The Role of Cloud Top Entrainment in Cumulus Clouds

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ABSTRACT

The entrainment process and its resultant effects on the microphysics and dynamics within cumuli are not yet clearly understood. This research was undertaken to discover the role which cloud top plays in the entrainment process and to determine whether observed downdraft magnitudes could be explained on the basis of evaporative cooling.

An instrumented King Air research aircraft was used to acquire thermodynamic, microphysical and dynamical data within and near cumulus clouds of the high plains and midwestern United States. Temperature and liquid water content measurements made within the clouds were used to discover the source for any entrained air via a thermodynamic treatment initially pursued by Dufour (1956), and later expanded by Paluch (1979) and Betts (1982). The entrainment source regions found were either at or above the aircraft sampling level in 78 of the 87 cases examined. It was found that the environment within 20 mb of cloud top was the source for entrained air in these 78 cases. Evaporative cooling could not effectively transport air from above to the sampling level in the nine cases where entrained air from below the aircraft sampling level was measured.

Vertical velocity measurements acquired in the observed clouds were compared with those predicted by evaporative cooling, as suggested by Squires (1958b). It was concluded that evaporative cooling could adequately explain the magnitude of the observed downdrafts in the 51 cases where a comparison between the predicted and observed downdraft magnitude was possible.

1. Introduction

The existence and basic physics of cumulus convection was initially explained via parcel theory. A clouds' parcel theory temperature and liquid water content as a function of pressure may be found by conserving its entropy and water substance during lifting (see Irmane and Godsen; 1973). The resultant temperatures and liquid water contents will be referred to as the adiabatic values.

It was found that cloud–environment interactions were important, as measurements within cumulus clouds became available in the mid-1940's. Three models evolved from laboratory tank experiments to quantify the interactions between cumuli and their environment. Jet or plume models such as those of Stommel (1947, 1951), Morton et al. (1956) and Squires and Turner (1962) envisioned cumuli as vertical jets of air mixing laterally with their surroundings. Bubble models such as those of Scorer and Ludlam (1953), Malkus and Ronne (1954), Levine (1959) and Hall (1962) hypothesized cumulus clouds to be spherical bubbles of air that entrained while rising through their surroundings. The third type of model envisioned cumuli to be composed of a plume-like lower portion capped by a spherical bubble. This was really a merging of the jet and bubble models and is exemplified by the work of Turner (1962). Entrainment was envisioned to occur along the sides of a growing cloud in these treatments.

The measurements of Sloss (1967) did not support the basic plume model predictions of an inverse cloud-diameter-to-height relationship. Later observations by McCarthy (1974) did support the side entrainment hypothesis in a limited number of midwestern cumuli. Warner (1975) disputed the McCarthy (1974) findings primarily because temperature within cloud and in the near-cloud environment was not well known. Irrefutable evidence supporting the notion of side entrainment as the dominant entrainment mechanism in cumuli larger than a few hundred meters in diameter has not been presented.

Warner (1955) measured the liquid water content in a large number of cumulus clouds. He speculated that horizontal entrainment might not be important and that the presence of dry pockets within the cloud might correspond to regions of downdraft. Squires (1958a) used extensive microphysical observations within cumuli to postulate cloud top as a source for entrained air. He suggested that, "most of the dry air may enter by turbulent diffusion through the cloud top." Squires (1958b) demonstrated the plausibility of his previous hypothesis, using a mathematical
model formulated to produce downdrafts via evaporative cooling of previously entrained air.

Telford (1975) used the observations that the ratio of observed liquid water content to the adiabatic value decreased upward in clouds and the horizontal uniformity of liquid water content across clouds to propose a density equilibrium approach. He suggested that, once a cloud stopped rising, each parcel of entrained air within a cloud would tend to seek its own level of density equilibrium relative to the environment. The basic prediction of this model was that cloudy air would be composed of a mixture of environmental cloud top air and cloud base air, in hydrostatic equilibrium with its environment.

Paluch (1979) was able to demonstrate that a portion of the air sampled with a sailplane in several Colorado cumuli originated from above the sampling level. It was suggested that this air could have descended to the sampling level via the penetrative downdraft mechanism of Squires.

The work presented here was undertaken to further test the cloud top entrainment hypothesis of Squires (1958a) and Telford (1975) and to see whether the evaporatively cooled downdrafts predicted by Squires (1958b) were observable in the clouds examined. Not until recently have the aircraft instrumentation become available to adequately test these predictions.

2. Procedures

a. Thermodynamics

The thermodynamics set forth by Dufour (1956) and expanded by Paluch (1979) and Betts (1982) were adapted to yield predictions of temperature and liquid water content for various mixtures of clear and cloudy air. The saturation point technique developed by Betts (1982) was conceptually more elegant. That of Paluch (1979) offered the advantage of a temperature and total water content which were conserved for moist adiabatic processes. The technique used here allowed the convenience of predicting the observable variables (temperature and liquid water content) for different mixtures of clear and cloudy air.

The essential assumptions, common to the technique used in this study and the treatment of Dufour (1956), are as follows:

1) The cloud is initially composed of saturated air and liquid water.
2) The surrounding air is composed of humid non-saturated air.
3) The mixed parcels of environmental and cloudy air form a closed system.
4) The transformations within the closed system are adiabatic.

Assumption 1) precludes the existence of ice in the model cloud. A small amount of ice in a cloud is tolerable, provided it does not significantly reduce cloud liquid water content. Assumptions 3) and 4) exclude precipitation size particles within the cloud. Such particles could add or remove mass and sensible heat from the closed cloud-entrained air system.

The adiabatic temperature and liquid water mixing ratio at any sampling level within a cloud can be found. The mixing of different portions of environmental air into the initially undilute cloud at any entrainment level will serve to dilute these quantities.

The mixing was accomplished in the following way. A hypothetical entrainment parcel outside the model cloud with pressure, temperature and vapor mixing ratio \( P', T' \) and \( r' \), respectively, was chosen. This parcel was then moved reversibly and adiabatically to some sampling level \( P \). The vapor mixing ratio of the entrained parcel remained constant while the parcel temperature changed according to the Poisson relation

\[
T(P) = T(P')[(P/P')^{0.286}],
\]

where 0.286 is the ratio of the dry air gas constant to the dry air specific heat at constant pressure. This process is depicted in Fig. 1a.

Next, a hypothetical cloud base parcel with pressure \( P_c \), total water mixing ratio \( r_{tot} \) and temperature \( T_c \) was selected. It was also moved reversibly and adiabatically to the sampling level \( P \). This parcel's vapor mixing ratio also remained constant. Its temperature obeyed the Poisson relation derived from Eq. (1) by substituting the appropriate temperatures \( T_c, T, P_c \) and \( P \). This process is depicted in Fig. 1b.

The two parcels were then proportionately mixed with one another. Neglecting specific heat variations with temperature, the result was

\[
\tilde{T} = [T_c + k_c T(P)]/(1 + k_c),
\]

\[
\tilde{q} = [(r_{tot}/(1 + r_{tot})] + k_c (r'/1 + r')]/(1 + k_c),
\]

where \( T \) is the temperature of the mixed parcel, \( \tilde{q} \) is the specific humidity of the mixed parcel, and \( k_c \) is the proportion of entrained air.

If \( k_c = 0 \), no entrainment was allowed. If \( k_c = \infty \), the model cloud was replaced by entrained air. This process is depicted in Fig. 1c for \( k_c = 1 \). The mixing was irreversible. Telford (1975) demonstrated that this irreversibility resulted in a temperature deficit of less than 0.0005 K under typical conditions.

At this stage the mixed parcel with temperature \( \tilde{T} \) and vapor mixing ratio \( \tilde{r} \) remained subsaturated but could contain liquid water. A reversible wet bulb process at constant pressure was performed to overcome this. This is represented by

\[
T_{wet} = \tilde{T} + (L_v/c_p)[\tilde{r} - r_c(T_{wet})],
\]

where \( T_{wet} \) is the wet bulb temperature, and \( r_c(T_{wet}) \)
Fig. 1. The thermodynamics of mixing on a skew $T$-log $P$ diagram. In (a) an environmental parcel is transported reversibly and adiabatically to the sampling level. In (b) a cloud base parcel is transported reversibly and adiabatically to the sampling level. In (c) the two parcels are mixed proportionately. In (d) a wet-bulb process is performed to evaporate excess or condense additional liquid water.

The saturation vapor mixing ratio at the wet bulb temperature. The values for $T_{wba}$ and $r_s(T_{wba})$ were found by iteration.

The amount of liquid water remaining in the mixed parcel after the constant pressure wet bulb process was found by recalling that the total water mixing ratio ($r_{tot}$) must be conserved. This gives

$$r_f = \bar{r} - r_s(T_{wba}),$$

where $r_f$ is the final liquid water mixing ratio.

This process is approximated in Fig. 1d where an adiabatic wet bulb process is shown. The final temperature $T_{wba}$ and liquid water mixing ratio $r_f$, shown in Fig. 1d will be nearly identical to those found using the more realistic isobaric wet bulb process. Eqs. (1)–(5) can be used to predict the temperature ($T_{wba}$) and liquid water mixing ratio ($r_f$) at any sampling level due to entrainment at some source level.

The hypothetical mixing processes used in the model do not occur in real clouds. A more realistic, but numerically more complex, series of events is the one described by Squires (1958b). It was found that using the more physically realistic process of entrainment at cloud top followed by mixing, evaporative cooling and subsidence to a sampling level produced no detectable difference in the calculated temperatures and liquid water contents. The numerically simpler calculations were used in this work.

A series of predictions for temperature and liquid water content may be made by selecting an entrainment level and varying the proportion of entrained air. Fig. 2 shows an example of this procedure. A hypothetical cloud base pressure (740 mb) and temperature (7.9°C) were chosen. Then a sampling level was selected (595 mb). The center of the box in the upper right portion of the graph represents the resultant adiabatic temperature and liquid water content (271.9 K, 2.4 g m$^{-3}$). The lines emanating from this point represent the predicted dilution achieved by mixing different amounts of cloudy and environmental air from selected entrainment levels. These curves are similar to the water saturated portions of the mixing lines described by Betts (1982).

The curve labeled 500 represents the predicted temperature and liquid water content reduction produced by mixing environmental air from 500 mb with cloudy air at that level, and then bringing the mixed parcel to the sampling level. The dilution achieved by mixing one part adiabatic cloud air with one-half
part environmental air is achieved by following down the curve labeled 500 from the adiabatic value to the first small cross. The next small cross represents the mixing of one part adiabatic cloud air with one part environmental air. The other curves labeled 460, 480 and 520 depict the same procedure for source regions of 460, 480 and 520 mb, respectively. Dilution of an adiabatic cloud by its surrounding environment will produce cooling and drying within the cloud if the mixture remains saturated.

The box surrounding the adiabatic temperature and liquid water content in Fig. 2 represents the resultant error in this estimate produced by the uncertainty in cloud base pressure and temperature. The uncertainty in adiabatic temperature (0.2°C) was produced, predominantly, by the estimated inaccuracy in cloud base temperature (0.5°C). The uncertainty in adiabatic liquid water content (5%) was produced, predominantly, by the estimated inaccuracy in cloud base pressure (2 mb). Similar boxes bounding the uncertainty in adiabatic temperature and liquid water content will appear during succeeding uses of this technique.

The variations resultant from 1) inaccuracy in environmental temperature (0.5°C) and 2) inaccuracy in environmental humidity (10%) are shown in Fig. 3. The errors in both predicted temperature and liquid water content were increased at greater dilutions. Variations in predicted temperature as large as 0.2°C were observed at the greatest dilutions. Liquid water content variations less than 0.15 g m\(^{-3}\) were observed at the greatest dilutions.

It was the intent of this study to compare the prediction curves with observations of temperature and liquid water content made at different sampling levels within cloud. Several potential patterns may exist in the observations.

Consider Fig. 4a. Here, a hypothetical pattern of temperature and liquid water content measurements within cloud have been overlaid on Fig. 2. All the observations are characterized by nearly adiabatic values of temperature and liquid water content. One might conclude here that this cloud was undiluted by environmental air.

Next, consider Fig. 4b. Here, a different possible pattern of measurements have been superimposed on Fig. 2. All the observations have undergone significant and nearly equal dilution. The origin for the air entrained to produce this mixture is not one level but a larger region bounded by 460–520 mb.

Yet another pattern of measurements is presented in Fig. 4c. The range of dilutions undergone varies from none to enough to completely eliminate liquid water in the cloud. The data all fall between the 480 and 500 curves. This would mean that the source for the entrained air was in the environment between 480 and 500 mb.

b. Dynamics

The equation of motion for a parcel of environmental air immersed in a cloud near its top and subject to evaporative cooling is adapted from Squires (1958b) as

\[
dw/dt = [(T_0 - T_{ve})/T_{ve} - r_j]g - k(w - w'),
\]

where

- \(T_{ve}\) virtual temperature in the environment
- \(w\) vertical velocity of the parcel
- \(r_j\) liquid water mixing ratio
- \(w'\) vertical velocity of the adiabatic cloud
- \(k\) rate of mixing
- \(T_e\) virtual temperature of the mixing parcel (including liquid water).

Pressure field disturbances and the Coriolis force were neglected, following the Squires (1958b) approach.

The trajectory and vertical motion history of an entrained parcel may be computed using Eq. (6). This will allow an estimation of the time necessary for a previously entrained parcel to reach a sampling level. The vertical velocity of the entrained parcel upon reaching the sampling level can also be predicted. The following restrictions were applied to this technique:

1) The mixing rate \(k\) was set to 0.001 s\(^{-1}\).
2) The vertical velocities \(w\) and \(w'\) were set to 0 at \(t = 0\).
3) Parcels of air below cloud base were given an artificial temperature excess (0.5°C) at \(t = 0\).

A sensitivity test of the model to the parameter \(k\) was carried out. The bulk motions predicted by the
model were insensitive to changes in $k$ in the range 0.0005 to 0.002 s$^{-1}$. The parameter $w'$ was set to zero. The values for $k$ and $w'$ were found appropriate after testing the model under the following criteria:

- desire to just maintain saturation of the parcel being mixed;
- desire to achieve the greatest penetration depth possible.

The first criterion was considered important since subsaturated regions within cumulus clouds have not been observed either by previous workers (see Squires; 1958a) or in this work, except at isolated points. The
Fig. 4. As in Fig. 2, but with observations from (a) an unmixed cloud, (b) a cloud diluted by 50%, and (c) a cloud diluted in the range 0-75%.
second criterion was used to establish the maximum penetration depths and largest downdraft speeds that could be generated using evaporative cooling.

The integration process began as a motionless environmental air parcel was immersed in an adiabatic cloud at some pressure level. The parcel was then proportionately mixed with the adiabatic cloud until saturated, using Eqs. (1)-(5). The resultant virtual temperature $T_v$ and liquid water mixing ratio $r_f$ were used in Eq. (6).

A numerical integration of Eq. (6) was next performed. This was done using the finite difference scheme of Petersen and Uccellini (1979). Integrating once in time produced the vertical velocity of the parcel. This step was repeated at 10 s intervals for 20 min. The parcel vertical velocity as a function of time resulted.

Fig. 5 is a sample of the results of integrating Eq. (6). It is a plot of pressure versus vertical velocity. The family of curves shown are the results of following the trajectories of numerous parcels initially at selected pressure levels and plotting their vertical velocity at 10 s intervals for a 20 min period. For example, a hypothetical parcel immersed in a cloud at 300 mb would have a vertical velocity of roughly $-13 \text{ m s}^{-1}$ when it reached 400 mb.

It was suspected that errors in estimating environmental temperature and humidity could affect the predictions of the dynamic model. Repeated test runs were made while varying the environmental temperature and humidity within their stated errors (0.5°C and 10%). It was found that the model predictions were essentially unchanged when the errors in environmental temperature and humidity were included.

The dynamical model was sensitive to the buoyancy deficit produced between cloud and environment by evaporative cooling. The observational errors in temperature and moisture could have resulted in much larger differences in downdraft magnitudes than were found. The resultant average error was reduced by integrating over a significant depth.

3. Experimental data

Observations included in this work were collected as a part of the Hlgh PLains EXperiment (HIPLEX),

<table>
<thead>
<tr>
<th>Variable</th>
<th>Instrument</th>
<th>Accuracy</th>
<th>Response recording</th>
<th>Availability</th>
<th>Limitations</th>
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<td>Temperature</td>
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<td>Humidity</td>
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<td></td>
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<td></td>
<td>rawinsonde</td>
<td>±10%</td>
<td>—  — 1978–80 advection in time and space</td>
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<td>Liquid water</td>
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<td>±20%</td>
<td>1–2 s 1 s 1978–80 drops &lt; 30 µm diameter</td>
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<tr>
<td>Liquid water</td>
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<td>±20%</td>
<td>&lt;0.1 s 0.1 s 1980 drops &lt; 45 µm diameter</td>
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<td>Hydrometeors</td>
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<td></td>
<td>2D-P</td>
<td>—</td>
<td>—        — 1978–80 200–6000 µm</td>
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<td></td>
<td>oil-coated slides</td>
<td>—</td>
<td>—        as needed 1978–80 few samples</td>
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<tr>
<td>Cloud top</td>
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<td>—        as needed 1978–80 within 6 km</td>
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<td></td>
<td>visual</td>
<td>±150 m</td>
<td>—        as needed 1978–80 within 600 m</td>
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<td>—        as needed 1978–80 few samples</td>
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<td>±1.5 m s$^{-1}$ 0.5 s 0.1 s 1978–80 no turns</td>
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and the Precipitation Augmentation for Crops Experiment (PACE). The western Kansas HIPLEX data were collected during May 1978, in a region near Goodland. The southeast Montana HIPLEX data were collected during June and July 1978, and July 1980, in a region near Miles City. The Illinois PACE data were collected during August 1980 in a region near Champaign.

a. Instrumentation

Temperature was measured by a reverse flow device similar to that discussed by Rodi and Spyers-Duran (1972) during 1978 and 1980. A lyman-alpha device was used as a temperature sensor within clouds during 1980.

Two instruments were used to sample liquid water content. A Johnson Williams (JW) hot wire probe was functional during all the flights. A Forward Scattering Spectrometer Probe (FSSP) was also operational during both 1978 and 1980. A period of instrument modifications made the FSSP probe unsatisfactory for liquid water content measurement during 1978.

The observation of environmental humidity using

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**Fig. 6.** The (a) hodograph valid at 1700, and (b) representative sounding valid at 1440 (surface–460 mb) and 1700 (430–140 mb).
the research aircraft was very important for obtaining representative thermodynamic soundings near to the clouds studied. A Cambridge dewpoint system was operated during 1978 and 1980. A lyman-alpha vapor density sensor was available during 1980.

Two ice crystal shadowing probes (a 2D-C and 2D-P), manufactured by Particle Measurement Systems, Boulder, Colorado were used during 1978 and 1980. Ice crystal slides were also taken at intervals during each cloud penetration.

Photographs of the clouds being studied were routinely taken by both the aircraft pilot and onboard scientist. The photos were used to determine the altitude of cloud top using the technique outlined by Boatman (1981).

Rawinsonde launches were routinely made, at times and locations near the research flights. These data were used to supplement aircraft soundings from altitudes above cloud top to about 250 mb.

Specifications for each of these instrument systems are given in Table 1. A more complete discussion of these devices and their associated errors has been given by Boatman (1981).

b. Flight procedures

Flights were designed to make both upshear-downshear and crossshear penetrations of studied clouds. Constant altitude penetrations were made, followed by a descent or climb of ~350 m. Many related types of cumulus clouds were studied. They varied from small post-frontal cumulus congestus to large and extremely vigorous feeder clouds associated with a cumulonimbus complex. Most clouds were of a size (2–6 km in diameter) such that only 3–5 min elapsed between penetrations. The data from clouds which possessed radar echoes were not included in these studies to avoid invalidating the no-precipitation assumption in the thermodynamic model.

Clouds were selected for study based on their appearance, rate of growth, size, and distance from the aircraft. Clouds which had firm, turbulent boundaries and a flat base were good candidates. Those clouds which were growing in size and depth were always preferred. Often, a field of cumuli contained several clouds which were larger and taller than their neighbors. These were sought out. Those candidates which

![Graphs showing liquid water content versus temperature measurements at 0.1 s (10 m) intervals for penntation 1, penetration 2, penetration 3, and penetration 4 of the cloud.]

**FIG. 7.** The liquid water content versus temperature measurements at 0.1 s (10 m) intervals for (a) penetration 1, (b) penetration 2, (c) penetration 3, and (d) penetration 4 of the cloud.
were closest to the aircraft were chosen for study. By the time the aircraft reached the study cloud it had often reached its mature stage and begun to decay.

The result was a sampling of cumulus clouds in all their various phases.

4. Case study results

Eight days (21, 23 May, 2, 15 June, and 8 July 1978; 15 July and 3, 17 August 1980) were selected for case study analysis on the merit of available data. This section gives a detailed discussion of the thermodynamic setting, the predicted versus observed temperature and liquid water content structure, the ice crystal habits and sizes, and the vertical motion structure in the studied clouds. A single cloud was chosen for detailed discussion. It was considered representative of the 30 clouds examined in detail. A summary of the results from the remaining 29 clouds is given.

a. 15 July 1980

A short wave trough was situated just west of Miles City at 500 mb. Cold air advection and divergence at this level aided in the development of a surface cyclone on the remains of a weak cold front trailing down the Montana–North Dakota border.
Data were gathered in an area 130–160 km northeast of Miles City. Two clouds were of particular interest. The latter cloud was seeded with dry ice from the top and its behavior will be examined in greater detail here.

The cloud selected for discussion was a growing mass at 1337, with visibly higher tops than its neighbors. It continued to grow until after the first penetration. Then its top subsided at a rate of $-2 \text{ m s}^{-1}$ during the remainder of the study period. Cloud top reached 470 mb (6280 m, $-19^\circ\text{C}$) at its highest point. This was near the middle of the synoptic-scale frontal zone (see Fig. 6b).

Temperature and liquid water content measurements were made in this cloud using the lyman-alpha instrument and FSSP device. Scattergrams of these measurements from the four penetrations are shown in Figs. 7a–d.

Distinct regions of temperature and liquid water content were present in Fig. 7a. No adiabatic zone was measured but areas with mean temperature and liquid water content values of 264.2 K, 1 g m$^{-3}$ or 263.3 K, 0.7 g m$^{-3}$ or 262.4 K, 0.2 g m$^{-3}$ were observed. The observations all fell within the source layer between 520 and 560 mb. Their clustering indicated a dilution between environmental and cloudy air of approximately 0.5 to 1 (33%), 1 to 1 (50%) or 1.5 to 1 (60%), respectively. The primary conclusion to be drawn from Fig. 7a is that the cloudy air observed at 569 mb was partly composed of air entrained between 520–560 mb.

It is reasonable to assume that some time would be necessary for air entrained above the sampling level to subside to that level. An estimate of this time was attained using the dynamical framework previously discussed. Fig. 8 shows the modeled trajectories of parcels entrained at 520, 540 and 560 mb as their vertical motions are influenced by evaporative cooling. The model predicted that air parcels entrained in the 520–560 mb layer would require 6.5–15.3 min for descent to 569 mb. An entrainment time in the interval 1323:40–1332:30 was found by accounting for this time lag.

Fig. 9 is a pressure versus time graph of the changing altitude of cloud top. Also shown are the times...
and altitudes of each aircraft penetration. The cloud top was near 480 mb at the time of penetration 1.

One can estimate that the top of the cloud ascended in the layer 580–510 mb between the specified entrainment times. The top of the cloud was within 20 mb of the observed source for entrained air during the time when entrainment could have occurred. Thermodynamically, the observations were consistent with cloud top as the source for entrained air.

The dynamic model was used to predict the vertical velocity expected at 569 mb. These predictions are shown in Fig. 10. The plot suggests that air entrained from the environment within the 520–560 mb layer could attain a vertical velocity of $-1$ m s$^{-1}$ upon reaching the sampling level (569 mb).

These predictions were compared with the vertical velocity observations made during the first penetration of the cloud. Fig. 11 is a vertical velocity versus time plot for the interval 1339–1340. An updraft with a maximum of 7–10 m s$^{-1}$ was encountered along the southern third of the cloud. The northern two-thirds of the cloud was composed of weak downdrafts of $-2$ to $-3$ m s$^{-1}$ at this altitude. The least dilute portion of the cloud was within the updrafts. The maximum observed downdrafts were slightly larger than those predicted.

The second penetration of the cloud was made $\sim 2$ min after seeding with a curtain of dry ice pellets. The penetration was made from upshear to downshear at an altitude of 571 mb. Fig. 9 shows that the cloud just reached its highest point during this penetration.

The temperature and liquid water content measurements from penetration 2 are shown in Fig. 7b. Some clustering of those data was still evident. The two primary features of Fig. 7b are the prediction that entrained air originated in the 520–560 mb layer and the repeatability of the measurements when compared to Fig. 7a. This penetration was made nearly perpendicular to the previous one. The entrainment and mixing process was not found to be a function of environmental wind direction in this case.

The dynamical model was used to predict that air entrained between 520–560 mb could reach 571 mb, 6.5–20 min after entrainment. Fig. 9 shows that the top of the cloud was ascending between $\sim 580$–480 mb during those times. The altitude of cloud top was consistent with the observed entrainment level.

Fig. 12 presents the downdraft predictions for the appropriate entrainment source region (520–560 mb). Downdrafts of the order $-1$ m s$^{-1}$ were forecast. The observed vertical motions during penetration 2 are shown in Fig. 13. A majority of the cloud was composed of air with little upward velocity during this penetration. Updrafts of magnitude 7–8 m s$^{-1}$ were encountered during the east-southeast portion of the penetration. The largest negative vertical velocities were $-1$ to $-3$ m s$^{-1}$, near the center of the penetration. The maximum downdrafts were, again, slightly larger than those predicted.

The third penetration of this cloud was begun about 1347. It was made at a heading of 290° (upshear) at an altitude of 570 mb. The temperature and liquid water content measurements from this penetration are shown in Fig. 7c. The clustering from the previous two penetrations was no longer present. Mixing within the cloud, apparently, had destroyed the distinctions between previously entrained eddies.
These data remained consistent with a source region between 520–560 mb. The repeatability of these measurements indicated stability of the entrainment process in time.

The dynamical model indicated that evaporative cooling could force air entrained between 520–560 mb to the sampling level in 6.5–20 minutes. Fig. 9 shows that the top of the cloud was ascending between 560–470 mb during this time interval. Cloud top was associated with this entrainment event.

The predicted vertical motions were the same for this and the previous penetration. Fig. 14 shows the observed vertical velocities. The velocity structure remained essentially unchanged. The upshear portion of the cloud was composed of weak updrafts of the order 0–3 m s⁻¹. The center portion contained a steady updraft with a magnitude of 6–7 m s⁻¹. The downshear portion of the cloud contained air with weak upward and downward motions and much variability at the 10 m level. This is significant in that the mean vertical velocity structure remained in a steady state during at least the period of these two penetrations (4 min). The maximum observed downdraft speed (−1 m s⁻¹) was similar to that forecast.

Ice crystals from the seeding of this cloud were also encountered during this penetration. Fig. 14 shows the region of this cloud where two ice crystal curtains were observed. Also shown is a region of graupel. The two curtains of crystals, as observed with the 2D-C probe, had diameters in the range 100–300 μm. A conclusive identification of their habits was not possible.

An ice crystal slide was exposed in the downshear seed curtain for 5.1 s beginning at 1346:57. Fig. 15 shows a representative portion of that slide. Circles with diameter of the order 20 μm are cloud droplet

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**Fig. 14.** The vertical velocity trace observed during penetration 3 of the cloud. The region of cloud is unshaded.

**Fig. 15.** A representative portion of the ice crystal slide exposed beginning at 1346:57.
impact craters. Unrecognizable irregular pieces are ice fragments from the inlet to the decelerator slide sampling tube. Occasional tiny branched crystals are vapor grown artifacts which occurred after the ice crystal slide was exposed.

The unrime hexagonal crystals at 1, 2, 3 and 4 are samples of the crystal types observed in the downshear portion of the seed curtain. These crystals had diameters in the range 120–200 μm. They were designated type P1a using the classification scheme of Magono and Lee (1966).

The presence of cloud water in Fig. 15 indicated that the observed P1a crystals were growing in an environment with vapor pressure saturated with respect to water. The observations of Magono and Lee (1966) showed that crystals of this habit will grow in water saturated environments with temperatures in the range −12 to −13°C, or −17 to −18°C. In this case the environmental temperature at the time of sampling (1346:57) was −11°C. At this temperature Magono and Lee (1966) showed that thick plates will exist. The crystal labeled 1 in Fig. 16 appears to be transforming into a thick plate. Crystals 2–4 appear as thin plates.

The ice crystals observed at 1346:57 were part of the downshear seed curtain. They were nucleated [according to the calculations of Davis (1974)] 150–200 s before sampling. Descending air must have carried them to the observation level (570 mb). The −12 to −13°C level was near 550 mb on this day (see Fig. 6b). A downdraft of −1.5 to −2 m s⁻¹ would be required for descent to 570 mb in the required 150–200 s of crystal growth.

The source for entrained air during this penetration was within the 520–560 mb layer. The ice crystal observations offered separate evidence that air from at least 550 mb had descended to the 570 mb sampling level at a speed consistent with both prediction and observation.

The two ice crystal curtains expanded in size during the period 1344–1347. At the time of penetration 2 (1344:17) the central ice crystal curtain was confined within the updraft. By the time of penetration 3 (1347:05) the central crystal curtain had diffused into a region of small negative vertical velocities. This showed that air was being exchanged between the cloud updraft and its immediate surroundings. This mixing process was consistent with the observed destruction of the initially clustered thermodynamic measurements.

The last penetration of this cloud was made downshear (heading 110°) at an altitude of 627 mb. Fig. 9 shows that cloud top continued to decay during this time. The pilot made the comment, “The cloud is very thin and we can frequently see the ground.” The onboard scientist reported that cloud base had risen by 1359.

The temperature and liquid water content measurements made during this penetration are plotted in Fig. 7d. The adiabatic temperature (269.7 K) and liquid water content (0.82 g m⁻³) were not approached. The highest temperature (267.8 K) was 2°C colder than the adiabatic, and the highest liquid water content (0.24 g m⁻³) was just 29% of the adiabatic value. The thermodynamic model shows that the source for dilution during this penetration was near cloud base (640–680 mb). None of the air observed at this altitude came from levels above.

In contrast to the first three penetrations of this cloud, entrainment at cloud top was not indicated in this case. Fig. 16 shows that air entrained from above
could not descend to this sampling level via evaporative cooling. These observations indicated that the penetration of cloud top air to a sampling level was contingent upon evaporative cooling as a driving mechanism. They supported the Telford (1975) suggestion that air parcels entrained at cloud top can subside to unique equilibrium levels and no further.

Fig. 17 depicts the observed vertical velocity structure during this penetration. It was characterized as weak. Peak updraft velocities of the order of 1.5–3 m s$^{-1}$ were encountered. A small region of possible downdraft (−1 m s$^{-1}$ maximum) was also noted.

Ice crystals which resulted from the seeding of this cloud were again observed. The entire central portion of the cloud contained graupel. The central and downshear parts of the cloud were occupied by needle and columnar crystals.

The 2D-C device sampled the ice crystals within this crystal curtain. Fig. 18 is an example of the output from this instrument. A majority of the observed crystals were columnar in habit with a c axis ranging between 200–400 μm in size. Intermixed with these crystals was an occasional graupel particle of 600 μm to 3 mm in size.

An ice crystal slide was exposed beginning at 1350:18 for 7.3 s. It was exposed within the overlapping region of graupel and columnar crystals. Fig. 19 is a typical view of a portion of this slide. Two N1c crystals and an N2b crystal are visible. Also seen are some small irregular chunks of graupel.

These ice crystals were sampled in a region saturated with respect to water at temperatures between −7.2 to −5.7°C. The works of Magono and Lee (1966) and Rottner and Vali (1974) have shown that
columnar crystals can exist and grow above water saturation at temperatures in the range −6 to −7.5°C. Thus, the crystal habits observed were consistent with formation and growth near the sampling level (627 mb).

The crystals varied in c axis length from 300–400 μm. Integration of the growth equations given by Davis (1974) for such crystals yields a growth time of 400–600 s. The time available for growth was 500 s, after including the 25 s necessary for dry ice pellets of average diameter 14 mm to fall from 500 to 627 mb. The invocation of downdrafts to account for the observed crystals was unnecessary. This was consistent with the idea that air from above the sampling level was not present during this penetration.

b. Summary

A total of 30 cumulus clouds were studied in detail on 8 days during 1978 and 1980. Penetrations were made through several types of cumulus clouds. A total of 22 penetrations were made through cumulonimbus clouds. Cumulus congestus clouds not retarded in their growth by either a dry layer aloft or an inversion were penetrated on 31 occasions. Cumulus or cumulus congestus clouds capped by a frontal inversion were penetrated 54 times. Cumulus clouds capped by a dry layer were penetrated on 10 occasions.

A principal goal of this research was to discern the predominant source(s) for air entrained by the many large cumuli examined. This was achieved by measuring the temperature and liquid water content within the clouds at intervals as small as 10 m and comparing the measurements with the thermodynamic predictions made, using a technique similar to those of Paluch (1979) and Betts (1982).

Fig. 20 is a comparison of the entrainment levels, found using this technique, with the aircraft flight levels, for all the available penetrations. The data were stratified by case study. The major feature of note is that a large majority of the measurements indicated the source for entrained air to be at or above the sampling level. This would not be surprising had the flight levels been predominantly near cloud base. However, most of the penetrations were intentionally made within the upper third of the clouds. This fact is suggested by the bias toward flight levels above 600 mb. The fact that entrained air from above was observed at the sampling levels is in agreement with the findings of Paluch (1979).

On two days, 15 July 1980 and 5 August 1980, the source for entrained air in some of the clouds studied was found to be near cloud base. One of these penetrations was presented in greater detail during the previous case study discussion. It was found that evaporative cooling was not sufficiently vigorous to drive air entrained from above to the sampling levels in these cases. This was consistent with the density equilibrium argument of Telford (1975).

A dynamical model based on the work of Squires (1958b) was used to predict the time necessary for air entrained at any particular level to be transported to a sampling level via evaporative cooling. An estimate

![Graph](image_url)

**Fig. 20.** A comparison of the entrainment levels with the aircraft flight levels for each penetration from 1978 and 1980.
of the time when entrainment occurred was obtained for each penetration by subtracting this transport time from the time of observation. The results of Fig. 20 were transformed into a comparison between entrainment altitude and observed cloud top altitude by noting the cloud top altitude at the estimated time of entrainment.

Fig. 21 is a graph of the entrainment pressure versus the observed cloud top pressure for all the available penetrations. It is evident that the observed entrainment pressures corresponded well with the observed cloud tops in these cases. Not only was an overall consistency present, but each case study was seen to be consistent with cloud top as the source for entrained air.

A second goal of this research was to test evaporative cooling as the physical mechanism responsible for the downdrafts observed in the clouds studied. The results from the penetrations made through one cloud were shown in the previous section. A comparison of the predicted and observed maximum downdraft speeds was also made for the remaining cloud penetrations from 1978 and 1980.

The outcome of this comparison is shown in Fig. 22. Here, the predicted and observed maximum downdrafts from each available cloud penetration are plotted against one another. Only a portion of the 117 cloud penetrations made as a part of this work were acceptable for this comparison. This was primarily because the vertical motion sensing system was inoperative during part of 1978. However, a few of the clouds studied contained a sufficient amount of ice to invalidate the dynamical model used.

The maximum downdrafts observed were adequately predicted by the dynamical model. This model was designed to predict the largest downdraft magnitudes which could result through evaporative cooling. Fig. 22 indicates that the model slightly underpredicted the downdrafts, at the smallest speeds.

It was found that as the proportion of ice to cloud water in the clouds increased, the ratio of observed to predicted downdraft speed also increased. Precipitation loading of the downdrafts by ice was one explanation for the underprediction.

The dynamical model was designed to yield an upper limit to the magnitude of the downdrafts produced by evaporative cooling. The agreement between model predictions and the maximum downdrafts observed was surprisingly good. This could mean that the assumption of a water saturated downdraft not retarded by updrafts was appropriate in the clouds studied. Indeed, water subsaturated regions were not observed at the scales examined (10 m).

Compensating vertical motions were not included in these analyses. A minority of the clouds studied, because of their size and location, could have been affected by these motions. The consistency of the assembled observations would indicate that compensating motions were not significant to the entrainment and evaporative cooling phenomenon examined. The insignificance of external compensating motions to these observations lends credence to the Emanuel (1981) similarity formulation. Failure to observe unsaturated downdrafts contrasts with his suggestions. Additional observations are necessary to assess the validity of the Emanuel (1981) approach.

5. Conclusions

This research was undertaken to test the cloud top entrainment hypothesis of Squires (1958a) and Telford (1975), and to see whether the evaporatively cooled downdrafts predicted by Squires (1958b) were observable in the clouds examined.

A thermodynamic model similar to those of Paluch
(1979) and Betts (1982) was developed which could predict the temperature and liquid water content within a cumulus cloud under different mixing conditions. This model was used, together with observed cloud temperatures, liquid water contents, and a representative atmospheric sounding, to discern the source(s) for entrained air within each cloud.

A dynamical model similar to that of Squires (1958b) was also created to predict the subsidence time and vertical velocity attained by entrained parcels under the influence of evaporative cooling. The predictions from this technique were compared with the downdraft magnitudes observed within each cloud.

Intensive studies were made of the clouds penetrated on eight different days during the summers of 1978 and 1980. Some 17 cloud penetrations over western Kansas, 59 penetrations above southeast Montana, and 41 penetrations over central Illinois were examined. Isolated cumulus, cumulus congestus and cumulonimbus clouds with diameters in the range 0.1–14.3 km and thicknesses between 0.8–6.4 km were studied. Data quality and completeness allowed detection of an entrainment source region in 87 of these penetrations and downdraft comparisons in 51 cases.

The entrainment source regions found were either at or above the aircraft sampling level in 78 of the 87 cases examined. The environment within 20 mb of cloud top was the source for entrained air in these 78 cases. It was also found that evaporative cooling could not effectively transport air from above to the sampling level, in the nine cases where only entrained air from near cloud base was measured. It was concluded that, in cases where evaporative cooling was an effective downward transport mechanism, entrained air observed within the clouds was originating near cloud top. Air originating near or below cloud base was observed in the remaining cases. These results supported the suggestions of Squires (1958b) and the discussions of Telford (1975).

It was also concluded that evaporative cooling could adequately explain the magnitude of the observed downdrafts, in the 51 cases tested. This was consistent with the suggestions of Squires (1958b). Downdrafts in the range 0–12 m s⁻¹ were sampled.

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REFERENCES