Entrainment in cumulus clouds. I: Thermodynamics and buoyancy

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SUMMARY

Conclusions drawn from thermodynamic composition diagrams are examined in terms of their applicability in real conditions. Displays show the temperature and wet-bulb temperature of samples calculated at 1000 mb. Additional lines show total mixing ratio and saturation pressure. A point giving the composition where there is a minimum of liquid water in cloud can be taken as a saturation pressure point. Such a point can be selected with a PC 'mouse' on the monitor display of the thermodynamic diagram, whereupon the program draws the associated constant virtual-temperature (density and buoyancy) or the constant temperature line.

Buoyancy can then be used to eliminate some sources of outside air as possible components for in-cloud mixtures. Similarly, constant temperature lines associated with constant-altitude-aircraft cloud measurements provide an estimate of the composition which would remain after precipitation removed the condensed water and ice.

Examination of Cooperative Convective Precipitation Experiment data show that many cloud compositions consist of cloud-base air mixed with air remaining from previous clouds. Sometimes this air is from clouds which have precipitated, even though the sampled cloud is not precipitating. Similarly, balloon soundings in clear air may show parcels containing moist patches from previous clouds. Such soundings, not representing air near the cloud under study, cannot be used to give unambiguous information about the level of mixing. Studies based on balloon soundings often suggest that the entrained air originates from above the level where the cloud is sampled, but several claim otherwise. The moist air may be important in radiation studies.

1. INTRODUCTION

Since it became apparent that dry air enters small cumulus clouds from their tops there has been a great interest in seeking direct methods to confirm this phenomenon. Warner (1955) showed that clouds were essentially uniform from side to side (when measured during penetrations perpendicular to the shear direction), thus showing that the source of dry air was not diffusing inwards horizontally from the surrounding air from beyond the vertical sides of the cloud. Warner (1955) also showed that the maximum dilution is at the cloud tops, decreasing downwards towards the cloud base. This has been widely confirmed since by others, thus strongly suggesting that the source of dry air is from above. Squires (1958) studied penetrative downdraughts (Squires and Turner (1962) studied updraughts), and initiated a simple theory on this basis, using a thermal descending from above (see Morton et al. 1956).

This conceptual picture of small cloud growth has been filled out by observations which show that the cloud outline moves upshear relative to the surrounding air (Malkus 1949). Later air-motion measurements show that this occurs as the new cloud grows

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adjacent to the upshear side and the cloud evaporates on the downshear side (Telford and Wagner 1980). When sampled along the shear direction, an isolated small cumulus cloud (say 2000 m or so in depth to avoid heavy precipitation, and preferably everywhere warmer than freezing to avoid ice-driven precipitation processes) has the highest liquid-water mixing ratio on the upshear side. This decreases to about half this value on the downshear side (Mossop 1985; Rogers et al. 1985). The clear air beyond the upshear side is almost free from turbulence and variations in temperature and humidity, while the downshear side has a clear volume about the size of the actual cloud, with turbulence and large moisture and temperature fluctuations comparable with those found in the cloud (Ackerman 1958, 1959; Telford and Wagner 1980). This latter region is former cloud that has been diluted by entrained dry air until the drops have all evaporated. The only part of the cloud where an updraught is consistently found is inside the upshear edge where this new growth is occurring. Other positions in the cloud have either updraughts or downdraughts depending on how the air parcel is responding to the vertical mixing and dilution processes.

This cloud structure has important effects on the microphysics of the cloud particles; this will be discussed in Part II (Telford et al. 1993).

In Part I we discuss the use of the thermodynamic mixing diagram in its application as a tool for determining the origin of the air entrained into clouds (Paluch 1979). This type of analysis has played a very important part in recent cloud-physics studies, but as we shall show it must be used with care because it often appears to have been misinterpreted.

The density of diluted cloud parcels, in addition to and distinct from their previously emphasized composition, is shown to provide important information. Soundings from the Cooperative Convective Precipitation Experiment (CCOPE) are examined, which show that moist cloudy regions remain in cloud-free air after clouds evaporate. We further present data that show that the growing cloud may entrain air that remains from a previous cloud, after that earlier cloud has totally evaporated. This makes the interpretation of the mixing diagram uncertain because, even if the cloud under study is not precipitating, the air which mixes into the cloud could have been the remains from an earlier cloud where precipitation did remove water substance. An example of this is discussed. It is of particular concern where samples come from nonprecipitating cloud, when the freezing process is producing ice in the older part of the cloud. This usually ensures, in this type of cloud, the later formation of precipitation, and water redistribution by particles falling through the air. These changes are quite separate from the composition changes resulting from mixing.

The way a cloud disperses water vapour into the atmosphere is important for two reasons: it determines how the modified air dilutes the later clouds growing in the same atmospheric region, and the increased thermal radiation from such moist air greatly cools it on top; so it is likely to affect both cloud growth and the radiation balance of the atmosphere as a whole.

2. THE USE OF DENSITY WITH THE MIXING DIAGRAM

It is commonly implied that if a cloud does not contain precipitation particles, then the total mixing ratio is that which would result if the air parcels rising through the cloud base were mixed with air of the properties measured at some level in a vertical balloon sounding made in nearby clear air. This assumption, as used for example by Hill and Choularton (1985), will be examined and in some cases shown to be quite unlikely.

In order to show clearly the density of the cloud and its surroundings on a thermo-
dynamic diagram, so that such complex data are easy to visualize, we have chosen a different pair of variables to those usually employed. We use the absolute potential temperature, $\theta_A$, and the moist potential temperature, $\theta_M$, as the two variables representing the air (or cloud) parcels. Since each of the points on a thermodynamic diagram can be expressed as values of pressure, temperature and mixing ratio, they can be replotted on any other thermodynamic diagram, such as that of Paluch (1979). Now all the transformations are monotonic, so any two lines that do not cross on one diagram can never cross on another. Thus sounding points that lie at an increasing distance from a constant density line on the first will similarly, on the other, show an increasing density. This applies to all constant temperature and constant virtual-temperature lines at a given pressure, and to any mixing lines. Relative positions of points are preserved but the scale changes, so some such lines are no longer nearly straight and parts of some diagrams become cramped and the directions may be reversed (Telford and Chai 1993).

The absolute potential temperature, $\theta_A$, is a modified potential temperature that includes the latent heat of cloud water as it evaporates when the pressure increases to 1000 mb (Telford and Chai 1993). The moist potential temperature, $\theta_M$, is close to a wet-bulb potential temperature, but is based on the water evaporated into the air being from a reservoir at the final parcel temperature. This ensures the independence of $\theta_M$ from the initial pressure for all parcels with the same composition (the usual definition uses colder water to saturate the air at colder temperatures). The differences of $\theta_A$ from potential temperature $\theta$, and $\theta_M$ from wet-bulb potential temperature, $\theta_w$, are a fraction of a degree Celsius in subsaturated air, but are very substantial in cloud. $\theta$ is greater than $\theta_A$ by more than 4 degC/m at 1000 mb, and to compare the density differences needed to drive up-and-down motion inside clouds requires accuracies of about 0.1 degC. Both these variables describe the air properties independently of pressure or cloud.

Thus we define the absolute potential temperature, physically, as the temperature after adiabatic compression to 1000 mb, and the moist potential temperature as the wet-bulb temperature of this parcel at 1000 mb. (The calculation of these quantities can be accomplished to good accuracy using the perfect gas laws and a small computer. Any future advances in the gas theory can be incorporated at any time if they are ever shown to be significant.)

The diagram can be plotted using other variables, since $\theta_A$ and $\theta_M$ can be uniquely transformed into total mixing ratio, saturation pressure, and other mathematical combinations of these (Telford and Chai 1993). Only two independent variables are needed. Previous work by Paluch (1979) used total mixing ratio as the ordinate and the wet equivalent potential temperature, but these coordinates compress the graph of the higher altitudes into a restricted region at the bottom of the graph (because of their smaller mixing-ratio range), and the lower altitudes are plotted higher on the diagram and expanded in scale to occupy an unnecessary large area of the graph. Such problems in displaying the data are discussed in detail in Telford and Chai (1993).

On the ($\theta_M$, $\theta_A$) diagram, shown in Fig. 1(a) as seen on a computer monitor screen, these problems are minimized. Four constant density lines are plotted at 700 mb. The constant virtual-temperature lines are for $T_V = 1, 3, 5$, and $7^\circ C$ (at 700 mb), and include both the density of the cloud water and the water vapour. Outside cloud these lines for subsaturated air have an almost constant $\theta_A$, and in cloud they are near to the vertical. Thus the lines for equal steps in $T$ or $T_V$ at specified pressures are almost constant and equally spaced in $\theta_A$ outside the cloud, and inside cloud equal steps in $\theta_M$ occur (with some linear variation in $\theta_M$ as $\theta_A$ changes). Since equal steps correspond to equal steps in $T$ and $T_V$, two such lines at a selected pressure enable other values to be estimated at that pressure. Hence the relative buoyancy of different parcels can be compared visually.
Figure 1. Balloon soundings (small circles) are displayed for Miles City for 6 August 1981, at 1140 h and 1610 h, together with data from two aircraft passes at 1644 h and 1647 h through the cloud. Two constant temperature lines are drawn at 508 mb, with $T = -12.2^\circ$C and $-14.1^\circ$C. A constant density line is also drawn with the same saturation-point temperature, $T = -14.1^\circ$C at 508 mb, and joins points with a constant virtual temperature of $T_v = -13.7^\circ$C.

The constant virtual-temperature line from the 1140 balloon sounding at the aircraft penetration height (508 mb) gives $T_v = -12.4^\circ$C (see Fig. 2).

The curved lines join points at 100 mb pressure increments where just-saturated air would have the same density as a rising parcel from 700 mb. These zero-buoyancy profiles were formed by adjusting constant $T_v$ lines through the lower point at 700 mb to match the successive saturation pressures. The point on the saturation-pressure line then gives the cloud-free air composition of equal density. Such adjustments are accomplished by moving the points on the computer screen with the computer mouse.

On the right diagram, plotting the above calculated zero-buoyancy displays $\theta_a$ for the atmosphere in which a rising cloud parcel would remain about neutrally buoyant. The cloud parcels are just buoyant for the sounding atmosphere, up to the level of the aircraft pass, but not at higher altitudes. All the points on the aircraft passes are close to having the same density, with $T_v = -13.7^\circ$C (as seen on the left-hand diagram). The points with the lower $\theta_a$ come from the less diluted cloud parcels with a composition close to surface air.

without calculation. (Any of these lines can be added to the diagram by the computer, when selected.)

Saturation (with zero liquid water) occurs where these lines bend in direction at the transition from cloud to clear air. In Fig. 1(a) the saturation-pressure lines are almost straight.

3. COMPOSITION IN CUMULUS CLOUDS

A ($\theta_d$, $\theta_a$) diagram is used in Fig. 1(a) and a pressure versus $\theta_a$ diagram in Fig. 1(b) to display data obtained from the CCOPE on 6 August 1981 near Miles City, Montana, USA. The small circles show balloon-sounding measurements from soundings started at 1140 h and 1610 h local time (local time equals gmt minus 6 hours) (no data are available for later soundings), taken about 25 km from the position of the aircraft. The CCOPE data have been extensively used in such studies. Cloud traverses by aircraft at 1644 h and 1647 h are shown by plus signs and crosses respectively. These cloud data were used in previous studies (such as Rogers et al. 1985). The aircraft passes were made at 508 mb, and so using 500 mb as the saturation pressure a constant $T_v$ line has been drawn at $T_v = -13.7^\circ$C through the data. A constant-temperature line (i.e. joining all air parcels whose composition gives the same temperature at this altitude) has also been placed on this saturation point ($T = -14.1^\circ$C). A second constant-temperature line ($T =$
−12.2°C) has been drawn through the neutral buoyancy profile on the 500 mb saturation-pressure line. If precipitation removed water from the cloud, the in-cloud points would rise along such a constant-temperature line near $T = −14.1°C$ up to the saturation-pressure line. (Cloud samples from this day, 6 August 1981, are analysed in Part II in Figs. 4, 6 and 8.) A mixing line has been located through the in-cloud data, and is essentially straight.

Figure 2 uses similar diagrams but three typical mixing lines, and constant mixing-ratio lines have been added to show how they appear. Also the mixing ratio has been included on Fig. 2(b) as a function of pressure. The constant mixing-ratio lines on Fig. 2(a) show how changing temperature by radiative heating, which does not affect the total mixing ratio, can shift a point on the diagram.

Figures 1(b) and 2(b), where $\theta_A$ is displayed on the abscissa as a function of atmospheric pressure, are useful to show how warm the air needs to be for it to rise. The addition of neutral-buoyancy lines gives the absolute potential temperature of a saturated environment surrounding the cloud which would give an undiluted parcel of cloud-base air neutral buoyancy at each level. These lines join just-saturated points at each pressure with the same $T_v$ as the cloud-base parcels at the same pressure. Because the density of the surroundings depends only slightly on the mixing ratio, the just-saturated air at each successive 100 mb level is close enough in density to give a moderately accurate estimate of whether or not the cloud will be buoyant in the given sounding. Lower mixing ratios below saturation at the same temperature would make the cloud parcels slightly more buoyant. On occasions when higher accuracy is needed the difference between virtual temperature and temperature needs to be taken into account.

![Diagram](image)

Figure 2. This diagram repeats the data of Fig. 1 with the addition of constant mixing-ratio lines and three typical mixing lines on the left-hand graph, shown by the '*' symbols. The mixing ratios are displayed on the right-hand graph. The mixing lines are essentially straight and equally divided in mass proportions. All these lines are selectable options in the program and the graph can be redrawn in seconds, and then transferred to hard copy when ready.

The clear-air points outside cloud are almost exactly on this balloon-sounding data on the upshear side of the clouds. When the aircraft penetrated from the opposite direction from the other side, the outside parcels have the composition of cloud parcels from which all the water has precipitated. The data on dew-point, when the aircraft passes from cloud to subsaturated air, is unreliable because of wetting of the instruments, and has been removed before plotting.

All the parcels have approximately the same density. The virtual temperature line is from the 1140 h balloon sounding ($T_v = −12.4°C$), for the same altitude as the aircraft pass at 508 mb.
Allowing some cooling of the rising cloud parcels by entrainment as they grow upwards it is clear that no cloud parcel, for the data of Fig. 1, can be buoyant above 500 mb for the 1610 h sounding.

The wettest in-cloud parcels are just saturated at 700 mb, which corresponds to cloud base. In Fig. 2 compare the mixing ratio of the saturated neutral density lines with the surface mixing ratio of about 7 g kg\(^{-1}\) in Fig. 2(b). In Fig. 2(a) the lowest 1610 h balloon-sounding points lie near the 7 g kg\(^{-1}\) line, on which also lies the warmer neutral buoyancy line at 700 mb. At 500 mb, as seen in Fig. 2(a), the in-cloud parcels are denser than the warmer neutral buoyancy profile (and less dense than the cooler neutral buoyancy line), which is seen in Fig. 2(b) to be at the same temperature as the actual 1610 h sounding at this altitude. Hence all cloud parcels become negatively buoyant after rising to this level. The wettest, least diluted, cloud parcels can be seen to be the least buoyant parcels in the cloud (compare the in-cloud points with the \(T_V = -13.7^\circ C\) line in Fig. 1(a). From the \(T_V = -13.7^\circ C\) line on Fig. 1(a) it is clear that no cloudy parcels are buoyant relative to the warmer, neutral buoyancy, profile (Fig. 1(b)).

The wettest, least diluted, cloudy air lies roughly about the cooler neutral-buoyancy line, the more diluted parcels being slightly more buoyant. Since the sounding is roughly neutrally buoyant relative to the cooler neutral-buoyancy line of Fig. 1(b), these cloudy air parcels are just buoyant relative to the sounding from cloud base up to about 540 mb. Relatively, the wettest cloud air parcels are less buoyant at 500 mb than the \(T_V = -13.7^\circ C\) line, and the more diluted parcels more buoyant.

Cloud dilution which evaporated the drops was, therefore, due to warmer air, with a slightly higher wet-bulb temperature. No air on the balloon soundings meets this requirement near cloud levels.

There was no precipitation in this cloud, observed on the aircraft instruments during the collection of the data, except for small patches, which could not have affected the cloud as a whole. The precipitation was seen only in the older, more dilute part of the cloud, and was of negligible water content compared with the liquid water itself, which was about the same on both sides of the precipitation patches (see Rogers et al. (1985) Fig. 4). Thus this very light precipitation that had started to form in this cloud could not have shifted the composition points significantly on the thermodynamic diagram.

Entrainment in this cloud did not, therefore, produce cooler, less buoyant, parcels at this level, but actually increased the buoyancy where mixing occurred, and the liquid-water mixing ratio was reduced by evaporation. The entrained air must have had a higher \(\theta_M\) than the original cloud air. If the whole of the atmosphere in this region acted this way, descending diluted cloudy parcels would not form to dilute the lower levels of these clouds, and the clouds would fill in to produce a stratus cloud layer (Telford and Keck 1988). We show in Part II that most of the cloud parcels sampled at this level did not descend after dilution, so that up to the time when the samples were taken the clear air diluting these cloud parcels was of about the same \(\theta_w\) as the cloud air itself (i.e. same \(\theta_M\)). Perhaps parcels for which this was not true had already descended below the aircraft path.

These conclusions should be related to the mixing line drawn through the cloud data in Fig. 1(a). Extending this line to the balloon sounding intersects it at 371 mb, but cloud-base air can be seen to follow the density of the cooler neutral buoyancy line in Fig. 1(a) as it rises above 500 mb, where it is almost two degrees colder than the 1610 h sounding above this level. As can be seen in Fig. 1(b), negative buoyancy above 500 mb makes it unlikely that any cloud parcels could ever rise to the 371 mb level, which would be necessary in order to allow such air to be captured in cloud mixtures. If such mixed parcels were able to form they would then need to subside back to 500 mb without further
mixing, to reach the observed level, which does not seem likely. Only in this way could the composition of all the cloud mixtures lie on the required mixing line. Furthermore, cooling with altitude to \(-30^\circ\text{C}\) at 371 mb, for every parcel at the 500 mb level, would very likely produce more ice than the few isolated patches observed.

In Part II three aircraft passes through this cloud are shown as examples, demonstrating, by an entirely different method, that none of these mixed cloud parcels increased in altitude after dilution, or subsided more than a few tens of metres. In Part II in Fig. 4, for 1644 h 6 August 1981, we see the usual pattern, which shows neither detectable rise nor fall. Figure 6 of Part II, for 1618 h, shows a case where the diluted parcels did descend about 250 m in one section of the cloud. This descent is about 25 mb as compared with the 129 mb required for descent from the sounding point. Fig. 8 of Part II, for 1550 h, shows no rise or descent, but a wider scatter in mean drop radius than is usual.

Thus to explain the observed mixtures, moister (almost saturated) air with the density of the surroundings must have been present near 500 mb. We will now discuss how air of such a composition could have been formed near this level.

4. CLOUD REMNANTS AFTER EVAPORATION

Consider a previous cloud in this air mass. Forming from cloud base, parcels would be similar in composition to those forming the present cloud, and lie at the bottom of the cooler neutral buoyancy line drawn from 700 mb \((T_v = -13.7^\circ\text{C})\), as shown in Fig. 1. Some discussion of the dynamics following from density changes due to entrainment is necessary.

Many of these parcels from the earlier cloud will rapidly dilute with subsaturated air similar to that observed in the soundings from near the cloud tops, and then subside towards the cloud base. At this stage the least diluted parcels will be more buoyant and so will congregate near the inversion at 500 mb, until ice-forming processes later generate precipitation, and the whole cloud dissipates. A parcel with the cloud-base composition, raised to 500 mb, will, as the cloud drops are removed by precipitation, move up a constant temperature line on the \((\theta_M, \theta_A)\) diagram. The cloud-composition distribution is actually observed to be nearly parallel to such a constant \(T\) line, in Fig. 1(a). When no latent heat is transferred to the air, as during coalescence drop growth, the temperature will remain constant as the water is removed, except for the specific heat of the cold particles as they descend from above. If the water drops rime, and freeze on a falling ice particle, some latent heat of freezing will be released near or below that level as the particles fall, and the air will become a little warmer (about 1.5 degC maximum is available from latent heat, for this liquid-water content). This will tend to balance the cooling lower in the cloud, because falling precipitation is always cooler than the air, so this effect is partially cancelled.

If the parcels near the top of the cloud remain almost undiluted, as is initially likely because any parcel diluted with air from the sounding would be greatly cooled and descend, they would be slightly heated by the removal of their water as precipitation forms with the ice process. Such buoyancy increases would help them congregate at the inversion near 500 mb. Any remaining water would eventually be evaporated by mixing with the local subsaturated air. Parcels cooled appreciably by mixing will again descend. Thus saturated air will remain in equilibrium with the environment at the inversion. Parcels such as those at \(\theta_M \approx 17.5^\circ\text{C}\) and \(\theta_A \approx 44^\circ\text{C}\) will accumulate at 500 mb, as earlier clouds produce rain and dissipate. It is from this reservoir of saturated air at cloud top that the later cloud shown in Fig. 1 appears to have found air to entrain, and form the diluted mixtures of the composition observed.
Thus the data collected on this aircraft pass show:

(i) air outside the cloud matches the pre-existing soundings. See Fig. 1(a) at $\theta_M = 15.5^\circ C$, $\theta_A = 44^\circ C$,
(ii) unsaturated air mixtures outside the cloud at 500 mb lie between the earlier cloud-modified air reservoir and the pre-existing surroundings ($16.5^\circ C < \theta_M < 17^\circ C$, $\theta_A = 44^\circ C$), and
(iii) air in the cloud consists of mixtures between cloud-base air and the modified air remaining from earlier evaporated clouds ($\theta_M = 17.5^\circ C$ and $30^\circ C < \theta_A < 44^\circ C$).

All these mixtures, both inside the cloud and in the surroundings, have approximately the same density as the pre-existing soundings at 500 mb.

The assumption often used to interpret thermodynamic mixing diagrams, namely that the clouds have entrained air from where the extended mixing line through the in-cloud parcels intersects the sounding found from the balloon ascent (which in this case is at 371 mb and $-30^\circ C$, $\theta_M = 17.5^\circ C$, $\theta_A = 52^\circ C$), appears to be no longer either necessary or correct.

The sample points for this cloud, on 6 August 1981, cluster narrowly near a constant $\theta_M$ line, and in this way are quite different from the widely scattered data observed in the cases discussed later. When such a mechanism is present to produce a relatively narrow line, the observed departures from this line provide a good estimate for an upper limit to the measurement errors. This is rather more reliable than deriving an error from the somewhat speculative estimates about instrumental performance in clouds.

However, the data on the straight line reflect an accumulation of modified air which has been left behind by the precipitation processes in earlier clouds, not a single source for the entrained air detected from a nearby balloon sounding, as has been assumed in the past. In this case it has been trapped at the inversion, where it has been density sorted, which ensures its uniformity. The clustering of the composition of the entrained air, and the resulting line-up of the mixed cloud parcels, thus reflect more the presence of the inversion than some characteristic of the entrainment process.

It should be noted that the subsaturated air above and around a cloud is extremely stable to vertical motions, and so such air can only mix horizontally owing to wind motion and the disturbances from the displacement due to growing clouds. Inside the cloud, however, vertical mixing is easy because the cloud parcels are near neutral in buoyancy. Hence evaporation at the cloud top, which produces relatively small temperature decreases, gives cloud parcels with temperature deficits that maintain negative buoyancy as they descend. Because these cloud particles evaporate, and so cool the parcel as it descends, appreciable distances may be traversed before such diluted parcels lose their negative buoyancy.

5. Other Examples

The next two clouds we discuss show rather different characteristics. However, similar explanations appear to be necessary.

(a) 19 July 1981

The data for 19 July 1981, as can be seen in Fig. 3, show similar features. (An aircraft pass on this day at 1648 h is examined in Part II, Fig. 9.) In this case the balloon sounding has had a very substantial infusion of moisture between 500 and 600 mb, due no doubt to other clouds, before the time (1440 h) closest to the time of the aircraft
Figure 3. Three balloon soundings and two constant-altitude aircraft passes are shown for 19 July 1981 from CCOPE. This displays the very substantial differences in mixing ratio between successive balloon soundings on the same day. While the air density, as approximated by the absolute potential temperature, does not vary by more than a few degrees, except near the surface, the mixing ratio shows remarkable changes. The 1440 h sounding shows a great increase in mixing ratio between 500 and 600 mb. The layer from 700 to 900 mb shows a more uniform mixing ratio at 1440 h. The in-cloud data show little tendency to lie very close to any line which could join two points on the soundings.

The aircraft passes give data matching the 0550 h and 1310 h soundings very well on the upshear side of the cloud at both altitudes. The 1440 h sounding, the closest in time to the aircraft passes at 1620 h and 1630 h, cannot give the composition measured by aircraft near the cloud at 518 mb because there is no way to remove the moisture.

passes (there are no data for later soundings). The air outside the cloud, observed from the aircraft, is, however, essentially unmodified, matching the earlier balloon sounding at 1310 h, but much drier than the later balloon sounding at 1440 h (Fig. 3(b)). Aircraft passes at 1620 h (470 mb) and 1629 h (520 mb) (other passes at 1632 h, 1640 h and 1647 h lie over the same area of the diagram with as much, or more, scatter) show that the air inside the cloud forms a cluster of points for each pass, rather than an elongated distribution suggesting a line. There is no single source of entrained air, with any cloud-base composition, which could produce a line of mixtures to match these points.

The aircraft data gathered at 470 mb (the '+' points) lie in two distinct areas. Outside the cloud the area \( \theta_A = 48^\circ C, 16.5^\circ C < \theta_M < 17.2^\circ C \) is very close to the balloon soundings. Inside the cloud a cluster of points from 17.5\(^\circ C < \theta_M < 18.2^\circ C \) at \( \theta_A = 44^\circ C \) is as close to the constant \( T_V \) line through 520 mb as the one through 470 mb (for the aircraft at 470 mb).

All the in-cloud points at 470 mb are negatively buoyant for all three balloon soundings, as well as relative to the cloud surroundings measured by the aircraft at the same time, at this level. No straight line through these points has end points on soundings able to produce such mixtures.

The observed aircraft data at 518 mb (the '×' points) similarly have a cluster on the balloon sounding near \( \theta_A = 44^\circ C \), and another cluster at \( \theta_A = 44^\circ C, \theta_M = 18.5^\circ C \), with a few points as low as \( \theta_M = 17.7^\circ C \). Again the latter points do not suggest that they are mixtures of cloud-base air with any one air source from a sounding. They are, however, in density equilibrium with the actual soundings.

These distributions probably occur, in this case, from mixtures of air that involve several sources, and remain this way, since the vertical mixing is still underway because there has not been enough time for the stability to remove parcels not close to buoyancy
equilibrium. This probably did occur in the 6 August case discussed earlier. Air is available both from previous cloud activity and the environment. An inversion can collect a variety of mixed parcels that have about the same density as those that can form from the air available. At 470 mb the driest measurements outside cloud from the aircraft match both soundings well.

At 525 mb the aircraft values outside the cloud follow in outline the soundings at 0550 h and 1310 h, before clouds added moisture to the air in the area above the balloon-sounding site (Fig. 3(a)); the site is about 35 kilometres from this cloud.

The changes in the moisture measured in the rawin soundings from 0550 h to 1310 h, and then to 1440 h suggest that the air found by the 1440 h sounding had been modified itself by moisture remaining from some other cloud, so the mixing ratio had been increased from 0.5 g kg\(^{-1}\) to 2.5 g kg\(^{-1}\). In this case, however, similar cloudy-air mixtures did not form near the sampled cloud where the observed air is much drier. The temperature structure of the soundings does not change when the moisture changes, because the cloud parcels tend to dwell where their density approximates the density of the surroundings regardless of mixing ratios. Such gravity sorting within clouds was discussed (with other evidence) by Telford (1975).

Thus the balloon sounding closest in time to the cloud data frequently does not represent the air near the cloud, or entrained into it, and the mixtures within the cloud are not formed by mixing cloud-base air with a single source of subsaturated air from the sounding. While a simple explanation is not apparent, the mixtures in the cloud very likely involve some air modified as in the 6 August 1981 case, together with air from the unmodified sounding near to the sampling level.

Clearly, the use of the 1440 h balloon sounding as a source of entrained air for mixing into the cloud could not give these observed results. This sounding, taken an appreciable distance away from the cloud, has been modified locally.

(b) 12 July 1981

The data for 12 July 1981 are those analysed by Hill and Choularton (1985). We obtained four balloon soundings for this day, at 0557 h, 1319 h, 1440 h and 1610 h, and have used aircraft data from the clear air encountered before cloud entry, and in cloud. Figure 4 shows the balloon soundings.

Unfortunately there were no drop-size measurements for this flight to allow it to be discussed in Part II. There was no sounding between 0557 h and 1319 h reported. As remarked by Hill and Choularton: ‘A very moist layer from 520 to 470 mb contained some altocumulus clouds but not in the vicinity of the cumulus clouds studied’ (the 1415 h sounding (marked ‘*’) has a moist patch between 520 and 470 mb). Their temperature points agree well with the later three soundings given. This moist-layer feature also occurs in these later three soundings.

These data show, in Fig. 5, that this moist patch is not next to the cumulus cloud, since the aircraft samples in the cloud vicinity have a lower \(\theta_A\) than the points with the same \(\theta_M\) on the sounding at 1440 h. As also was the case on 19 July, it is not a moist layer in the sense that it is present all over the area. The 0557 h sounding is much drier near cloud level and agrees with the aircraft data for the vicinity of the cloud. This case is a good example of how the moisture can be highly variable, whereas above the lowest, surface-modified levels, the temperature variations are often relatively small and random. The temperature determines the density, which remains stably stratified, so the moisture remains in place. Approximate static equilibrium prevails over periods of a few hours to keep the temperature and density profile essentially unchanged above the surface layers up to where the moisture penetrates.
Figure 4. Data taken on 12 July 1981. The 1319 h, 1440 h and 1610 h soundings both show excess water vapour mixing ratio around 400 mb, and from 500–600 mb. The 'x' symbols show the data used by Hill and Choularton (1415 h sounding) in their analysis. These regions of moisture probably have resulted from evaporated clouds.

Figure 5. Data from the 0557 h and 1440 h balloon soundings. The aircraft data outside cloud are drier than the 1440 h sounding and so cannot have formed with such air. The 0557 h sounding lies close to that of the air near the cloud and so could have been a source of air for entrainment. The densities outside cloud match the virtual temperatures of the aircraft cloud passes at 484 mb, but the balloon soundings are considerably warmer. The material near the cloud could not be in equilibrium in such balloon soundings. Note that the cloud parcels have the same density as the surroundings at 508 mb for 0557 h, and 505 mb for 1440 h, whereas the cloud was actually at 484 mb, and about 2 degC cooler than the sounding at 484 mb. Also the unsaturated air outside the cloud is extremely stable in the vertical because it moves up and down along a dry adiabat corresponding to a constant $\theta_A$ in an environment where $\theta_A$ increases close to the wet adiabatic slope. Thus unsaturated air near the cloud must be close to static equilibrium. The parcels inside cloud have a substantial scatter and cannot be in buoyancy equilibrium.

In Fig. 5 we show an aircraft pass plotted on the thermodynamic diagrams with the 0557 h balloon sounding to the left, in Fig. 5(a), and the 1440 h sounding in Fig. 5(b). The 1440 h and 1610 h soundings are similar, as can be seen in Fig. 4. The time of the aircraft pass was 1425 h at 484 mb. Two constant density lines (constant $T_v$) have been drawn on Fig. 5(a) to pass through balloon sounding points taken at 484 mb and 508 mb.

All points, except one in-cloud point, lie between the density lines at 484 mb for the sounding, and the cooler 484 mb $T_v$ line passing through the air outside the cloud. The
air outside the cloud is about 1.6 degC cooler than the balloon sounding at 0557 h for the same pressure, but lines up along a constant $T_v$ line, which is 2.4 degC colder than the 1440 h balloon sounding. Relative to the actual surroundings measured by the aircraft, the cloud parcels are buoyant, but not in comparison with either balloon sounding. The line up of the points outside the cloud suggests mixtures formed from environmental air with air from this, or a previous, cloud which is saturated but water free (as was produced by the earlier clouds on 6 August).

There are several anomalies:

(i) The air outside the cloud does not correspond to either of the balloon soundings at the altitude of cloud penetration, 484 mb, and is considerably cooler than either, and drier than the 1440 h sounding. There is sufficient difference in temperature to indicate that these soundings do not represent the air outside the cloud at the same level.

(ii) The aircraft soundings outside the cloud line up precisely, with the same density, from the driest sample to the just-saturated air at 484 mb ($T_v = -11.1^\circ$C). For this to occur, all these samples must be in density equilibrium. For the 1440 h case most of these samples have a composition drier than the balloon-sounding air.

(iii) The in-cloud samples are considerably scattered, and, except for one sample, are less dense and more buoyant than the air sampled at the same time outside the cloud.

(iv) A mixing line fitted by eye through the centre of the in-cloud samples intersects the driest air outside the cloud, which corresponds to air from a level where the pressure is 508 mb at 0557 h, and 505 mb at 1440 h.

The facts (i) and (ii) indicate that neither the 0557 h sounding nor the 1440 h sounding can be representative of the air near the cloud. Because of the line up of the samples outside the cloud, which can only be the result of stable vertical equilibrium and mixtures of a sounding with cloud air, the actual surroundings must have this same density (to produce the same vertical pressure gradient).

Inside the cloud at 484 mb the mixing line shown seems to be as good as any other choice to represent a straight mixing line using only two sources of air. However, the composition requires mixing of air from a level in the soundings at 508 mb (for 0557 h) or 505 mb (for 1440 h, where in addition the air must be drier than for the sounding). Such posulated mixing cannot produce, however, the range of air mixtures found just outside the cloud.

Consider, as a more realistic alternative, a source of air, produced as proposed for the case of 6 August 1981, where a previously raining cloud is thought to have produced the just-saturated air gathered at cloud-top levels in buoyancy equilibrium. Such air is necessary to produce the range of compositions seen just outside this cloud; mixtures of cloud-base air and other air mixed similar to that found outside the cloud can give all the compositions found inside the cloud.

Thus, inside the cloud, the range of buoyancy of the parcels (see the range of $T_v$ of the in-cloud parcels of Fig. 5) shows that the almost straight line composition does not occur in some clouds, and the use of a composition line to find the level of entrainment based on the balloon sounding is not valid. The data show that mixtures could not have formed from the sounding air but require a source far from the sounding. The variation in buoyancy indicated by the range of in-cloud densities seems to be necessary in clouds to promote the vigorous vertical mixing of subsaturated air from above cloud top. This is necessary to create the mixing needed to dilute the cloud to the point where it eventually completely evaporates.
Figure 5(b) shows two density lines for the 1440 h balloon sounding. The in-cloud points are denser than both these levels in the surroundings, which suggests that the area of the balloon sounding is substantially warmer than where the clouds formed.

Thus in-cloud samples aligned along a constant density line seem unlikely to occur unless there is an inversion to stabilize and select parcels of the same density, as occurred with the 6 August case, and such alignment cannot be used in general to deduce information about the level from which the entrained air originates.

In this case (i.e., 12 July, as seen in Fig. 5) the 0557 h balloon sounding, at a distance of 80 km from the aircraft, differs from the 1319 h and later soundings (see Fig. 4) in the same way as the 19 July 0550 h and 1310 h soundings differ from the 1440 h sounding (see Fig. 3). In that region the sounding, found near the aircraft penetration height, shows that the moisture is much larger and varying at 1319 h, 1440 h, and 1610 h. The soundings are also substantially warmer than the air near the cloud. The early morning sounding also shows the cool surface air, which solar heating quickly removes. The moisture, from 800 to 900 mb, decreases at later times. In this case many cloud mixtures are negatively buoyant rather than in neutral equilibrium, indicating that buoyancy equilibrium is not necessarily related to a balloon sounding, and that rapid vertical mixing is still in progress.

However, in general, the mixing process as described in explaining the data shown for 6 August 1981 is also appropriate in this case.

(c) 9 June 1981 and 27 July 1981

The two examples for 9 June 1981 and 27 July 1981 do not fit the idea of a composition due to a mixing line between the air feeding the cloud base and air from any level on the balloon sounding at nearly the same time on the same day.

In Fig. 6(b), for 9 June 1981, the cloud base is at the top of the usual well mixed layer, at about 700 mb, where the sounding is saturated (100% relative humidity); this level corresponds to the point where $\theta_A$ begins to rise. The aircraft penetration of the cloud is at 535 mb. The lowest point on the sounding that could produce this composition when mixed with the warmest surface air (to lower the mixing point as much as possible)
is at 423 mb and -30 °C, whereas the cloud temperature is at -16 °C. As discussed earlier, it is unlikely that the parcels of cloud could have reached this level, entrained environmental air, and then descended again to 535 mb without mixing in further outside air or becoming full of ice crystals. As is discussed in Part II, in reference to its Fig. 6, the drop-size distribution of this sample is somewhat unusual but shows no signs of a large descent after entrainment. The first 3 seconds of in-cloud droplet data, in the driest part of the cloud, are in a region where the cloud is in the process of completely evaporating. The remaining 6 seconds show cloud parcels from a cloud after some descent, but no region that had risen after entrainment.

Figure 7, for 27 July 1981, is interesting because the thermodynamic data line through the data is almost horizontal, and parallel to saturation pressure lines; a composition which cannot be explained by any conceivable mixture of cloud-base air and a point from any likely sounding. These data are also treated in Fig. 4 of Part II. The average drop size in the parcels forms a straight line, with little scattering in the mean radius and a variation of only 6 to 7 μm for concentration changes from 100–450 drops mg⁻¹. Thus these mixed parcels have not descended after entrainment.

As can be seen in Fig. 7(b), the driest parcels are just saturated at the sampling level of 646 mb (compared with the saturated pressure line at 650 mb), and the mean liquid-water mixing ratio is about 0.6 gm kg⁻¹. The \( T_v \) lines in Fig. 7(a) show that \( T_v = 1.7 \) °C on the sounding at cloud level, while the cloud virtual temperatures range from 2.6 °C to 5.3 °C; this cloud would be extremely buoyant if surrounded by this sounding.

Figure 8 shows the neutral buoyancy line for this cloud in a saturated atmosphere. At the cloud level, the dry air of the same density would be about 1.2 degC warmer than this saturated air, as can be seen in Fig. 7(a). So in this case a dry neutral buoyancy line would be about 1.2 degC warmer at its bottom end in comparison with the sounding shown, and, consequently, also with the cloudy material, which would thus all be buoyant rather than partly in equilibrium as Fig. 8(b) indicates. In this case the difference between temperature and virtual temperature is not negligible.

The thermodynamic composition in this case cannot be explained by the assumption that any likely sounding could be the source, quite apart from the appropriateness of this particular sounding. The explanation may involve information not recorded here,

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Figure 7. Miles City sounding for 1444 h 27 July 1981 and aircraft passes at 1601 h at 646 mb. These aircraft data again do not lie along a line between two sounding points. However, in this case, as seen in Fig. 7(b) they do seem to lie parallel to the saturation pressure line at 646 mb, the pressure of the aircraft pass.
such as variation in the feeder flow due to precipitation, or the very low $\theta_M$ at the cloud level may be producing so much cloud evaporation by entrainment that the mixing is occurring so rapidly at this level, as the analysis in Part II shows, that the buoyancy cannot produce growth. Regardless of the true explanation it is clear that the simple mixing-line approach is inappropriate.

6. DISCUSSION

The evidence presented shows that the mixing ratio from balloon soundings changes irregularly after the evaporation of earlier clouds. These earlier clouds bring water to cloud levels to leave a moistened volume (Telford and Wagner 1980) a few times the size of the cloud itself. Consequently, the use of such soundings to deduce the origin of air entrained into clouds is less than conclusive, and occasionally can lead to poorly founded inferences about the level from which the subsaturated air is entrained. Individual case histories are essential in uncovering active mechanisms but they must be interpreted correctly, since the atmospheric data are seldom simple enough for an explanation to be obvious without considering all the circumstances.

The idea that clouds may form in the remnants of earlier clouds has been recognized as a possibility for a long time, and the Mason and Jonas (1974) and Jonas and Mason (1982) models attempted to provide working descriptions of possible consequences of such an occurrence. These studies were, however, unrealistic, primarily because they assumed that, regardless of height within the cloud, the well mixed cloud produced a uniform drop spectra and liquid-water content throughout (see Telford and Chai 1983). This was equivalent to assuming an equal pressure throughout, at all heights, equal to the pressure at the cloud’s centre. However, these present data confirm the basic hypothesis about the source of cloud air, if not the mechanism.

Hill and Choularton (1985) used the data for 12 July 1981 to conclude, contrary to the analysis in this paper, that the entrained air was from below the sampling level. Apart from this, their analysis supported many of the conclusions of the Telford and Chai
(1980) model. This latter paper explored the consequences of the entity-type entrainment mixing (ETEM) process on the development of the drop spectra. However, the ETEM process does not depend on updraught velocity as Hill and Choularton implied, since height alone (and so pressure, not its rate of change) and dilution, determine the water released. Hence big drops are not to be expected in downdraughts as they state, but in diluted parcels that have moved up and down, and perhaps up a second time. Hill and Choularton (1985) found the large drops in diluted parcels to be as expected. However, the entrained air does leave an indication of the level from which entrained air entered the cloud, preserved in the mean radius of the droplet spectra. This effect is discussed in Part II of this paper.

These present two papers, Part I and Part II, draw attention to the processes needed to account for the cloud dilution. While much of the evidence seems to be consistent with cloud-top origin for the entrained air, its composition cannot be inferred as well as is often supposed from balloon soundings. There seems little doubt that rising parcels entrain some outside air on the way up (Blythe et al. 1988), but the important question is whether the cloud-top dilution is dominant in aging the cloud (and maturing the microphysics), as these data suggest. It is clear from this paper that the use of balloon soundings cannot be used to decide such questions. LaMontagne and Telford (1982) used soundings from observing aircraft in close proximity to the clouds.

When water loss through precipitation occurs in previous clouds in the same vicinity, the air remains as a source for diluting later clouds. Mixing with new cloud parcels then provides the composition needed to generate the observed in-cloud air.

Thus, in these cases studied here, the air mixed into the cloud does not come from the extension of the mixing line to where it encounters environmental air inferred from a balloon sounding of the properties needed to allow a two-source mixing process, as previously conjectured. The ideal composition along a straight line, as seen in the cloud of 6 August 1981, appears to have been as much a result of the local atmosphere undergoing earlier precipitation, and density sorting at an inversion near the level of aircraft penetration, as by entrainment. The balloon sounding is not the source of the entrained air.

Apart from this, entrainment and the dynamical mixing it causes still seem to control the microphysical development and the drop sizes. Thus the use of the thermodynamic diagram displaying $\theta_A$ and $\theta_M$, when presented with buoyancy lines, allows more information about clouds to be derived than simply assuming that the source of the entrained air is from a single level derived from a nearby sounding. Such soundings were shown to be inappropriate in examples discussed here. In the case where a single source of entrained air was apparently confirmed, it had in fact originated in previous clouds. It was also the result of density sorting near an inversion, not a single source of air as deduced from a balloon sounding away from the cloud. In Part II another technique, based on the cloud droplet spectra, is presented, which gives, independently, evidence of the level at which entrainment occurs.

It seems likely that when a narrow line is found for the cloud composition on a thermodynamic diagram, the line will be vertical, indicating a constant temperature for all in-cloud parcels.

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