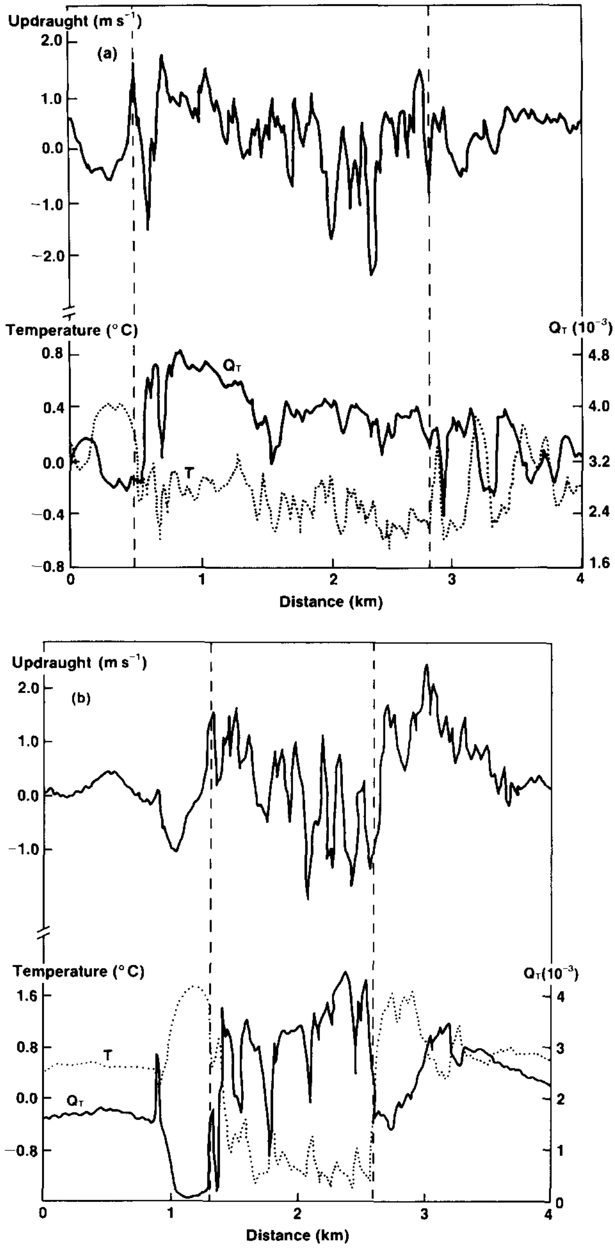


Fig. 2. Traverses through a small cumulus cloud showing the updraught, temperature and total water mixing ratio, Q_T: (a) near the mid level; (b) near cloud top. The locations of the cloud edges are denoted by dashed lines.

profiles of temperature and humidity and were flown avoiding cloud where possible.

The high-frequency (typically 40 Hz) flight data were subsequently processed to give 5 Hz average values of updraught, temperature and specific humidity. This corresponds to a spatial resolution of about 20 m. At the time when the flights were made no instrument was available to provide, directly, specific water content in cloud so this was derived from specific vapour content measurements from the microwave cavity refractometer or Cambridge hygrometer together with the liquid water content obtained from the Johnson Williams hot wire instrument.

Data from typical mid cloud level and near cloud top penetrations of a small isolated cumulus are presented in Fig. 2. These observations show clearly the anti-correlation between temperature and total water content which was a feature of most of the observations. In this example the cloud extended horizontally near cloud top level (Fig. 2b) from about 1.3 to 2.7 km; between 1.0 and 1.3 km there is clear evidence of a subsiding shell of relatively dry cloud-free air adjacent to the edge of the cloud which extends from cloud top to at least the mid cloud level. (The data were obtained on reciprocal headings about 5 min apart but one diagram has been reversed in this presentation so that the levels are more easily compared.) The other cloud edge is rather less distinct and here no descending layer is evident.

DATA ANALYSIS

In order to identify the source level of the air entrained into the clouds, the analysis technique of Paluch (1979) was used. The 5 Hz level run data were processed to give wet equivalent potential temperature (θ_e) and total water content (Q_T). Regions of cloud were identified as contiguous regions extending over more than 500 m (approx. 5 s) in which the liquid water content fell below 0.05 g m^{-3} only in regions less than 200 m in extent. The analysis therefore assumes that subsaturated regions less than 200 m across surrounded by air containing cloud droplets are holes in a cloud while larger cloud free regions are considered to separate different clouds. The values of θ_e and Q_T from the level runs were averaged to give 2.5 Hz values in cloud and within 500 m of cloud edges while 0.25 Hz average values were formed from the remaining data. Data from the profile ascents and descents were processed to give 0.1 Hz values which, at the normal ascent and descent speeds used in the experiment yield a vertical resolution of about 25 m.

A further stratification of the data was undertaken to identify coherent downdraught regions within the cloud. These were defined as contiguous regions in which the individual measurements of updraught were less than -0.1 m s^{-1} with the mean value within the downdraught being less than -0.2 m s^{-1}. The analysis of the observations defines downdraught regions with respect

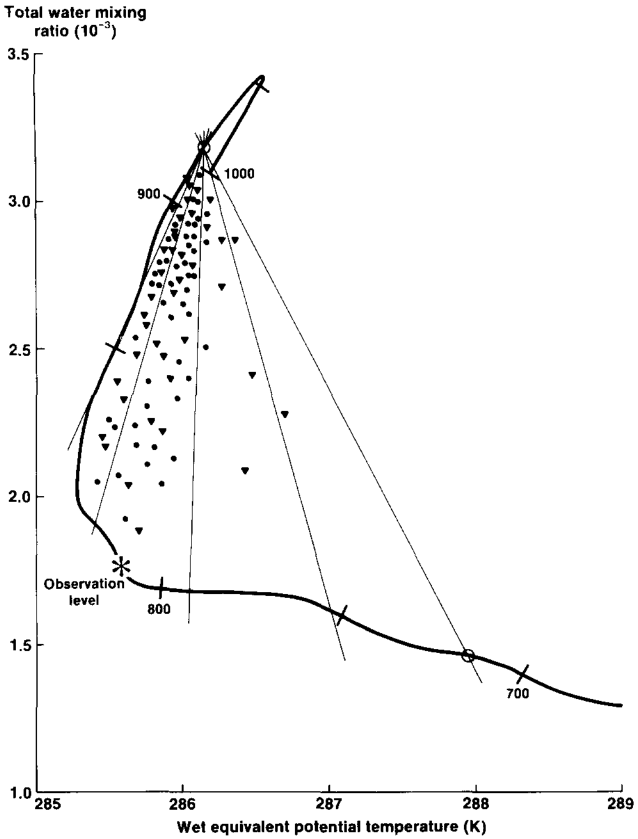


Fig. 3. Paluch diagram showing data obtained at $h^1 = 0.5$ in several clouds 2.1 km deep on one occasion. Triangles denote data from coherent downdraught regions. See text for further details.

to a fixed reference frame: ideally the downdraughts should be defined with respect to a frame moving either with the rising thermal or with the updraught averaged over some coherent part of the cloud. The use of data from a single aircraft makes it impossible to obtain realistic values for the reference updraught and therefore the assumption of a stationary frame of reference was adopted. This gives rise to quantitative difficulties in the interpretation of the observations since, for example, a negatively buoyant region may continue to rise with respect to a fixed frame while descending relative to adjacent regions of strong updraught. However, the qualitative description of the circulation around the cloud is not affected by the choice of reference frame.

Paluch diagrams (plots of Q_T against θ_e) were constructed using the data from the profile flights on each occasion. Data from the parts of the level runs more than 500 m from cloud edges in general showed good agreement with the profile data, confirming that there were few systematic variations in the profile in the observational area. The exception to this was during the statistical flights where level runs were made at different distances downwind of the coast. In these cases the plotted profiles were interpolated between extreme upwind and downwind profiles using the out of cloud level run data to guide the interpolation.

Individual 2.5 Hz data obtained in cloud were plotted on the Paluch diagram and a typical example is shown in Fig. 3. The data shown on this diagram exclude those points at cloud edge, that is points which represent averages across a partly cloudy and partly cloud-free subsaturated region. These data points were also excluded from the analysis. It was assumed that the local in-cloud air properties are a consequence of mixing between air entering the cloud at cloud base with environmental air from some level h. The value of h was determined by extrapolating the line joining the properties of the air immediately below cloud base to the local observation until it cut the curve representing the environmental profile at the level corresponding to the level of the entrained air. It was found convenient to non-dimensionalise the value of h by defining:

$$h^1 = (h - h_B)/(h_T - h_B)$$

where h_B and h_T are the observed levels of cloud base and cloud top. In the statistical experiments it was found that while the values of h_B for individual clouds were very similar along the flight path, a range of values of h_T was encountered. This is to be expected since clouds in all stages of development were sampled. For the purposes of the non-dimensionalisation the maximum value of h_T along the flight path was chosen since this represents the top of the clouds at their mature phase under the prevailing conditions.

RESULTS

Thermodynamic analysis

The data presented in Fig. 3 are typical of the data obtained on the statistical runs; in this example, the value of $(h_T - h_B)$ was 2.1 ± 0.1 km. Also shown on this Paluch diagram are lines which join the properties of cloud base air with those at $h^1 = 0.2, 0.4, \ldots, 1.0$. Data points lying within the region bounded between the lines drawn to points representing (for example) $h^1 = 0.6$ and $h^1 = 0.8$ and the environmental curve represent air with the properties of a mixture of cloud base air and air originating in the environment at a height $0.6 \leq h^1 < 0.8$.

Two points are apparent from the figure. First, the dilution of these clouds is generally rather weak. Many of the data points lie above a line representing cloud base air from which 50% of the adiabatic liquid water content at the observation level has been removed implying that the typical values of the ratio of the actual liquid water content to the adiabatic water content exceeded 50%. In general this ratio was much lower (around 30%) for observations made above the mid level in the clouds while it remained around 50% in the lower half of the cloud. Values of the ratio were rather lower (by about 10%) in the shallowest clouds studied. The second point concerns the origin of the entrained air. It is apparent that the data include a wide variety of values of h^1 with the highest values generally associated with downdraught regions. Some entrained air originates above the observation level.

The second point is considered further in Fig. 4. This analysis of the downdraught regions alone shows the frequency of occurrence of downdraughts containing environmental air from different levels. In this sample it appears that while at all observation levels h_o^1 (non dimensionalised in the same manner as h^1) most of the downdraughts incorporate air entrained from close to the observation level there is evidence of a few downdraughts which appear to originate at much higher levels. It does not follow from the presence of the entrained observation level air that lateral entrainment dominates cloud top entrainment since cloud top entrainment occurring when the cloud top was rising through the observation level earlier during the cloud life would also result in entrainment of air from this level.

Turning attention to the presence of penetrative downdraughts, some of which appear to be present in the data of Fig. 3, the observations can be used to identify their frequency of occurrence. Penetrative downdraughts are arbitrarily defined, for the purpose of this analysis, as downdraught regions which contain air entrained from a level h^1 such that $h^1 \geq h_o^1 + 0.2$. Fig. 5 presents averages of the frequency of occurrence of downdraughts at different levels in

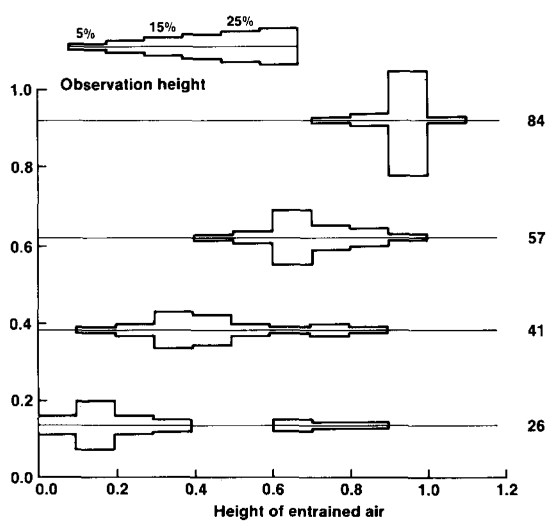


Fig. 4. Diagram showing the origin of downdraughts at different observation levels in clouds 2 km deep. The histograms show (using the scale at the top of the figure) the percentage of downdraughts containing air entrained from the indicated range of heights and the figures at the right of the diagram give the number of downdraught observations.

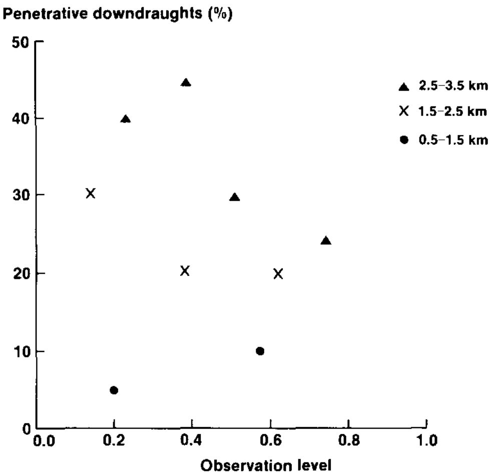


Fig. 5. The percentage of downdraughts considered to be penetrative (as defined in text) for different cloud depths.

the clouds, data from a number of statistical flights and isolated cumulus penetrations being combined. It is clear from these results that while the frequency of penetrative downdraughts shows some systematic variation with the observation level there is also a pronounced variation with cloud size.

Cloud edge instability

The general increase in frequency of penetrative downdraughts low in the cloud is a reflection of the facts, that, once initiated, penetrative downdraughts are relatively easily maintained, as suggested by the calculations of Jonas and Mason (1982) and that the total number of downdraughts is smaller at low levels in the clouds (Knight, 1986). The increase in the frequency of penetrative downdraughts with cloud height is consistent with the observations of Squires (1958a), Paluch (1979) and Nicholls and Knight (1984), although it is difficult to explain. It is to be expected that vigorous clouds with stronger updraughts will require much greater negatively buoyant parcels to be present following entrainment to initiate a penetrative downdraught, since momentum transfer between the upward moving cloud and the downward moving region of subsaturated air is normally the mechanism by which the descent is reversed as the downdraughts remain negatively buoyant through evaporation into them. Jonas and Mason (1982) demonstrated the sensitivity of downdraught penetration to the properties of the entrained air and it is of interest to compare the instability existing at cloud top under conditions giving rise to deep clouds and those when shallow clouds were observed.

The instability at cloud top was obtained as suggested by Deardorff (1980) by comparing the average equivalent potential temperature with values obtained just above cloud top using observations made within cloud and less than 200 m below cloud top. The results, shown in Table I, exhibit a large scatter but it is apparent that the degree of instability at cloud top tends to increase with the vigour of the cloud.

The motion of the air within a cloud can give rise to entrainment of air at cloud edges in addition to entrainment at cloud top. The entrainment may result from laminar flow in which overturning results in surrounding air being engulfed, or it may arise from the gradual (but spatially variable) erosion of the interface between the turbulent cloud and its less turbulent surroundings. As suggested by Klaarssen and Clark (1985) baroclinic instabilities at the cloud edge can also give rise to the entrainment of air at the cloud edge. The numerical experiments of these authors show several examples of essentially laminar entrainment at the edges of small clouds. An analysis of the instability at cloud edge was carried out using cloud edge data in a similar way to that using the

TABLE I

Values of the cloud top instability parameter, i.e., the vertical difference in equivalent potential temperature across the cloud top boundary

Cloud depth (km)	Instability parameter (K)
0.5-1.5	2.1 ± 1.9
1.5-2.5	4.3 ± 3.2
2.5-3.5	5.6 ± 3.8

TABLE II

Values of the cloud edge instability parameter, i.e., the horizontal difference of equivalent potential temperature between in-cloud and out of cloud points

Cloud depth (km)	Observation level h_o [1]	Instability parameter*[1] (K) (a)	(b)
1.5-2.5	0.2 ± 0.1	3.6 ± 1.7	0.5 ± 1.5
	0.5 ± 0.1	4.2 ± 2.6	1.3 ± 3.3
	0.8 ± 0.1	4.4 ± 2.9	1.6 ± 3.4
0.5-1.5	0.5 ± 0.1	2.1 ± 1.9	0.3 ± 1.7
2.5-3.5	0.5 ± 0.1	4.9 ± 2.6	1.2 ± 2.9
	0.8 ± 0.1	5.8 ± 3.7	1.8 ± 3.6

*[1] (a) Out of cloud data from within 100 m of cloud edge; (b) remote out of cloud data.

cloud top data although the equivalent potential temperature difference alone cannot be expected to represent the range of possible entrainment mechanisms. The in-cloud data were confined to averages of data within 200 m of cloud edge. The horizontal profiles displayed in Fig. 2 suggest that, outside the cloud, there may be large differences between the properties of the air close to the cloud and the properties of the air at a greater distance. The instability calculations summarised in Table II show that while there is little systematic equivalent potential temperature difference between a cloud and its distant environment there is a much larger difference between the cloud and the air adjacent to the cloud. This suggests that the motion of the air around the rising thermal may, through entrainment instability, enhance the turbulence with the body of the cloud.

Analysis of air flow around the clouds

The horizontal traverses through isolated cumulus clouds (for example, Fig. 2) show in many cases evidence of a thin shell of subsiding air outside the cloud. This is consistent with the observations of Woodward (1959) who investigated the motion of plumes with rising cores and subsiding edges although her measurements were of liquid plumes with no internal buoyancy sources. When the wind shear was weak a subsiding layer was observed on the upwind and downwind edges of the clouds but with strong wind shear the layer was only present on the downwind edge. In most cases the downdraughts were around 2 m s^{-1} as can be seen from the examples shown in Fig. 6. The origin of the subsiding air was identified using the thermodynamic analysis outlined earlier.

In Fig. 7 values of θ_e and Q_T are shown which are derived from the observations within the cloud edge downdraughts and those obtained at greater distances from the cloud. The example is the same active cloud for which the in-cloud data at mid level are shown in Fig. 3. As indicated earlier the remote data at both the near cloud top and mid cloud levels are close to the profile data. The data from close to cloud edge (4 points only at each level due to the limited extent of the downdraught region) are close to the sounding curve corresponding to a level rather higher than the observation level. In contrast the in-cloud data points (not shown) showed values of total water content in excess of the environmental values at the observation level. The proximity of the out of cloud data points to the sounding suggests that the descent of the shell of air is due to mechanical forcing rather than being driven by evaporative cooling following entrainment although the latter may modify the motion. If the downdraught was a consequence of evaporative cooling it would be expected that the values of θ_e and Q_T within it would differ from those found on the environment curve because evaporation could only occur after entrainment of air from within the cloud.

The experiments on rising plumes (e.g. Woodward, 1959) suggest that forced

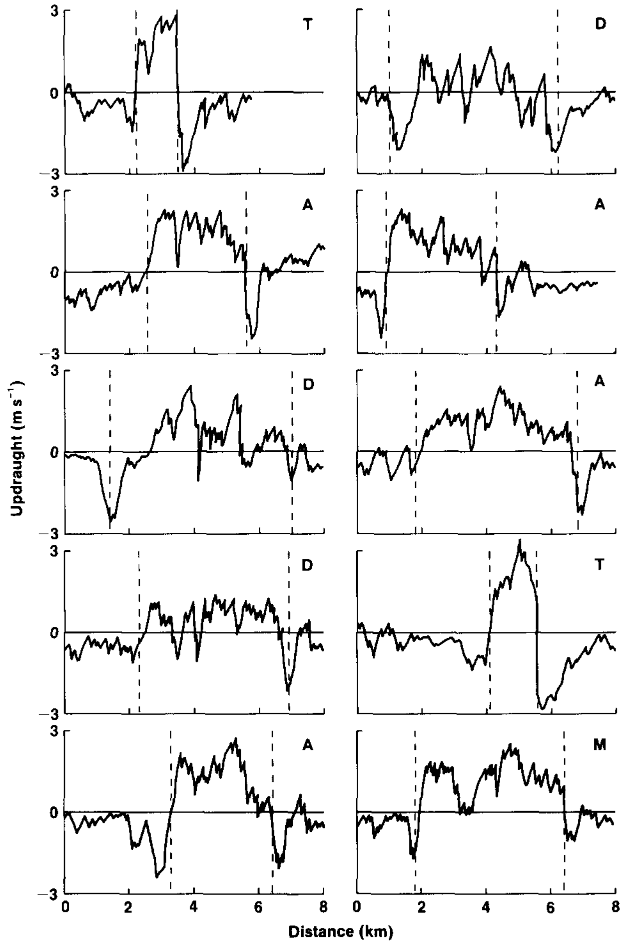


Fig. 6. Traverses through small cumuli showing the updraught. The cloud boundaries are indicated by the dashed lines. Traverses were made at a level 2.1 km above cloud base on one day when the general cloud top was 3.9 km above cloud base. The letters *T*, *A*, *M*, *D* indicate that a turret, active, mature or decaying cloud was sampled according to the aircraft scientists log.

descent of a shell of air is to be expected with air originally just above the rising cloud being forced downwards and around the cloud. The present observations show little evidence of air in the shell originating at cloud top level, that is from just above the base of the inversion but this probably is a consequence of the fact that the cloud is growing. The air will take several minutes to reach the observation level from the cloud top and during this time it is necessary, if the shell is to be sustained, that the cloud continues to develop upwards.

The idea that the cloud edge downdraught is mechanically forced, rather than being forced by evaporation as in the case of the penetrative down-

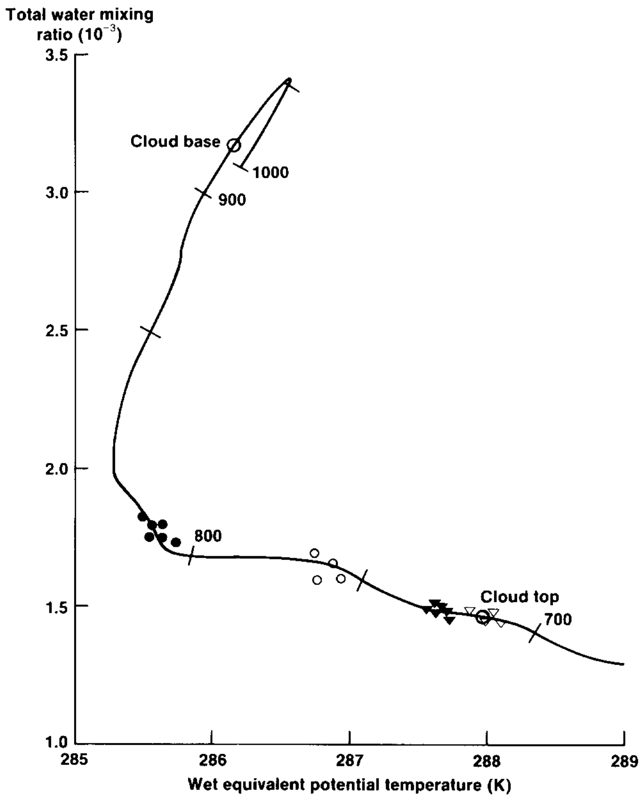


Fig. 7. Paluch diagram showing the environment profile together with values observed within 100 m of cloud edge (open symbols) and remote from the cloud edge (solid symbols). Circles denote data at mid cloud level and triangles data near cloud top.

draughts in the cloud interior is supported by a comparison between observations made in an active, growing cloud and observations made at the same level in a cloud which was visibly beginning to decay. The horizontal traverses through the two clouds made on the same day in a similar location are shown in Fig. 8. (Although the active cloud was similar to that shown in Fig. 2, a different example is shown here to provide a comparison with a decaying cloud under, essentially, the same conditions.) The decaying nature of one cloud is apparent in the relative weakness of the updraught regions, the frequency of downdraughts and the low liquid water content when compared with the active cloud at the same level and growing in a similar environment. The decaying cloud exhibits no sign of a descending shell outside the cloud although there is a coherent region of descent just within the cloud. The idea that the downdraught is mechanically forced around active clouds but is partly driven by evaporative cooling following mixing with cloudy air during the decaying phase is supported by analysis similar to that shown in Fig. 7. Analysis of the data

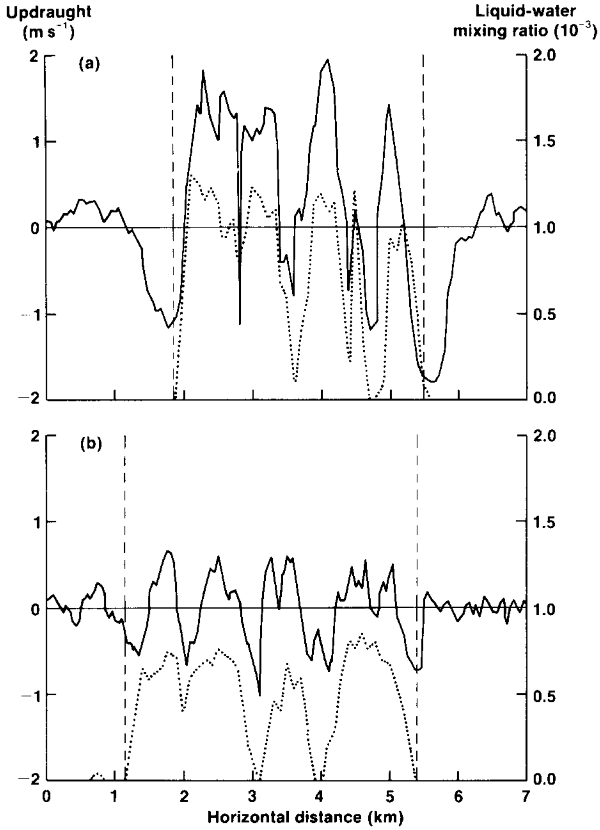


Fig. 8. Traverses through active (a) and decaying (b) clouds showing the updraught (solid line) and liquid water mixing ratio (dotted line). The cloud edges are indicated by the dashed lines.

from decaying clouds (not shown) generally indicates that the downdraught contains air which, while originating above the observation level has been modified by mixing with cloud air. In some examples of active clouds there was also descent within the cloud, as will be discussed later; it is the absence of the descending cloud-free shell which distinguishes the decaying cloud from the active growing one.

The descent within the cloud appears to be driven by a combination of mechanical effects (entrainment of downward momentum from the descending shell) and evaporative cooling as subsaturated air is entrained into the outer regions of the cloud although other processes may also influence the downdraught; these include interactions with adjacent clouds and possible subsidence of the whole cloud following overshooting. The latter process is, however, probably negligible in view of the inversion strength and limited available potential energy on these occasions. As was mentioned earlier this entrainment is facilitated by the cloud edge instability. As the cloud begins to decay, the mechanical forcing from outside the cloud is removed but the evaporative cooling remains to drive the downdraught within the cloud. This hypothesis was tested by a thermodynamic analysis of the air within the downdraught regions within, but adjacent to, the edge of the cloud. The results (not shown) confirm this suggestion since the water content is intermediate between that of the surrounding air and typical values within the body of the cloud (excluding penetrative downdraught regions).

Microphysical observations

The role of entrainment on the form of the cloud droplet size spectrum and on the growth of a small number of large droplets was briefly outlined in the introduction. In recent years the emphasis of work in this area has been on the role of entrainment in reducing the droplet concentration in some regions of the cloud without significantly reducing the mean droplet size; subsequent as-

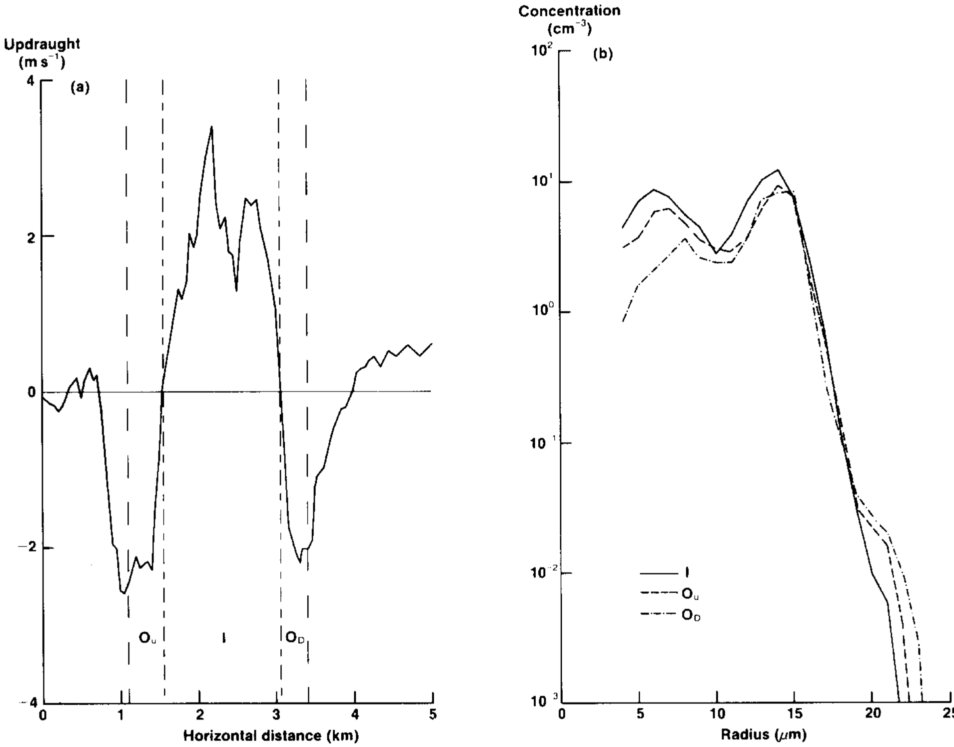


Fig. 9. (a) Traverse through an active cloud showing the updraught. Dashed lines denote the boundaries of the cloud (i.e., regions of non-zero liquid water content) and chain lines the interior region. (b) Droplet spectra averaged over the interior (I) upwind and downwind outer (O_u, O_D) regions.

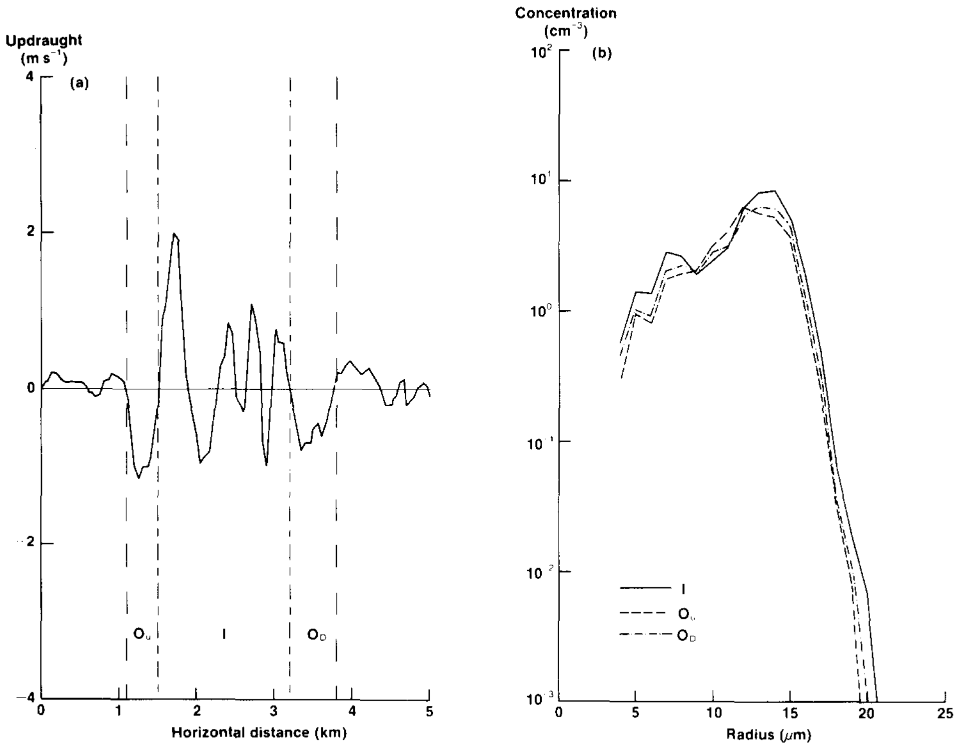


Fig. 10. As Fig. 9 except for a decaying cloud.

cent of air with a reduced droplet concentration results in higher than usual values of the supersaturation and more rapid growth of the droplets than would have been possible with the original droplet concentration. Of course such a process will be complicated by the entrainment of additional nuclei. Bower and Choularton (1988) have shown that this mechanism may increase the mean supersaturation experienced by a small fraction of the droplets but it is not clear that this is sufficient to explain the observed concentrations of "superadiabatic" droplets.

Interest in the role of entrainment on droplet growth has concentrated on the formation of large droplets in any part of the cloud. However, in the light of the observations noted above it is of interest to examine the droplet spectra at cloud edge where significant entrainment appears to occur at all stages during the growth of the clouds. The limitations of the available data preclude observations of the development of the droplet spectrum during the lifetime of a single cloud. However, the results in Fig. 9 demonstrate that within a moderately active cloud in which there was a downdraught region which extended through the cloud boundaries, the largest droplets (and lowest droplet concentration and water content) were to be found within the subsiding regions. In

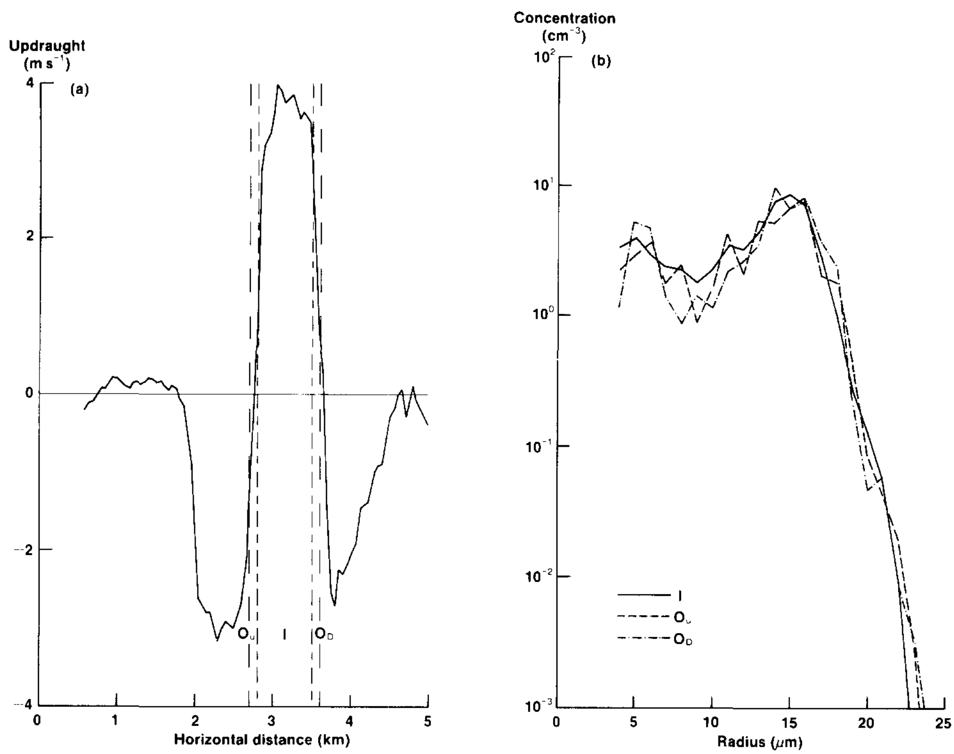


Fig. 11. As Fig. 9 except for a rapidly growing cloud turret. The outer regions are defined as regions within 100 m of the cloud edge.

contrast, the results in Fig. 10, obtained in a decaying cloud with no evidence of a surrounding shell of subsiding air, clearly show a reduction in droplet radius in the evaporatively driven region of subsidence near the cloud edges. Fig. 11 shows observations obtained in a rapidly growing cloud turret in which there was little sign of subsidence within the cloud despite the presence of a marked surrounding shell of descending air. In this example the droplet spectrum within 100 m of cloud edge was indistinguishable from that deeper into the cloud.

The results suggest that when the cloud edge downdraught is, at least partially, driven by entrainment of momentum from the descending shell of air outside the cloud it is possible for droplets to be brought down from higher levels in the cloud, where in general the mean radius is higher, without suffering evaporation, which is a necessary consequence if evaporative cooling forces the downdraught. This results in the presence of large drops at the edge of the cloud in a region of descent which could not be explained by the mechanism proposed by Bower and Choularton (1988).

Clearly such maintenance of large droplets in cloud edge downdraughts requires rather special mixing conditions which are sufficient to maintain the relative humidity against the adiabatic warming in the forced downdraught. It is unlikely that homogeneous mixing of cloudy air into the downdraught could provide the necessary conditions for survival of large drops as the air is warmed due to the descent. However, inhomogeneous mixing, leading to regions where, locally, the subsaturation is small, might provide the necessary conditions for the survival of a small number of large drops. Although beyond the scope of the present work calculations of the mixing necessary to prevent evaporation of all of the large drops in the subsiding air are presently being carried out. The large drops brought down by such a mechanism are likely to be re-entrained into the body of the cloud with the potential for subsequent growth leading to further broadening of the droplet spectrum as suggested by Mason and Jonas (1974).

DISCUSSION AND CONCLUSIONS

The results presented in this paper suggest that in considering the physics of the entrainment process and the consequent effects on the droplet spectrum, the cloud must be considered together with the surrounding cloud-free air since the entrainment of air is influenced by the presence of a shell of subsiding air. This shell brings air from the level of the cloud top to the lower edges of the cloud, increasing the entrainment instability at cloud edge. This effect is most apparent in growing clouds and is partly responsible for the findings, using thermodynamic analysis alone, that most of the air entrained into a cloud and reaching a particular observation level originates at much higher levels. Air which is brought down outside the cloud and entrained laterally is, thermodynamically, indistinguishable from air entrained at cloud top. The apparent increase in the frequency of penetrative downdraughts with increasing cloud size (and vigour) probably reflects the increased strength of the subsidence adjacent to the cloud, increased cloud edge instability and increased lateral entrainment. There is however evidence that some downdraughts penetrate from cloud top since regions of negatively buoyant air could not be mixed into the interior of the cloud by turbulent motions following lateral entrainment.

The shell of subsiding air outside the cloud may give rise to a mechanically forced region of descent within the cloud which is reinforced by evaporative cooling following lateral entrainment of subsaturated air. In decaying clouds the mechanical forcing cannot occur since there is no subsiding shell of air while in the most active parts of a cloud the latent heating is sufficient to overcome the effects of entrainment of downward momentum at the cloud edge.

The observations of the droplet spectra close to cloud edge show evidence for large drops being brought down from higher levels without significant evaporation. This process can however only occur when the cloud edge downdraught is mechanically forced and cannot explain superadiabatic droplet growth in an actively growing cloud, although it may be significant as the cloud reaches maturity.

The limited observations which have been presented above are clearly suggestive of the way in which the flow around a cloud influences its development. Experimental difficulties prevent a detailed observational study of the lifecycle of individual clouds and the way in which the cloud structure is influenced by such factors as shear in the environmental wind profile. Previous studies have however suggested that, for example, the horizontal distribution of cloud water content is sensitive to the wind shear. It would be particularly useful to carry out studies with the high resolution numerical models now becoming available (e.g. Clark et al., 1986) to investigate the flow in the immediate vicinity of a growing cloud. However, since the surrounding shell is often around 100–200 m thick it is essential that models have a resolution of, at most, a few tens of meters. The results of Klaarssen and Clark (1985) include some examples of the vertical velocity field which show strong descent near cloud edge but it is not clear whether such downdraughts are transitory or whether they represent a continuous flow of air around the rising cloud.

The results also suggest that models in which entrainment is parametrised using a scheme which, essentially, mixes environmental air and cloud air at the same level is likely to be misleading and to underestimate cloud dilution since in general the dilution takes place by entrainment of air from higher levels with lower specific humidity.

Finally it is worth commenting that in this work clouds have been considered as self contained structures consisting of a cloud and a region immediately surrounding it. As Clark et al. (1986) have shown in many cases the air circulations associated with each cloud may interact. While this is of particular importance during the initial phases of cloud growth, leading to the growth of some clouds while others decay, it is possible that the circulations around even mature clouds will be influenced by those around adjacent clouds.

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