A field study of nocturnal stratocumulus; III. High resolution radiative and microphysical observations

By A. SLINGO, R. BROWN and C. L. WRENCH
Meteorological Office, Bracknell  Appleton Laboratory Slough

(Received 9 April 1980; revised 11 April 1981)

SUMMARY

High resolution observations from a tethered balloon of nocturnal stratocumulus on three occasions are presented. Measurements of the microphysical properties of the clouds (drop-size distributions, concentrations and liquid water contents) were obtained with an Axially Scattering Spectrometer Probe (ASSP). A ground based 95 GHz radiometer was used to infer the integrated liquid water path through the cloud. In the two thick clouds studied the drop-size data show an almost monotonic increase of mean radius from cloud base to top. The liquid water content increases with height above cloud base at slightly less than the adiabatic rate and shows considerable variability towards cloud top. The observations support the concept of the inhomogeneous mixing of the cloudy air with the dry air entrained at the cloud top. Measurements were also made of infrared net radiative fluxes, and very good agreement is found with the theoretical fluxes from a high resolution radiative transfer scheme, using the ASSP drop spectra and liquid water contents, scaled by the 95 GHz radiometer data.

1. INTRODUCTION

This paper presents detailed observations of the radiative and microphysical structure of nocturnal stratocumulus clouds on three occasions. It forms part of a study of stratocumulus, using a tethered balloon facility at Cardington, Bedfordshire. The use of a tethered balloon as opposed to an aircraft results in data with high vertical resolution. The first case study (19–20 November 1976) has been the subject of concentrated research and the two accompanying papers describe in detail the design of the experiment and the derivation of the energy balance (Roach et al. 1982; Paper I) and the turbulence measurements (Caughey et al. 1982; Paper II). In addition, results are presented here from two further case studies (26–27 October 1977 and 15 January 1978) for which the microphysical and radiation data have been analysed.

Apart from the contribution of this work to the analysis of the 1976 case study described in Paper I, the observations throw light on two important aspects of cloud physics. The first is the study of the transfer of radiation through clouds and the application of this work to models of the cloudy boundary layer. There is an extensive literature dealing with the numerous mathematical techniques which have been devised for treating radiative transfer through clouds and many theoretical studies of ideal clouds have been made (for reviews see Paltridge and Platt 1976, Bolle 1977, Lenoble 1977, Feigelzon 1978). Radiation and turbulence schemes of various degrees of complexity have also been incorporated into one-dimensional models of the evolving cloudy boundary layer which treat liquid water as an explicit model variable (Herman and Goody 1976, Oliver et al. 1978, Fravalto et al. 1978). Comparisons of theoretical radiative flux profiles with those observed from instrumented aircraft have shown broad agreement (Goya et al. 1970, Paltridge 1974, Kuhn et al. 1974, Platt 1976, Stephens et al. 1978). However, the aircraft observations reported so far do not resolve adequately the large flux gradients which exist at cloud tops, where the most sensitive test of the theoretical profiles can be made, nor do they include sufficiently detailed measurements of the drop-size distribution and liquid water content. The observations presented here allow such a comparison to be made and show good agreement with the theoretical profiles from a high resolution infrared radiation scheme (Roach and Slingo 1979). The influence of the large cooling rates on the cloud top entrainment rate and the turbulence levels within the cloud are discussed further in Papers I and II.

The second field is the study of the microphysical structure and mixing processes within
clouds and the evolution of the drop-size distribution function. The considerable effort which has been put into improving the performance of an Axially Scattering Spectrometer Probe (ASSP) (Knollenberg 1976) has resulted in an instrument which gives accurate drop-size distributions, although absolute calibration of the estimated liquid water content relies on other instruments (Ryder 1976, Roach 1977). High quality profiles of drop-size distribution were obtained in all three case studies.

Measurements were also made of the thermal emission from the atmosphere at a frequency of 95 GHz, using a ground-based microwave radiometer operated by the Appleton Laboratory. The contribution to the emission from the liquid water component was deduced and used to derive the integrated liquid water content of the column above the instrument. Apart from demonstrating the meteorological applications of this instrument, the data provided the independent measure of liquid water content necessary to calibrate the values obtained with the ASSP. Good agreement was found between the observed net infrared fluxes and those predicted by the high resolution radiation scheme using the ASSP drop spectra and liquid water contents, scaled by the microwave radiometer.

2. INSTRUMENTATION

Descriptions will be given here of the droplet spectrometer probe, net radiometers and the microwave radiometer. Details of the other instruments used will be found in Papers I and II.

(a) Droplet Spectrometer Probe (ASSP)

The droplet spectrometer sizes cloud droplets in the ranges 1–15 µm or 1.5–22.5 µm radius by measuring the amount of light scattered by individual drops drawn through a laser beam. Only droplets transiting a small area of the beam (around 0.3 mm²), selected optically and electronically, are accepted for sizing. This reduces the problem of droplet coincidences, and the effect of axial and radial variations of beam intensity, to insignificant proportions. Laboratory comparisons with magnesium oxide and oil coated slides have shown that the spectrometer will measure mode radii to within ±0.5 µm and dispersions within about ±2%. In contrast, estimates of droplet concentration are uncertain to within a factor of about 2, due to the difficulty in estimating the sampling area. Values of droplet concentration and liquid water content have been refined by comparison with the infrared and microwave radiometer measurements as described later.

For use on the balloon, air was drawn through the spectrometer sampling tube at about 5 m s⁻¹ by a fan attached to one end. This necessitated minor modifications to the electronics which had been designed for aircraft sampling speeds. The resultant sampling rate of approximately 1.5 cm³ s⁻¹ allowed a spectrum containing about 2000 droplets to be obtained every ten seconds, although occasionally a one second sampling time was used. The aerodynamic shaping of the balloon ensured that the spectrometer sampling tube was constrained to point approximately into the wind. Errors in drop concentration due to departures from isokinetic sampling conditions are estimated to be of order 5% for droplets of 5 µm radius and 15% for droplets of 10 µm radius. Roach (1977) has discussed errors in the sampling area and representativeness of the atmospheric measurements.

(b) Net Radiometers

Two CSIRO pattern net radiometers were mounted on gimbals for attachment to the balloon cable. The periodic time of the gimbal-radiometer combination (around 2 s) is much less than the radiometer time constant (around 10 s) so that any short period oscillation in output due to the motion of the radiometers is smoothed out. The air ring and heater supplied by the manufacturer to keep the radiometer domes free of dew were not capable of keeping the domes dry in fog and cloud. Experiments in thick fog showed that a combination of a guard ring 10 cm in diameter and 2.5 cm high and a larger air ring successfully kept the
domes free of drops. A battery operated pump delivered eight litres per minute of dried air to the domes. The dry air supply was split and a small fraction used to keep the domes inflated. By passing the dried air through airways drilled in the gimbal bearings the possibility of the air supply tubing upsetting the radiometer level was avoided. It was originally intended that the radiometers would be used to measure the flux divergence over their 5 m separation but it proved more practical to use the individual flux profiles. However, the use of two radiometers provided a valuable mutual performance check; for example that they were maintaining a horizontal attitude.

(c) Microwave Radiometer

A Dicke-switched 95 GHz superheterodyne radiometer (Gibbins et al. 1975) was pointed horizontally at an inclined reflecting plate to detect thermal atmospheric radiation from the zenith. The radiometer, which was calibrated using liquid nitrogen as a reference source, produces an output proportional to the sky brightness temperature, from which the integrated liquid water content can be derived as described in the next section. A horn antenna was used with a half power beamwidth of 10° and sidelobes more than 20 dB down on the main beam. At a height of 1 km the beam width was approximately 175 m.

3. Data reduction

After initial processing, the ASSP output consisted of event data in digital form representing particle size and various housekeeping signals. These were telemetered to the ground using a Pulse Coded Modulation system. Information on each drop detected in the sampling volume was sent individually and a statistical correction applied during data processing for counts lost during the transmission periods. Besides being recorded on a digital cassette, the build-up of each spectrum was displayed visually in real time, allowing precise control of the position of the balloon package in relation to the cloud top. Two estimates of the concentration of drops were obtained. The first was derived from the rate of accumulation of photodetector events which the signal electronics recognise as being suitable for sizing. These are due to non-overlapping, in-focus drops passing close to the axis of the laser beam, within the so-called ‘Inner’ volume. As a check, a second estimate was derived from those drops which are capable of producing a signal at the main photodetector above some threshold, but which are not necessarily accepted for sizing. These define the larger ‘Outer’ volume. The rationale for this approach has been discussed by Ryder (1976), and the determination of the effective sampling volumes was described by Roach (1977). Both estimates were stored and used to scale the drop-size distribution data so as to produce two estimates of the liquid water content.

The vertical profiles of the various parameters presented in the next section were obtained by matching the time series of the data with that of the pressure sensor, allowing for the vertical separation of the instruments. Such data were also interpolated onto a uniform pressure grid so that profiles of temperature, humidity mixing ratio, liquid water content and drop-size distribution could be used in the high resolution infrared radiation scheme to calculate theoretical radiative fluxes and heating rates.

The observed net infrared radiative fluxes were corrected for the obscuration of the sky by the radiometer guard rings and by the balloon. In the absence of a radiation scheme capable of giving the detailed angular distribution of sky intensity, the results of Unsworth and Monteith (1975) were used for the distribution of downward sky intensity beneath cloud-free inversions, which approximates the conditions at cloud top where the correction factor is largest. The correction factor was found by inserting temperatures and water vapour paths from the balloon data into their Eq. (1), integrating the intensity over the solid angles subtended by the guard rings, the balloon and the sky and comparing with the unobscured sky flux. The resulting correction factor is relatively insensitive to the assumed angular intensity distribution, as this is not strongly anisotropic. The observed net fluxes were
increased by, on average, 30% throughout the profile. This is undoubtedly an overestimate within and below cloud, but in these regions the net fluxes are so small in any case that the error introduced can be ignored. The absolute accuracy of the corrected net fluxes is estimated to be 10%, although it will be seen later that relative changes smaller than this can be identified reliably.

Data from the microwave radiometer were recorded on paper tape at one minute intervals. The sky brightness temperature $T_B$ can be related to the total attenuation $\tau$ by (Falcone et al. 1971):

$$\tau = 10 \log_{10} \left( \frac{T_M}{(T_M - T_B)} \right) \quad dB . \quad (1)$$

The integrated liquid water path $w$ in the column above the instrument is given by:

$$w = (\tau - \tau_{O_2} - \tau_{H_2O})/K_L \quad g \text{ m}^{-2} . \quad (2)$$

The additional parameters in these equations were estimated as follows:

1. The mean radiating temperature of the atmosphere, $T_M$, depends on the distribution of absorbing constituents, but it must lie between the value for a clear sky (obtained from a suitable radiosonde ascent) and the value obtained by assuming the cloud to be optically thick, when $T_m$ is the cloud base temperature. The range of $T_m$ was reduced by adding a first estimate of liquid water content to the radiosonde data and recalculating $T_m$. In practice the error introduced into the derived liquid water path from this uncertainty is small.

2. $\tau_{O_2}$ and $\tau_{H_2O}$ are the contributions to the total attenuation from oxygen and water vapour, respectively. These were estimated from the balloon data using the results of a long term study of clear sky attenuation, under a variety of conditions, carried out at the Appleton Laboratory, Slough, approximately 70 km south of Cardington.

3. The path-averaged mean absorption coefficient of liquid water, $K_L$, was calculated by assuming that the attenuation by the cloud drops could be found using the Rayleigh approximation (e.g. Gunn and East 1954), the validity of which was confirmed by computations using Mie theory (e.g. Zavody 1974). It was also shown that back-scattering of ground emission added a negligible contribution to the received signal.

4. RESULTS

Parameters derived from the microwave radiometer data for each case study are listed in Table 1 and time series of the integrated liquid water paths are presented in Fig. 1. It is assumed that there is no cloud above the stratocumulus, which is confirmed by the radio-

<table>
<thead>
<tr>
<th>TABLE 1. Summary of microwave radiometer data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Range of $T_m$</td>
</tr>
<tr>
<td>Clear sky contribution to attenuation</td>
</tr>
<tr>
<td>Mean absorption coefficient of liquid water in cloud, $K_L$</td>
</tr>
<tr>
<td>Range of attenuation over observing period</td>
</tr>
<tr>
<td>Standard Deviation of liquid water content measurements, averaged over one minute</td>
</tr>
</tbody>
</table>
Figure 1. Time series of the integrated liquid water paths derived from the microwave radiometer data for the three case studies. The points are one minute averages. The numbered lines above the points indicate the times of the balloon profiles through cloud. The lines below the points indicate an advection distance of 10 km, calculated using the mean observed wind in the cloud layer at that time.

sonde and radiometer data. All three traces show high frequency variability due to irregularities on a spatial scale of about 1 km, superimposed on longer period drifts which presumably reflect mesoscale changes in the boundary layer structure. Comparison of Fig. 1 with the acoustic sounder record for the first case study (Paper II) reveals a significant correlation between the two traces. Larger liquid water paths are in general associated with a higher inversion base, which suggests that the longer period variations of liquid water path are due primarily to changes in the thickness of the cloud. Above each trace the balloon
profiles through cloud are marked. Averaging the liquid water paths during these periods
gave the values which were used to scale the ASSP data.

The balloon observations for each of the three case studies will now be presented and
discussed in section 5.

(a) 19–20 November 1976

This case study is discussed in detail in Paper I, where the profiles of temperature and
humidity mixing ratio are presented. Table 2 compares the liquid water paths measured by
the microwave radiometer with the values obtained by vertical integration of the ASSP
liquid water content profiles and the theoretical values derived by assuming adiabatic ascent
from cloud base to top. The liquid water path from the microwave radiometer is on average
about 0.7 times the value for adiabatic ascent. The two ASSP liquid water content estimates
are systematically larger than the microwave radiometer values and differ from each other
by a factor of about 2. This indicates that the true sampling volumes are larger than the
provisional values calculated theoretically by Roach (1977) and underlines the importance of
an independent liquid water content estimate to calibrate ASSP data. To aid comparisons
between the case studies, the provisional sampling volumes have been used throughout this
table to calculate liquid water contents from the ASSP data.

Figure 2 illustrates the cloud microphysical data obtained with the ASSP during profile
1. The liquid water contents are the inner volume estimates, scaled by a single factor so that

![Figure 2](image-url)

Figure 2. Profiles of total number density, droplet size spectra and liquid water content from the scaled ASSP
data for profile 1, 19–20 November 1976. The droplet size spectra are presented as contours of the percentage
normalized spectral density, such that at any height the sum of the values in each 1 μm interval is 100%. The
liquid water content profile produced by adiabatic ascent from cloud base is shown as the dashed line.
<table>
<thead>
<tr>
<th>Date</th>
<th>Case study</th>
<th>Profile</th>
<th>Cloud base Pressure (mb)</th>
<th>Temp. °C</th>
<th>Temperature mb</th>
<th>Cloud top Pressure (mb)</th>
<th>Liquid Water Content at cloud top g m⁻³</th>
<th>Adiabatic Liquid Water Path g m⁻³</th>
<th>Microwave Radiometer g m⁻³</th>
<th>ASSP Inner Volume g m⁻³</th>
<th>ASSP Outer Volume g m⁻³</th>
<th>Ratio of Microwave Liquid Water Path to Adiabatic</th>
<th>Ratio of ASSP Liquid Water Paths to Microwave Inner</th>
<th>Ratio of ASSP Liquid Water Paths to Microwave Outer</th>
<th>Ratio of ASSP Liquid Water Paths to Microwave Inner</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-20 November</td>
<td>1976</td>
<td>1</td>
<td>943.5</td>
<td>1.15</td>
<td>905.0</td>
<td>0.535</td>
<td>91.2</td>
<td>68.9</td>
<td>94.4</td>
<td>205.1</td>
<td>0.76</td>
<td>1.37</td>
<td>2.98</td>
<td>2.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>944.5</td>
<td>1.30</td>
<td>907.6</td>
<td>0.516</td>
<td>84.1</td>
<td>61.9</td>
<td>76.5</td>
<td>161.4</td>
<td>0.74</td>
<td>1.24</td>
<td>2.61</td>
<td>2.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>943.5</td>
<td>1.25</td>
<td>904.8</td>
<td>0.540</td>
<td>92.5</td>
<td>63.2</td>
<td>91.7</td>
<td>189.7</td>
<td>0.68</td>
<td>1.45</td>
<td>3.00</td>
<td>2.07</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>949.0</td>
<td>1.35</td>
<td>905.6</td>
<td>0.602</td>
<td>115.6</td>
<td>62.0</td>
<td>95.0</td>
<td>183.7</td>
<td>0.54</td>
<td>1.53</td>
<td>2.96</td>
<td>1.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>945.0</td>
<td>1.15</td>
<td>908.3</td>
<td>0.511</td>
<td>82.7</td>
<td>47.1</td>
<td>72.3</td>
<td>124.6</td>
<td>0.57</td>
<td>1.54</td>
<td>2.65</td>
<td>1.72</td>
<td></td>
</tr>
<tr>
<td>26-27 October</td>
<td>1977</td>
<td>1</td>
<td>924.0</td>
<td>3.95</td>
<td>902.1</td>
<td>0.346</td>
<td>34.0</td>
<td>27.2</td>
<td>6.71</td>
<td>131.5</td>
<td>0.80</td>
<td>0.247</td>
<td>4.83</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>921.0</td>
<td>4.00</td>
<td>897.0</td>
<td>0.379</td>
<td>41.1</td>
<td>31.6</td>
<td>9.20</td>
<td>186.2</td>
<td>0.77</td>
<td>0.291</td>
<td>5.89</td>
<td>20.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>912.0</td>
<td>3.70</td>
<td>891.5</td>
<td>0.323</td>
<td>30.1</td>
<td>27.6</td>
<td>6.79</td>
<td>130.0</td>
<td>0.92</td>
<td>0.246</td>
<td>4.71</td>
<td>19.1</td>
<td></td>
</tr>
<tr>
<td>15 January 1978</td>
<td>2</td>
<td>956.0*</td>
<td>-0.50*</td>
<td>874.2</td>
<td>1.002*</td>
<td>372.1*</td>
<td>261.4</td>
<td>671.0*</td>
<td>1298*</td>
<td>0.70*</td>
<td>2.57*</td>
<td>4.97*</td>
<td>1.93</td>
<td>1.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>955.0*</td>
<td>-1.25*</td>
<td>871.5</td>
<td>0.989*</td>
<td>375.3*</td>
<td>262.9</td>
<td>417.0*</td>
<td>673*</td>
<td>0.70*</td>
<td>1.59*</td>
<td>2.56*</td>
<td>1.61</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>955.0</td>
<td>-1.25</td>
<td>862.1</td>
<td>1.086</td>
<td>463.3</td>
<td>398.3</td>
<td>486.9</td>
<td>878*</td>
<td>0.86*</td>
<td>1.22</td>
<td>2.20*</td>
<td>1.80</td>
<td>1.28</td>
</tr>
</tbody>
</table>
the integrated liquid water path is equal to that measured by the microwave radiometer during the same period. The other profiles are very similar and are not shown. The liquid water contents on the right hand side of Fig. 2 show considerable variability from point to point, but there is a systematic increase with height above cloud base at slightly less than the adiabatic rate. There is some evidence for increased variability above 920 mb, the amplitude of which varies from profile to profile. Note the sharply defined cloud top. The drop spectra are presented as contours of the percentage normalized spectral density, which allows the shape of the spectrum to be studied independently of the total liquid water content. The size distribution at any height may be reconstructed by noting that, for example, a value of 25 at 5-5 μm means that 25% of the drops lie in the radius range 5-6 μm. The mode radius rises from about 3 μm at cloud base to about 8 μm at cloud top. The spectral dispersion, which is the ratio of the standard deviation to the mode, is roughly constant with height at about 25%.

It is remarkable that the raw drop spectra could be contoured in this way without the need for any numerical smoothing or interpolation, despite the large fluctuations in liquid water content throughout the cloud. The shape of the spectrum and the mode radius are virtually unaffected by the liquid water content fluctuations. This means that the fluctuations are caused principally by variations in the total number of drops per unit volume. This is confirmed by the left hand plot, which represents the drop total number density profile. The plot also shows that the total number of drops per unit volume is roughly constant with height, so that the progressive increase of liquid water content with height is almost entirely provided by the increase in the mode radius.

The observed net radiative fluxes and the theoretical fluxes from the high resolution radiation scheme are compared in Fig. 3. Data from the initial balloon ascent (see Paper 1) have been merged with profile 1 to obtain the complete profile. The midnight radiosonde ascent from Hembsy (roughly 100 km upwind of Cardington) was used to complete the temperature and humidity profile above the balloon data. The radiation scheme was run with a surface temperature of 7.5°C (the observed screen temperature) and 1000 vertical levels, giving a resolution of about 1 mb.

The observed flux profile in the inversion shows a gradually increasing curvature as the cloud is approached due to the increasing contribution of the upward flux from the cooler cloud top. It is suggested in Paper 1 that the energy balance in this region is between radiative cooling and subsidence heating. The net fluxes show the expected rapid decrease as the cloud is entered, with the cloud becoming optically thick after about 10 mb or 30 g m⁻² liquid water path. The rise of the net flux towards the nearly constant value in the sub-cloud region is more gradual, due to the lower liquid water content at cloud base. The agreement between the observed and theoretical net fluxes is very good and the sharpness of the cloud top profile is well reproduced. The overestimate of the net flux above cloud top may be due to the radiosonde data being unrepresentative of the real profile, or to inaccuracies in the correction of the observed fluxes. The small overestimate in the sub-cloud region can be accounted for by only a 1°C error in the surface temperature. Strictly this should be the equivalent radiating temperature of the ground in a wide area beneath the balloon and such an uncertainty in its determination is not unreasonable.

The radiative heating rates derived from the flux profiles are shown on the right hand side of Fig. 3. A smooth curve was fitted to all the observed fluxes and the heating rates were calculated from the flux gradient over 5 mb slabs. The theoretical heating rates are shown at full resolution. The two heating rate profiles compare very favourably with each other. The theoretical cooling over the top 5 mb of the cloud is indicated by the arrow, and shows reasonable agreement with the value derived from the observed net fluxes. The size of the predicted cooling rate maximum at cloud top is extremely sensitive to the liquid water content profile and uncertainties as to the exact structure of the cloud top make exact agreement unlikely. The overestimate of the net flux below cloud results in a corresponding overestimate of the small heating rate at cloud base.
Figure 3. Comparison of the observed and theoretical net infrared fluxes and heating rates for profile 1, 19-20 November 1976. The continuous lines are from the radiation scheme, using the balloon temperatures and humidities and the scaled ASSP data. The dots and crosses represent the corrected fluxes from the upper and lower radiometers, respectively. Only every fifth value has been plotted.

High resolution net flux profiles through the cloud top are presented in Fig. 4. Only the first three profiles were used as the later profiles suffered from increased noise. The purpose of profile 2 was to investigate the cloud top entrainment structure so data well into the inversion were not obtained. The microwave radiometer was switched off during the latter part of profile 3, but this should not lead to appreciable error in the flux comparisons as data were obtained for the beginning of the profile when the balloon was traversing the cloud top. The solid curves indicate the theoretical profiles using the liquid water content estimates from the ASSP inner and outer volumes and also from the ASSP inner volume estimate, scaled by the microwave radiometer. The theoretical profiles for integrated liquid water paths of half and twice the microwave radiometer value are also shown. There is an uncertainty of about 0.5 mb in the positioning of the theoretical profiles owing to the 10 s sampling period and the resolution of the radiation scheme. The closeness of the theoretical curves makes it difficult to assess which is the best liquid water content estimate, but the outer volume value can be seen to be too high, while both the inner and microwave values give good agreement. The first observed profile shows a more complicated shape than the later two, suggesting that the cloud top had a more detailed liquid water structure than the ASSP was able to measure.

(b) 26-27 October 1977

During the period of these observations Cardington lay in a southerly airstream on the
edge of an anticyclone which was centred over northern Germany. A trailing cold front over the west of Ireland eventually passed through Cardington late the following day, leading to a more westerly airflow. The synoptic situation was less settled than in the previous case study and the cloud was thinner and more broken.

Figure 5 illustrates the temperatures and humidity mixing ratios measured during profile 1. The temperature profile shows similar features to the first case study, namely a shallow surface stable layer, an adiabatic sub-cloud layer topped by the thin cloud, with a strong inversion above. The humidity profile shows a weak hydrolapse and a sharp transition into the very dry inversion. Although the extremely low relative humidities of only a few per cent measured just above cloud top may be under-estimates (being below the nominal range of the sensor), the Crawley midnight radiosonde, used for continuation above the balloon profile, confirms the dryness of the inversion air, with relative humidities below 20% between 820 and 870 mb.

The wind speed in the cloud layer increased progressively during the observing period.
from about 6 m s\(^{-1}\) to about 11 m s\(^{-1}\), which was associated with a thinning and rising of the cloud, a reduction of the inversion step to about 5 °C and a stabilization of the sub-cloud layer as the surface temperature dropped from 11 °C to about 10 °C. It is interesting to note that at about 2300 (all times are GMT) the cloud was optically thin at microwave wavelengths, in the infrared (see later) and also in the visible (the moon could be seen through the cloud).

Some problems were experienced with the ASSP on this occasion. Table 2 shows a large discrepancy between the two liquid water content estimates. The microwave and infrared radiometer data show that the inner volume particle counts were seriously underestimated and the outer volume counts overestimated, in comparison with the previous case study. The problem appears to have been caused by low frequency fluctuations of the signal baseline voltage. Such fluctuations allow small voltage pulses due to noise or very small or out of focus drops, which normally are rejected, to increase the outer volume count. The generally higher voltage level artificially increases the derived average pulse width, which reduces the inner sampling volume and decreases the rate of acceptable inner volume events. All the characteristics of the fault have been reproduced quantitatively in laboratory simulations. No significant changes in the shape of the drop size spectrum from an ultrasonic drop generator have been observed at applied interference levels which reproduced the fault, despite large errors in the inferred total number densities. It is therefore believed that the size distributions obtained during this case study may be relied upon.
Figure 6. Profiles of total number density, drop-size spectra and liquid water content from the scaled ASSP data for profile 1, 26–27 October 1977. See caption to Fig. 2. For an explanation of the bold dashed profiles see the text.

The scaled microphysical data obtained during profile 1 are presented in Fig. 6. There is a progressive increase of the mean radius with height above cloud base, as observed in the first case study, but the variability of the liquid water contents is less pronounced. The data suggest an increase in the drop number density near the base of the cloud, but this may be an instrumental effect, as described below.

The observed and theoretical net fluxes and heating rates for the first profile are compared in Fig. 7. The radiation scheme was run with 1000 vertical levels and a surface temperature of 11.0°C (the observed screen temperature). In this and the later profiles the liquid water data were taken from the ASSP to assess the effect of the fault discussed above. The flux profiles shown in Fig. 7 are similar to those from the first case study, except that the observed net flux does not fall to zero within the cloud, indicating that it was not optically thick. The high resolution net flux profiles shown in Fig. 8 illustrate how sensitive these profiles are to liquid water content in such a thin cloud, as the two uncorrected ASSP liquid water content estimates give completely different flux profiles. Despite the ASSP problem, however, the observed and theoretical fluxes show good agreement when the liquid water paths are corrected to the values obtained from the microwave radiometer. All the corrected profiles tend to underestimate the net flux towards cloud base, which suggests that the ASSP overestimated the liquid water content in this region of the cloud.

To ascertain the difference between the ASSP liquid water content profile and that implied by the observed net fluxes, the radiation scheme was run with the liquid water
contents progressively adjusted until agreement was reached between the observed and theoretical net fluxes for profile 1. The resulting number densities and liquid water contents are shown as the dashed-dotted curves on Fig. 6. The radiation data imply a liquid water content profile which is more nearly triangular in shape than the ASSP data, the largest change being towards the base of the cloud. The liquid water path for this profile is 22 g m\(^{-2}\), which agrees to within the experimental errors with the value of 27.2 g m\(^{-2}\) obtained independently from the microwave radiometer.

Breaks were seen in the cloud during the final profile and this is reflected in the variability of the observed fluxes (Fig. 8). Under these circumstances a single profile is not sufficient to describe the liquid water distribution fully and this probably accounts for the systematic differences between the observed and theoretical fluxes at the cloud top.

(c) 15 January 1978

On this occasion the British Isles were covered by a complex area of falling pressure between two anticyclones, centred over the North Atlantic and over western Russia. At Cardington winds were light (1-3 m s\(^{-1}\)) and variable in direction between east and south, with a persistent and deep cloud layer variously reported as stratus or stratocumulus. The surface temperature was just above freezing point and riming occurred on the balloon and instruments, leading to some loss of data.

The first profile indicated on Fig. 1 was affected seriously by icing on the ASSP and the net radiometer (only one was used on this occasion), but good data were obtained for the remaining profiles. The temperature and humidity mixing ratio data obtained during the final profile are shown in Fig. 9. The instruments were unfortunately not taken very far into
the inversion, so in this region the data were supplemented by measurements from earlier in the night, the profile being completed with the midnight radiosonde ascent from Crawley. The temperature profile is stable throughout the sub-cloud layer and slightly stable in the cloud itself, although earlier in the night the lapse rates were much closer to the adiabatic values. There is a systematic disagreement of about 1 °C between the balloon temperatures and the synoptic observations made at the same time, but this does not significantly affect the results presented below.
The liquid water data listed in Table 2 show that the ASSP was not affected by the problems experienced in the previous case study, the performance being essentially as in the first case study. During the second and third profiles a complete traverse of the cloud was not carried out. Data from the other two traverses were used to complete the profiles, so that the entries marked with an asterisk in Table 2 should be regarded as estimates only. The microphysical data obtained during profile 4 are presented in Fig. 10. The greater depth of the cloud results in a much larger peak liquid water content than in the previous case studies. The trend is to follow the adiabatic curve, but the variability is large towards cloud top, where a thin, almost dry, region is seen, presumably being the result of entrainment of inversion air into the cloud. Apart from the perturbation associated with this feature, the drop-size distributions show very little variability, only the steady increase of the mode radius from about 4 μm at cloud base to about 8 μm at cloud top. The spectral dispersion is extremely steady at 22 ± 1%, rising to over 30% close to the cloud base. As in the first case study, the fluctuations in liquid water content appear to be related to variations in the total
Figure 10. Profiles of total number density, drop-size spectra and liquid water content from the scaled ASSP data for profile 4, 15 January 1978. See caption to Fig. 2.

Figure 11. Comparison of the observed and theoretical net infrared fluxes and heating rates for profile 4, 15 January 1978. Only every fourth observed flux has been plotted. See caption to Fig. 3.
number density, without affecting the shape of the drop-size spectrum. The particle transit
time data showed that the fan used to draw air through the sampling volume gradually
slowed down during the profile descent. Such changes in fan speed are taken into account in
the computer programs used to process the data. By about 905 mb, however, the fan speed
was very low and variable and at 920 mb the fan appears to have stopped completely,
followed by a sudden return to the expected velocity of about 5 m s\(^{-1}\). This behaviour was
probably due to the gradual accretion on to the fan of ice, which fell off at 920 mb. The data
between these pressure limits are therefore suspect and in particular the large variations in
the number densities and liquid water contents are not considered to be real. Taking this
into account, it appears that the real variability is confined to the top of the cloud, as was
also found in the first case study.

The dry zone near the cloud top has the effect of creating two distinct maxima in the
cooling rate profile (Fig. 11). The resulting convective instability would rapidly destroy this
feature and it is therefore suggested that it must be transitory. The optical thickness of the
cloud top is so large that all the liquid water content estimates lead to similar theoretical net
flux profiles, which fall rapidly to near zero within the cloud as shown in Fig. 12. The
observed fluxes show similar gradients to the theoretical curves, the vertical displacements
being within the expected error in positioning the theoretical fluxes. Profile 2 shows some
evidence of icing on the radiometer, leading to a small offset flux of 5 W m\(^{-2}\) within the
cloud.

![Figure 12](image)

Figure 12. Comparison of the observed and theoretical net infrared fluxes at the cloud top for profiles 2 and 4, 15 January 1978. The curves indicate the theoretical profiles obtained by using the ASSP outer volume liquid water content estimate (O), the inner volume estimate (I) and the scaled estimate (M). See caption to
Fig. 4.

5. DISCUSSION

Stephens (1978a) has described radiation models for calculating and parametrizing
infrared and shortwave flux profiles inside clouds, and the theoretical profiles have been
compared with aircraft observations (Stephens et al. 1978). The computational techniques used by Stephens and by Roach and Slingo (1979) are very different and it is interesting to compare the predictions of the two schemes. Stephens et al. (1978) noted poor agreement between the observed and predicted values of the effective downward emissivity, due to the large experimental errors. The effective downward emissivity may be defined as:

$$\varepsilon(p) = \left\{ F(p) - F(p_o) \right\} / \left\{ B(p) - F(p_o) \right\}$$

(3)

The emissivity is calculated at pressure level $p$ within the cloud, where the downward longwave flux is $F(p)$, and the Planck function flux is $B(p)$. The downward flux at the cloud top is $F(p_o)$. The radiometer observations presented here are of net flux only, so they cannot be used to calculate the emissivity directly. The values plotted on Fig. 13 were therefore calculated from the radiation scheme, using data from the three case studies. The solid curve represents the parametrized form of the effective downward emissivity which Stephens (1978b) fitted to the results from his theoretical model. This curve gives an excellent fit to the emissivities calculated here, indicating that, despite their different structure, the two schemes are essentially identical in their treatment of cloud liquid water. The goodness of fit and the small scatter about the parametrized curve also illustrate the well known insensitivity of the flux profiles to the drop-size distribution function and the minor role played by scattering (e.g. Paltridge and Platt 1976).

The shape of the net flux profiles and their position relative to the cloud top and

![Figure 13. Effective downward emissivity as a function of liquid water path through cloud top, calculated by the radiation scheme for the three profiles indicated. Stephens (1978b) parametrized form of the emissivity is also shown.](image)
inversion step are important in visualizing the cloud top entrainment process. It is clear that, while there is a small flux divergence within the inversion layer, which in steady state conditions leads to an energy balance between subsidence heating and radiative cooling (see Paper I), the bulk of the infrared cooling occurs in the cloud itself and is due directly to the opacity of the cloud liquid water. The flux profiles are therefore constrained to follow the liquid water distribution, so that if the cloud top is deformed by turrets or gravity waves, the flux profiles will also deform to follow the liquid water. The amount of flux divergence available to initiate the entrainment directly from above the cloud is therefore small, which supports Kahn and Businger’s (1979) arguments that entrainment results indirectly from the motions induced within the cloud by the cloud top flux divergence. It is suggested in Paper II that entrainment may be initiated by wind shear across the inversion/cloud interface, leading to the development and breakdown into turbulence of Kelvin-Helmholtz billows. It is possible that buoyancy fluctuations at the cloud top, driven by the radiative cooling, could themselves supply the necessary wind shear and hence drive the entrainment.

It is also important to note that since the majority of the infrared cooling takes place within the cloud top, this term must be included in the energy budget of the boundary layer, where it makes the dominant contribution (see Paper I).

The cloud microphysical data presented in the previous section show some striking properties. For the two case studies of thick stratocumulus (November 1976 and January 1978) the total number of drops was nearly constant with height, the increase of liquid water content with height being provided by a progressive increase in the mean drop radius, while small scale fluctuations in liquid water content were observed to be related to fluctuations in the total number of drops, the drop-size spectrum being unaffected. Latham and Reed (1977) have described laboratory studies of the evolution of cloud drop spectra following the mixing in of controlled amounts of undersaturated air. They found that changes in the total number of drops and in the liquid water content resulted, while the shape of the drop-size spectrum remained essentially unchanged. This result is inexplicable if the two air streams are mixed homogeneously, as this would lead to a significant reduction in the mean drop size and an increase in the spectral dispersion as the drops evaporate in the now uniformly undersaturated air. If the mixing process is inhomogeneous, however, the new air mass consists of some regions where very little dry air has been mixed in and others where the proportion is much larger and has led to complete evaporation of all the drops. Inhomogeneous mixing therefore removes some drops of all sizes and results in changes in the total number density without affecting the spectrum, which is what Latham and Reed observed. The present observations show similar behaviour and it seems possible that the inhomogeneous mixing process is also operating in these clouds. The effect is most striking towards cloud top which suggests that the two streams being mixed are the cloudy air with the dry inversion air entrained at the cloud top. It is also interesting that evidence for this process is apparent through a considerable fraction of the cloud depth.

Coulman (1978) presented aircraft observations of stratocumulus clouds off the east coast of Australia, which show a marked change in the slope of the wet bulb temperature profile half-way through the cloud. He interpreted this point as a level of buoyancy equilibrium, convective elements above this level being on average denser than the environment, while those below are lighter. None of the profiles obtained during the present study show this property, however, the tendency being for the temperature to follow the wet adiabatic lapse rate. The clouds observed by Coulman were much warmer, were observed during the daytime under very different meteorological conditions and it is possible that a different organisation of the convective motion would account for this apparent conflict. Nevertheless, it is interesting that the liquid water content data presented in Figs. 2 and 10 show a tendency for a transition from the gradual increase of liquid water content with height near the cloud base, to a region of much greater variability in the upper region of the cloud, where the inhomogeneous mixing process appears to be operating.
The total number density of drops in a cloud is determined primarily by the concentration of cloud condensation nuclei (CCN) (e.g., Twomey 1977). If the liquid water content increases with height at about the adiabatic rate and the CCN concentration is constant inside the cloud, the mean drop size may thereby be constrained to increase gradually towards the cloud top. It is tempting to interpret the observations for the two thick clouds in this way, but it would be dangerous to apply qualitative arguments alone and it appears that simultaneous microphysical and CCN measurements are needed to examine the role of the condensation nuclei in the evolution of the drop-size distribution.

As discussed earlier, it is believed that signal baseline fluctuations affected the ASSP performance on the night of 26–27 October 1977, and this accounts for the large disparity between the two liquid water content estimates. Even in the presence of this fault, however, reliable drop spectra were obtained and it also proved possible to reconstruct a liquid water content profile by comparison of the observed and theoretical net radiative flux profiles. The agreement between the liquid water paths implied by the net radiation measurements and those derived from the microwave radiometer data was very good. The ASSP drop spectra and liquid water content profiles for the other two case studies have yielded extremely useful information, although careful monitoring of the instrument diagnostics and an independent estimate of the liquid water content have been shown to be essential.

Acknowledgments

It is a pleasure to thank the staff of the Cloud Physics branch of the Meteorological Office and of the Meteorological Research Unit at Cardington for their help in carrying out the observations. The work of Mr A. N. Bentley on the ASSP is particularly appreciated, as are the criticisms and encouragements of Dr P. Ryder and Dr W. T. Roach during the writing of this paper.

References


