Field studies of the optical and microphysical characteristics of clouds enveloping Great Dun Fell


Physics Department, UMIST, Manchester.

(Received 4 November 1984; revised 10 June 1985)

SUMMARY

In an effort to study aspects of their evolution, simultaneous measurements have been made, in two separate studies, of the microphysical properties of cap clouds over Great Dun Fell, in Cumbria, at two vertically displaced sites along the line of the wind. Dynamical, optical (10-6 μm) and acoustic sounder measurements were also made.

Influences upon the cloud properties of humidity fluctuations near to cloud base, turbulent deposition of droplets to ground, additional activation caused by orographically induced accelerations within the clouds, entrainment of environmental air and long-wave radiation to space were identified and examined.

The clouds studied exhibited structure in their microphysical and optical properties on all scales from a few metres to several hundred metres.

The cloud model of Carruthers and Choularton was found to predict the optical and microphysical characteristics of clouds not significantly influenced by entrainment, to a reasonable degree of accuracy.

1. INTRODUCTION

The influence of dry air entrainment upon the microphysical development and structure of cap clouds enveloping the UMIST field research station on the summit of Great Dun Fell (GDF), in Cumbria, has been examined in field experiments described by Blyth et al. (1980) and Baker et al. (1982). A major deficiency of these studies was that microphysical measurements were confined to a single site (the mountain summit), and thus it was not possible to examine the evolution of the droplet spectrum.

This paper describes two case studies (performed on 24 March and 6 April 1982) in which microphysical measurements were made from two sites, vertically separated by about 160 m. Some of these were recorded, on occasion, at a frequency of 10 Hz, ten times faster than in the earlier experiments, thus permitting the internal structure of the clouds to be examined on much smaller scales (down to about 0.5 m) than hitherto. A further additional feature was the utilization of a transmissometer to measure the electromagnetic extinction at a wavelength of 10-6 μm, thus enabling an attempt to be made to relate the microphysical and optical characteristics of the clouds studied.

The goals of the present experiment were: to study the evolution of the cloud droplet spectra as cloudy air parcels passed from the lower measurement site to the summit station; to determine the effects of dry air entrainment, humidity fluctuations near cloud base, radiative cooling and turbulent deposition upon the microphysical structure of the clouds — all of these processes having been examined theoretically by Carruthers and Choularton (1984) and — in more detailed form — (1986, paper (I)), thus permitting comparisons to be made between their predictions and the present observations; to examine the variability produced in the microphysical characteristics by dry air entrainment and subsequent turbulent mixing, over as wide a spatial range as possible, and to determine the extent to which it is consistent with the mixing mechanism proposed by Baker et al. (1984); and to explore the relationships between the microphysical and optical characteristics of the clouds, and thereby determine the extent to which the latter may be predictable from basic meteorological measurements. In section 2 we describe the four sites at which measurements were made in these studies, the equipment employed at each one, and the techniques and procedures utilized in treating the recorded
data. Sections 3 and 4 are concerned with the microphysical aspects of the two case studies. The experiment performed on 6 April 1982 (case 1) is dealt with first, as it covers a wider range of effects than the other. The optical measurements, and their relationship with the microphysical ones, are described in section 5. Overall conclusions emanating from these studies are presented in section 6.

2. INSTRUMENTATION AND PROCEDURES

Figure 1 is a map of the Great Dun Fell area, on which are indicated the four sites at which data were obtained: Wharleycroft, the UMIST station at the foot of the fell (altitude 205 m), used for accommodation and some basic meteorological measurements; the Silverband Mine (686 m), where our mobile laboratory was parked, in a well-exposed position on the upwind face; and the research station on the summit of GDF (847 m), at which the most comprehensive measurements were made, primarily from an instrument platform adjacent to the laboratory. Measurements—primarily of the location of cloud base—were made from a Land-Rover which travelled along the SW-facing road from the base of the mountain to its summit.

Table 1 indicates the measurements made at each of the four sites. In addition, visual estimations of visibility were made at each site, and observations of cloud type were made from sites 1 and 2. \( N(m_a) \) was measured continuously with a Mee CCN counter. Preparatory tests, in which it was operated on alternate days at sites 1 and 3, on cloudless days with steady SW winds, revealed no significant variations in activity.

![Contour map of research area](image)

**Figure 1.** Contour map of research area. North is vertically upwards. Contours at 50 m height intervals, 200 m contour to west of 1, 800 m contour surrounding 4. Horizontal range is 3 km. 1, Wharleycroft; 2, mobile site; 3, Silverband Mine; 4, GDF summit.
### CHARACTERISTICS OF CLOUDS

#### TABLE 1. PARAMETERS MEASURED AT THE FOUR SITES

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N(m_n) is CCN actively spectrum; T_D, dry-bulb temperature; T_W, wet-bulb temperature; U, wind speed; W.D., wind direction; Z_b, altitude of cloud base; N(d), the size distribution of cloud droplets (2 to 32 μm); L, the liquid water content; N(D), the size distribution of particles in the diameter range 15 to 300 μm; H, the relative humidity; E, the electromagnetic extinction at 10-6 μm; and Z_T, the altitude of cloud top.

spectra. Thus it was considered justifiable to make measurements of N(m_n) from Wharleycroft—a much easier operation than from the Silverband Mine—whenever there was no blocking of the air at the valley floor. The airflow was assumed not to be blocked when a significant wind blowing in approximately the same direction was detectable at all three sites. In these conditions the increase in wind speed between the upstream site and the summit of the hill was broadly consistent with that predicted by Carruthers and Choularton (1982). N(d) was measured at sites 3 and 4 with a PMS FSS Probe, and values of L could be obtained by integrating over the droplet spectrum. L was determined in an independent manner with a Barnes transmissometer, which also measured the extinction E at a wavelength of 10-6 μm. The transmissometer utilized a 14-4 m path-length perpendicular to the airflow. N(D) was measured with a PMS OA Probe, and H with a humidity sensor, developed at UMIST (Mill and Stromberg, to be published), which it is hoped ultimately to use for tracing the origins of air entrained into clouds. Z_T was measured with an acoustic sounder, developed at UMIST, which also provided information on the scales of cloud top structure. It was situated about 40 m from the instrument platform and was prevented by wind-noise from yielding useful information when U > 25 knots. Its vertical range is 70 to 1000 m, and data were recorded as scans, each of 180 samples, every 7-5 seconds. The other parameters listed in Table 1 were measured with conventional meteorological equipment.

The principal measurements made at Wharleycroft were logged on magnetic tape. Those made at cloud base were hand-recorded. The N(d) data obtained at the Silverband Mine were accumulated on 51⁄4" magnetic discs via a Nascom 2 microcomputer. Spectra were recorded every second. The meteorological parameters measured at this site (at a height of 2 m) were recorded at 1 Hz on magnetic cassette tape; and were supplemented every half-hour by hand measurements, to provide a calibration. The basic meteorological measurements at the summit of GDF were made from a 10 m mast, operated by the Civil Aviation Authority. The FSSP data obtained at this site were recorded at 1 Hz (occasionally 10 Hz) on 51⁄4" magnetic discs, the data from the other devices being accumulated on magnetic cassette tapes.
Some preliminary data reduction was carried out at this stage. The particle concentrations obtained with the FSSP devices were corrected for the effects of wind ramming (employing a specially developed technique described in the appendix), and used to calculate the liquid water content, $L$, the total droplet concentration, $N$, the channel containing the highest number of droplets, the mean droplet diameter $\bar{d}$ and the standard deviation of the droplet spectrum, $\sigma$. Also, values of the extinction $E$, at wavelength 10.6 $\mu$m, corresponding to the droplet size distributions, were derived using the Mie coefficients as given by the Dave (1968) routines. Finally, the approximation of Chylek (1978) was used to calculate, from the Barnes transmissometer data, values of the cloud liquid water content. These last two procedures allow comparisons to be made of the responses of the two devices.

3. CASE I: 6 APRIL 1982

The experiment lasted from 0955 to 1245 GMT. The meteorological situation for this day is illustrated in Fig. 2. A complex elongated upper 'low' was situated between Ireland and 40°W, with an adjoining trough over south-west England. This trough had produced
extensive rain over parts of Britain, but this had ceased in northern England by 0955 GMT, when the experiment began. An associated 'low' was gradually filling as it moved NE towards Ireland. Throughout this period the GDF area was in light SW winds, adveecting cold air off the Atlantic. Further south, winds were more stagnant, due to a weak surface low associated with the upper trough. Stations in NW England recorded between 4/8 and 7/8 stratocumulus cloud cover at 1300 m throughout the experimental period.

The vertical structure of the atmosphere was examined using ascents from Aughton, Long Kesh and Shanwell. Based on these and the synoptic pattern it was concluded that Aughton ascent data, obtained about 150 km to the SW of GDF, presented in Fig. 3, were representative of the conditions there. They reveal that the atmosphere was slightly unstable in the lowest 200 m, and above this conditionally unstable up to 875 mb. A weak inversion is evident between 875 and 850 mb. Its base is about 300 m above the summit of GDF. The acoustic sounder record for the period of the experiment is displayed in Fig. 4. It indicates that the inversion layer is about 250 to 300 m above the summit, with some weak convective motions up to this level, which probably corresponds to the upper boundary of the cloud.

When measurements commenced at the GDF summit, at 0955 GMT, the station was already enveloped in cloud, of liquid water content $L \sim 0.5 \text{ g m}^{-3}$. $L$ remained constant for the first few minutes of measurement and then slowly decreased, as cloud base lifted, until about 1034 GMT. The gradual diminution of $L$ throughout this period was punctuated by occasional significant fluctuations with associated variations in total droplet concentration, $N$. After 1034 GMT, when the cloud enveloping the summit was reported to be thinning, large and rapid fluctuations in $L$ were observed (up to $\sim 0.2 \text{ g m}^{-3}$). These features are illustrated in Fig. 5. A massive reduction in $L$ is evident over the period 1054 to 1100 GMT. The associated 1 s-averaged droplet spectra are presented in Fig. 6. The reduction in $L$ is seen to be caused by reductions of both $N$ and mean droplet
Figure 4. Acoustic sounder record for research period on 6 April 1982.

Figure 5. Measured time variations at the GDF summit of liquid water content, $L$, droplet concentration, $N$, and mean diameter $\bar{d}$ on 6 April 1982. 1-minute averages.
Figure 6. Consecutive (1 s) spectra measured at the GDF summit between 105530 and 105700 GMT on 6 April 1982. Ordinate, number concentration 0–250 cm\(^{-3}\); abscissa, droplet diameter 2–32 μm.

Figure 7. Measured time variations at Silverband site of liquid water content, \(L\), and droplet concentration, \(N\), on 6 April 1982. 1-minute averages.
diameter $\bar{d}$. The especially large reductions in $L$ were found to be generally coincident with particularly strong echoes in the acoustic sounder records, e.g. region $L$ in Fig. 4, which suggests that considerable entrainment was occurring.

Recording at the Silverband site commenced at 1005 GMT, when $L \sim 0.2 \text{ g m}^{-3}$. Thereafter, until cloud base rose unequivocally above the site, at 1053 GMT, large fluctuations in $L$ and $N$ were observed. Baker et al. (1982) reported that as cloud base approached the observation site large fluctuations in $L$ appeared. These are discussed in (I) and may be attributed to small-scale fluctuations in the humidity, $H$, of the air entering cloud base. It is likely, therefore, that much of the structure observed in Fig. 7 is attributable to this effect.

Comparison of Figs. 5 and 7 illustrates the general finding that pronounced features in the $L$ records from the Silverband site were duplicated at the summit about four minutes later. Calculations based on the measured wind speeds indicated that the transit time for an air parcel between these two sites would be around $3\frac{1}{2}$ minutes. The lifetime of these larger-scale features is estimated at around 10 minutes.

The temperatures at the summit and at the Silverband site remained constant throughout the period of investigation, being $6.0 \pm 0.2 \, ^\circ\text{C}$ and $7.0 \pm 0.2 \, ^\circ\text{C}$ respectively. At the summit the wind speed, $U$, ranged from 4 to 6 m s$^{-1}$, with direction varying

![Figure 8](image_url)

**Figure 8.** Maximum (A), average (B), minimum (C) and adiabatic (D) droplet spectra at the GDF summit for the 2-minute period commencing 101400 GMT on 6 April 1982.
between 240 and 260°. The associated values at the Silverband site were 3 m s\(^{-1}\) and 200 to 220°. Thus air parcels arriving at the summit passed within about 500 m of the Silverband site.

Figure 8 presents maximum, minimum and average liquid water content spectra obtained by taking averages respectively of the top and bottom 10-percentile and all 1 s spectra measured at the summit within the 3-minute period commencing 101400 GMT, in the early stages of the experiment, when the cloud was exhibiting small fluctuations. Figure 9 presents similar spectra for a 90 s period later in the experiment (commencing 103400 GMT), when the fluctuations in \(L\) were pronounced. These two figures also present 'adiabatic' spectra obtained from the model presented in (1), in which CCN activity spectra obtained with the Mie device, and 5-minute-averaged droplet spectra measured at the Silverband site were used to calculate the size distribution at the summit on the assumption that the cloudy air was lifted adiabatically between the two sites. The number of nuclei activated, \(N(\text{cm}^{-3})\), was related to the supersaturation \(S(\%)\) by \(N = CS^K\) where \(C = 300\) and \(K = 0.5\). In the earlier case (Fig. 8) there are much smaller departures (~15%) from the average value of \(L\) than in the later case (Fig. 9, ~40%). The 'maximum' spectrum in Fig. 8 has a liquid water content only 7% below the adiabatic value, but at the much more substantially fluctuating stage covered by Fig. 9, the reduction is about

![Figure 9. As Fig. 8 but for the 90-second period commencing 103400 GMT on 6 April 1982.](image-url)
25%. Figure 8 reveals a small amount of enhanced (superadiabatic) growth. The observed spectra are slightly broader than the adiabatic one. Figure 9, which reveals no evidence for enhanced growth, displays observed spectra which are much broader than the adiabatic one, and which contain substantially higher (≈20%) concentrations of droplets. These findings probably result from the combined effects of entrainment (in evaporating droplets) and activation of fresh nuclei as the diluted cloud flows from the Silverband site to the summit of GDF. In both cases the largest drops are seen to be in the regions of highest $L$, which suggests that the inhomogeneous mixing or dilution mechanisms (Baker et al. 1980; Telford and Chai 1980) were not responsible for the small amount of enhanced growth illustrated in Fig. 8. Also, in view of the extensive upper cloud in the course of this experiment, it is unlikely that radiative cooling was responsible (e.g. Choularton et al. 1981). It is probable that this enhanced growth of about 1 μm results from cloud base patchiness—its magnitude is consistent with that calculated in (1). The absence of enhanced growth in the later case (Fig. 9) presumably due to entrained air is sufficiently substantial to eliminate the effects of the significant cloud base patchiness.

Examination of consecutive 1 s-averaged droplet size distributions confirms the existence (already revealed in Fig. 5) of significant microphysical structure in the summit measurements on all scales down to the smallest detectable, which for the low wind speeds prevailing in this experiment, corresponds to about 0.5 m. This fine structure, which is on a much smaller scale than that of the cloud base patchiness, is almost certainly a consequence of mixing between cloudy air and the entrained environmental air responsible for the observed subadiabatic values of $L$. The spectral sequences show that, in general, small-scale fluctuations in $L$ result primarily from changes in droplet concentration $N$; whereas larger-scale fluctuations in $L$ are dominated by changes in mean drop diameter $\bar{d}$. This pattern is consistent with the model of entrainment/mixing/evaporation proposed by Baker et al. (1984). An illustration of these trends is presented in Figs. 10 and 11. Figure 10 shows 90 consecutive 1 s-averaged spectra measured at the Silverband site, commencing 100700 GMT. They are seen to be narrow and fairly consistent, with a concentration $N \sim 400$ cm$^{-3}$ and liquid water content $L \sim 0.2$ g m$^{-3}$ until about 100815 GMT, when a cloud patch of width around 25 m passed through. Its liquid water content was substantially reduced (with a minimum around 0.1 g m$^{-3}$) but the spectral shape was largely preserved—the reduction in $L$ being due principally to a diminution in $N$. Inspection of a similar set of 1-second consecutive spectra, recorded at the summit station, reveals a cloud patch, of width around 25 m, at around 101145 GMT, which may have been the same as the one observed at the Silverband site $3\frac{1}{2}$ minutes earlier. The spectra at the more elevated site were found to be much broader—presumably as a consequence of entrainment/activation—and the region of significantly reduced $L$ possessed spectral shapes similar to those in the surrounding cloud. The diminution in $L$ was due primarily to a reduction in $N$.

A drastically different relationship between $L$ and $N$, when the region of reduced $L$ is much more extensive, is displayed in Fig. 11. At around 103427 GMT the liquid water content measured at the summit station dropped suddenly (within 2 s, $\sim 10$ m) from about 0.35 to 0.2 g m$^{-3}$, and remained for about 30 s ($\sim 150$ m) at this reduced value before reverting to the original (higher) one. The number concentration $N$ remained essentially constant throughout this period—the reduction in $L$ being more or less entirely attributable to a reduction (due, presumably, to evaporation) in the mean size of the droplets in the cloud.
4. **CASE II: 24 MARCH 1982**

Great Dun Fell was in a SW airstream (geostrophic wind speed ~20 kt) on the margin of an anticyclone, of central pressure 1040 mb, centred just off East Anglia. During the run, which lasted from 1215 to 1410 GMT, northern England was covered with broken stratocumulus cloud with base around 1500 m. A broken layer of cirrostratus was observed at higher levels, with a little small cumulus at around 600 m. Satellite photo-

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**Figure 10.** As Fig. 6 but measured at the Silverband site, commencing 100700 GMT, on 6 April 1982.

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**Figure 11.** Measured time variations at the GDF summit of liquid water content, $L$, droplet concentration, $N$, and mean radius cubed $r^3$, on 6 April 1982. 1-second averages.
graphs taken at 1500 gmt showed an isolated cloud over the GDF area (presumably the cap cloud), with a small amount of higher-level cloud. The temperature increased steadily throughout the course of the run, with an associated rise in the base of the cap cloud over GDF. The midday ascents at Aughton and Long Kesh revealed a near-neutral layer extending from the surface (1035 mb) to around 1500 m (880 mb), above which level was a strong inversion with considerably warmer drier air aloft. Unfortunately, the winds were too strong on this day to operate the acoustic sounder satisfactorily, and it could not be used either to check this estimate of inversion height or to estimate scales of entrainment.

As the cloud base rose during the course of the run the fluctuations in liquid water content, $L$, observed at the Silverband site became more pronounced, as can be seen by comparing Figs. 12 and 13, which are separated by about one hour. Similar behaviour was observed in the records of the droplet number concentration, $N$. These fluctuations are probably attributable to variability in the relative humidity of the air entering cloud base, as proposed in (I) and discussed in connection with case I.

Figures 14 and 15 present (curve B in both cases) the average droplet spectra measured at the summit for the same two periods covered by Figs. 12 and 13, together with the 'adiabatic' summit spectra calculated, in each case, by taking the average spectrum observed at the Silverband site and growing it adiabatically to the altitude of the summit. It is seen that, in both cases, the measured spectrum extends to larger droplet sizes than the adiabatic spectrum, but that the enhancement is greater at the later time of observation (Fig. 15)—presumably because the cloud base is closer to the measurement point.

The extent of the superadiabatic growth observed at the summit in the two cases is substantially greater than predicted by the cloud base patchiness effect. It appeared possible that this significant enhancement might be due to entrainment of undersaturated environmental air, as discussed previously, and it is clear from Figs. 14 and 15 that the cloud is substantially subadiabatic in its liquid water content in both cases, presumably as a consequence of entrainment. This dilution of the cloud is confirmed by plotting the ten-percentile 'maximum' and 'minimum' water content spectra (curves A and C respectively). The observed differences in the minimum and maximum spectra are clearly attributable to the effects of dry air entrainment on the cloud; the spectral shifts, in moving from high to low values of $L$, are qualitatively consistent with the description of

![Figure 12. Measured time variations at the Silverband site of liquid water content, $L$, and droplet concentration, $N$, on 24 March 1982. 10-second averages.](image1)

![Figure 13. As Fig. 12.](image2)
mixing/evaporation proposed by Baker et al. (1984). However, the largest drops in the measured spectra are always found in the regions of highest $L$, which is inconsistent with the idea of superadiabatic growth resulting from entrainment/evaporation/dilution. Also, in such shallow clouds, calculations indicate that there is insufficient depth for significant enhanced growth to occur. Again, although entrainment unquestionably occurs, the overall level of dilution is much less than in case I, where the cloud top was considerably closer; the 'maximum' spectra in Figs. 14 and 15 possess values of $L$ very close to adiabatic. Thus we conclude that the significant superadiabatic growth is not a consequence of entrainment, but of radiative cooling—as discussed by Carruthers and Choularton (1984)—with which it is quantitatively consistent.

Figure 16 provides a characteristic record of high-frequency (10 Hz, ~2 m) fluctu-
ations in number concentration \( N \), which is seen to exhibit significant structure on the smallest scales detectable. In fact, the magnitude of the structure increases with decreasing scale, as predicted by the entrainment/mixing mechanism proposed by Baker et al. An alternative explanation for this high-frequency structure is turbulent deposition of droplets to ground, as discussed in (I). Their treatment of this process predicts structure on scales around 2 m, with variations from the mean of up to \( \pm 30\% \). These predictions fit well with the observations (as shown in Fig. 16), and we conclude that turbulent deposition provides a more likely explanation for these fluctuations in \( N \) than entrainment—a rather weak process in this cloud.

5. ELECTROMAGNETIC TRANSMISSION AT 10·6 \( \mu \)m

Measurements of extinction at a wavelength 10·6 \( \pm 0·3 \) \( \mu \)m were made with the Barnes transmissometer, operating in cloud over a path of length 14·4 \( \pm 0·1 \) m, on 6 April 1982 (case I). Figure 17 presents, for its complete data set, measurements of extinction, \( E \), made with the transmissometer, and liquid water content \( L \) obtained by integration of the droplet size distributions measured with the FSSP. A linear relationship between \( E \) and \( L \) is revealed, with the points scattered around the theoretical line (shown in the figure) of Chylek (1978).

Values of extinction at a chosen wavelength can be calculated directly from the droplet size distribution measured with the FSSP device, by using Mie theory to calculate extinction coefficients for each droplet radius in the spectrum. Figure 18, constructed from data points measured on 6 April (case I) shows reasonably good agreement between the extinction derived in this way, with that measured directly by means of the Barnes transmissometer, although a tendency is revealed for the FSSP-derived values of extinction to exceed slightly those measured directly.

![Figure 17](image-url)  The variation at the GDF summit of liquid water content, \( L \), with optical extinction, \( E \), at 10·6 \( \mu \)m on 6 April 1982. 1-second averages throughout.
Figure 17 demonstrates that for the rather narrow droplet spectra found on 6 April—and, indeed, generally at GDF—the Chylek approximation provides an accurate estimate of extinction. This question was examined further by plotting, for data obtained on 24 March (case II), when the Barnes transmissometer was not operating, the liquid water content \( L \)—obtained by integrating over the droplet size distribution measured with the FSSP—against the values of extinction derived from Mie theory, as described earlier. A well-defined straight-line relationship was found, but its slope was 15% less than that given by the Chylek relationship. This discrepancy is probably due to the fact that the extinction coefficients for the largest drops in the spectrum are underestimated by the Chylek approximation.

It is clear from the foregoing analysis that, in general, the relationship between the microphysical characteristics of the clouds enveloping Great Dun Fell, and the optical characteristics at a wavelength of 10.6 \( \mu m \) is simple and predictable. Thus the optical structure can readily be calculated, in most circumstances, from the observed microphysical structure, without the need for direct optical measurements (which are difficult to make); and the extent to which the optical characteristics can be determined from basic meteorological measurements (such as the soundings and the properties of the air mass) is essentially identical to that with which the microphysical characteristics can be so determined. Comparison of observations at Great Dun Fell with predictions from the models developed by Carruthers and Choularton (1982, 1984, 1986) suggests that this goal of predictability is likely to become achievable to a reasonable degree of accuracy. The microphysical/optical relationship becomes much more complex and unpredictable, of course, if the wavelength of the radiation is reduced, or if very large condensate droplets or small raindrops exist in significant quantities within the clouds.

\[ E \text{ (km}^3\text{)} \]

\[ E' \text{ (km}^{-1}\text{)} \]

Figure 18. Measured (\( E \)) and calculated (\( E' \)) values of optical extinction at 10.6 \( \mu m \) for case I. GDF summit.
6. CONCLUSIONS

Two advantages of the studies described in the foregoing sections, over those conducted earlier at GDF, are that in-cloud measurements were made at two levels simultaneously, and down to very small scales (~1 m). The microphysical structure of the cloud, as parcels of air ascend between the two sites, is modified by four effects.

1. Small-scale (~10–100 m) fluctuations in the humidity of the airstream entering cloud base. This produces a staggering of the activation process, resulting in a highly variable liquid water content in the cloud base region, a broadening of the droplet spectrum, and—by the time the droplets reach the summit—a small degree of superadiabatic growth (by about 1 µm diameter) of a minor fraction of the drops—those which have experienced the highest supersaturation for the longest period as droplet exchange occurs between neighbouring parcels with slightly different cloud bases. In other circumstances, where humidity fluctuations are larger, a bigger enhancement is to be expected than that observed, although this effect will always be confined to a region close to cloud base.

2. Radiative effects. When the sky above the cloud is clear, permitting long-wave emission to space from cloud top, radiative cooling produces an enhancement in the rate of growth of the droplets near cloud top. These larger drops are detectable in significant concentrations at the ground several hundred metres below the summit due to subsequent turbulent transport.

3. Dry air entrainment. This produces a reduction in the liquid water content of the cloud, associated with a reduction in both number concentration and a shift in the droplet spectrum towards smaller sizes. In the case studies discussed herein the latter effect is dominant, with some indication that suggests that this evaporation occurs on scales in

Figure A1. Circuit for the mean transit time frequency generator.
excess of about 10 m. As the scale is reduced below this value the changes in \( L \) are associated increasingly with ones in \( N \). This suggests that filaments of unmixed dry air are present on small scales, in conformity with the arguments of Baker et al. (1984). Continued ascent following evaporation can produce an increase in the concentration of small droplets, as a consequence of fresh activation of nuclei. However, there is no evidence of enhanced growth due to this effect in these shallow clouds.

4. **Loss of droplets to ground, predominantly by turbulent diffusion.** This produces a reduction in liquid water content and number concentration of about 30\% at 4 m above the ground. This effect also introduces structure into the cloud on scales of a few metres, in which changes in \( L \) closely parallel ones in \( N \).

**APPENDIX**

*Correction for wind-ramming in FSSP devices*

In order to determine the number concentration \( N \), using PMS FSS probes, it is essential that the volume sampling rate, \( V \), be known accurately. For these devices \( V \) is the product of sample area and ventilation speed. When supplied, the characteristics of an individual PMS device, including sample area, and methods for their verification are provided. The sample areas of both UMIST-operated FSSPs were found to be within \( \pm 10\% \) or so of their quoted values.

For ground-based measurements the FSSP is fitted with a Rotron fan to produce a ventilation speed of 26 m s\(^{-1}\). For one of the UMIST FSSPs, (A), this corresponds to a value for \( V \) of 8.14 cm\(^3\) s\(^{-1}\). In conditions other than still air, this ventilation speed and hence the volume sampling rate, is modified by ramming of air through the sample tube by the wind.

![Figure A2. Measured values of FSSP volume sampling rate, \( V \), and 10-second average wind speed, \( U \).](image-url)
The simplest method to determine the magnitude of this effect is to measure the average transit time, \( \tau \), of the particles as they pass through the device. To this end a circuit was designed and constructed (Fig. A1) which converts \( \tau \) in a linear manner, into a frequency.

\( \tau \) is dependent upon number concentration as well as wind speed. After applying standard linear regression techniques to many of the size distributions encountered at GDF, however, it proved possible to derive empirical formulae for the two UMIST-operated FSSP devices, (A) and (B); these are:

\[
V_A = V_A \times 2100/f_A \quad \text{(A.1a)}
\]
\[
V_B = V_B \times 1200/f_B \quad \text{(A.1b)}
\]

where \( V' \) is the actual sample volume, \( V \) is the manufacturer's quoted value and \( f \) is the output from the frequency generator circuit.

The results of this analysis for UMIST probe (A) are presented in Fig. A2. The volume sampling rate is plotted against ten-second averages of the wind speed measured as close to the probe as possible. The data were obtained on 7 April 1982. Whilst we appreciate that the probe and anemometer do not sample the same airflow, the correlation and extrapolation to zero wind speed, when the volume sampling rate is very close to that given by the manufacturer, lead us to conclude that this technique works satisfactorily at GDF.

**REFERENCES**


