Entrainment and Detrainment in Numerically Simulated Cumulus Congestus Clouds. 
Part III: Parcel Analysis

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ABSTRACT

This paper is the third in a three-part series in which a three-dimensional numerical cloud model is used to simulate cumulus congestus clouds. The authors conduct a detailed parcel trajectory and conserved variable analysis of the modeled clouds, with the principal goal of understanding the mechanisms associated with entrainment and detrainment.

At any point in their lifetime each of the modeled clouds contains multiple thermals that become detached from the boundary layer as they ascend. Undilute regions of subcloud air occur within the simulated clouds at all levels up to the cloud top. In the upper portion of the clouds, such air is found within small (compared with the overall width of the cloud) thermals that are continually eroding yet vigorously ascending. Such thermals are responsible for most of the entrainment and detrainment. Environmental air entrained by ascending thermals is shed in the wake of the thermal, which contains dilute cloud-base air moving at low velocities. There is no evidence for thermals ascending through the remnants of their predecessors as a favored means for new cloud growth. The source of entrained air within both updrafts and downdrafts is typically a few hundred meters above the observation level (although there is a tendency for updrafts at the highest levels to entrain air from just below that level).

Undilute cloud turrets tended to overshoot their level of neutral buoyancy by a considerable distance. Condensate loading triggers the collapse of individual turrets, with additional reductions in buoyancy resulting from the evaporative cooling due to entrainment as well as the transport of entrained environmental air upward. Strong, narrow downdrafts develop along the top and edges of overshooting turrets. These downdrafts are often marginally saturated (which would be the most dense mixture of two air masses) and are composed of a mixture of cloud-base and cloud-top air. They descend to mid levels within the modeled clouds before being detrained laterally.

1. Introduction

This paper is the third in a three-part series that seeks to understand the dynamics of entrainment and detrainment in numerically simulated cumulus congestus clouds. Part I (Carpenter et al. 1998a) described the modeling technique and presented general results for modeled and observed clouds, the latter of which formed in a summertime environment over the Magdalena Mountains of New Mexico. Part II (Carpenter et al. 1998b) discussed the time-averaged properties of the clouds and their effect on the environment as determined from budgets of mass and moisture. We focus here on the detailed analysis of individual cloud elements and present a conceptual model of cumulus convection.

The idea that cumulus clouds entrain air from their environment was first put forth by Stommel (1947), who envisioned that air entered a cloud through its sides in a process akin to a steady-state jet. Later researchers interpreted cumulus clouds in terms of fundamental fluid systems such as plumes and thermals. Morton et al. (1956), for instance, assumed that plumes and thermals maintain geometric similarity and entrain air at a rate proportional to the vertical velocity as they rise. Conceptual convection models based on thermals were proposed by Scorer and Ludlam (1953) and Scorer and Ronne (1956). Their work, along with other laboratory experiments (Scorer 1957; Woodward 1959), indicated that, as thermals rise, they mix environmental fluid into...
their tops as well as through their wake. Further, Scorer and Ronne noted that, in stratified media, parts of thermals were sometimes shed into the wake; this led to their shedding thermal model.

Recent laboratory experiments have helped refine earlier views of thermals. Sánchez et al. (1989) found that thermals starting from rest entrain ambient fluid at a much smaller rate than do self-similar thermals. This transition from near-field (accelerating phase) to far-field (similarity phase) behavior occurs when the thermal has traveled a distance of about six times its diameter and is thought to explain the presence of undulate cloud-base air in the upper regions of clouds. Johari (1992) found that entrainment occurs as ambient fluid moves in thin sheets around the perimeter of the thermal and enters through the rear. This is in contrast to the classic picture of mixing taking place along the advancing front of the thermal but is supported by passive tracer experiments in cumulus clouds (Stith 1992). Johari also noted the presence of unmixed ambient fluid deep inside the thermal, captured not by small-scale motions along the thermal’s leading edge but by the larger-scale motion set up by the advancing vortical circulation. He concluded that clouds share both near- and far-field properties of laboratory thermals.

In contrast to the lateral entrainment model popular at the time, Squires (1958) proposed that the most likely source of entrained air is the region just above the top of a growing cloud. He suggested that, as clouds grow, they engulf parcels of dry environmental air through their upper or leading edge. Liquid water then mixes into and evaporates and cools the parcels, causing them to descend. Squires termed such descending parcels penetrative downdrafts, and the instability mechanism has come to be known as cloud-top entrainment instability (CTEI). Although Lilly (1968) noted that CTEI may cause the breakup of stratocumulus decks capped by an inversion, numerical experiments (e.g., Siems and Bretherton 1992) and measurements of temperature and moisture in the vicinity of stratocumulus and trade-wind cumulus clouds (e.g., Kuo and Schubert 1988) tend to call into question the importance of that mechanism. Telford (1975) formulated an entrainment theory for small cumulus clouds in which air parcels enter the cloud through the top via penetrative downdrafts and then descend to a level at which they are neutrally buoyant; this stratification of parcels has come to be called buoyancy sorting.

The conserved variable technique developed by Paluch (1979) suggested that air at mid levels of cumulus congestus clouds is a nearly linear mixture of air from below cloud base and near cloud top (assuming a single mixing event between two parcels), thus seeming to confirm the Squires hypothesis. Austin et al. (1985) found only narrow, infrequent penetrative downdrafts, however, and concluded that they do not seem to be the primary means for cumulus entrainment. Further, Reuter and Yau (1987a) and Blyth et al. (1988) found that downdrafts near cloud top in the centers of small, growing cumuli are generally very weak, while strong downdrafts (similar in magnitude to the updrafts) are found along both the upshear and downshear edges of the clouds. Additionally, Taylor and Baker (1991) showed how buoyancy sorting can create a pattern on a conserved variable diagram that mimics mixing between two air masses.

In their study of more than 80 cumulus clouds over Montana, Blyth et al. (1988, hereafter BCJ88) also found that the source of entrained air was generally near the observation level to about 1 km above that level. This led them to propose a conceptual model of entrainment based upon the shedding thermal model of Scorer and Ronne (1956). At the heart of the BCJ88 model is a thermal-like core of undulate subcloud air that gradually erodes as it ascends and mixes with the environment. The ascent ends when the core has been completely eroded or when it reaches a level where its negative buoyancy causes it to stop rising. The circulation generated by the rising thermal forces air downward primarily along the sides of the cloud. The entrained material, shed into a turbulent wake below the ascending core of the cloud, descends to its level of neutral buoyancy (LNB). This shedding thermal model thus does not require the existence of penetrative downdrafts and explains the occasional observation of undulate regions (e.g., Heymsfield et al. 1978). The observation that entrained air sometimes originates at the maximum cloud top (e.g., Paluch 1979) can perhaps be explained by the continued large-scale descent of air after a cloud reaches its maximum height.

We are also interested here in the specific means by which mixed parcels are detrained into their environment, having discussed in Part II the time-averaged lateral mass fluxes of the simulated clouds. Several studies have indicated that detrainment occurs wherever parcel buoyancy decreases with height. Bretherton and Smolarkiewicz (1989), for instance, developed a simple linear gravity wave model that indicates that the efflux of material from the cloud will be a maximum where the buoyancy decreases most rapidly with height. Similarly, using a buoyancy length scale argument, Taylor and Baker (1991) found good agreement in their calculated detrainment fluxes with both observed fluxes and with the stochastic mixing model of Raymond and Blyth (1986). The latter model predicts that parcels aggregate at their levels of neutral buoyancy; hence, detrainment is maximized there. Parcel buoyancy generally decreases most rapidly at that height, explaining the agreement between the two methods.

Our goal is to determine, through high-resolution, 3D numerical simulations, the relative importance of processes such as buoyancy sorting, penetrative downdrafts, and shedding thermals in entrainment and detrainment associated with nonprecipitating cumulus clouds. The methodology of the numerical simulations, as well as analysis techniques used here, is presented.
in the following section. Sections 3 and 4 present detailed results from two nested-grid simulations, while a conceptual model of cumulus convection and concluding comments are offered in section 5.

2. Methodology

As described in Part I, we simulate cumulus congestus clouds using the three-dimensional cloud model of Straka (1989). The model employs a 1 ½-order turbulence parameterization, and we neglect precipitation and treat condensation in a bulk manner. The environment is that observed over the Magdalena Mountains on 9 and 10 August 1987, having a convective available potential energy (CAPE) of about 75 J kg⁻¹ on both days; the corresponding nested-grid numerical experiments are thus termed AUG09 and AUG10. The outer computational grid is 9.6 km in lateral dimension and 7.2 km high with a uniform grid spacing of 150 m; the top and sides are rigid. The clouds develop within a nested grid having a uniform resolution of 50 m. This grid is 4.8 × 4.8 × 6.0 km³ high for the AUG09 simulation and 5.4 km in each dimension for the AUG10 simulation. Rather than directly include the effects of terrain, we force the convection using continuous, non-uniform surface heating, thereby simulating the effects of an elevated heat source. The model’s lower boundary corresponds to the elevation of the surrounding plain (1.9 km). This is reasonable because, in the absence of strong environmental winds (as is true for both the simulated and observed clouds), thermal effects outweigh any mechanical lift provided by the mountains (Raymond and Wilkening 1980).

The simulated clouds are up to 3.6 km in vertical extent (Table 2 of Part I) and undergo episodes of growth and decay on a timescale of several minutes, in agreement with the actual clouds (Blyth and Latham 1993). At any given time the simulated clouds are composed of several thermal-like cores that become detached from the boundary layer. The AUG10 simulation produces the more vigorous cloud (note that cloud activity is present at all times during each simulation), which has a horizontal and vertical extent of 3.6 km and produces a prominent detrainment layer (discussed in Part II) approximately 1.5 km above cloud base. The AUG09 simulated cloud is up to 2.4 km tall, 4.3 km wide, and does not produce a prominent detrainment layer.

Our approach to analyzing entrainment and detrainment relies largely upon conserved variable diagrams and trajectory analyses. The former, developed by Paluch (1979), involves a graphical technique in which two nearly conserved variables—$Q$ (total water mixing ratio) and $\theta_e$ (wet-equivalent potential temperature)—yield information on the source region and relative amounts of air involved in mixing. This technique was used in Part I to examine the observed clouds upon which our experiments are based.

Trajectory analysis is used to examine the origin of air parcels and their time-dependent behavior. These massless tracers are carried along by the wind, with positions computed diagnostically using model data every 60 s. The second-order Adams–Moulton formula with a 1-s time step is used for the temporal integration, along with the parabolic scheme of Clark and Farley (1984) for spatial interpolation. Sensitivity tests indicate that, although the accuracy of the calculation is most strongly affected by the temporal availability of the data, position errors of no more than a few grid points are expected during an integration lasting several tens of minutes. It is important to note that the trajectories are calculated in an Eulerian framework with turbulent and computational mixing and therefore do not necessarily represent the actual paths of real parcels.

In order to understand the evolution of cloud thermals, and in particular, the physical processes involved in the collapse of a turret (e.g., overshooting of its LNB, evaporative cooling resulting from the entrainment of environmental air), we analyze the buoyancy and components of the model’s vertical acceleration acting upon the parcels [Reuter and Yau (1987b) performed a similar analysis in their 2D modeling study.] The buoyancy is presented as $\Delta \theta^*$, which is the difference between the cloudy virtual temperature of the parcel (defined in Part I; includes the effect of condensate loading) and that of the near environment (considered to be horizontal averages of all noncloudy inner grid points).

The model components of vertical acceleration acting upon a parcel are shown in Table I [cf. Eq. (3) of Part I]. The terms are computed by interpolating gridpoint values to the parcel’s location, while the net acceleration ($Dw/Dt$) is computed as the sum of those terms. It should be noted that the distribution of the dynamical forcing into perturbation pressure gradient and buoyancy forces within the model is somewhat arbitrary as it depends

<table>
<thead>
<tr>
<th>A</th>
<th>B1</th>
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<tr>
<td>$\frac{1}{\rho} \frac{\partial p}{\partial z}$</td>
<td>$\frac{g\theta'}{\partial z}$</td>
<td>0.608 g q'</td>
<td>$-g\theta_e$</td>
<td>$\frac{g\theta'}{\gamma \rho}$</td>
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Pressure gradient acceleration | Thermal buoyancy acceleration | Vapor buoyancy acceleration | Condensate loading (drag) | Pressure buoyancy acceleration | Subgrid-scale turbulent diffusion | Computational mixing
on the definition of the base state. Further, the model buoyancy does not explicitly include the mean water vapor content, that effect having been incorporated into the pressure gradient force. Therefore the model buoyancy force is not perfectly analogous to \( \Delta T^* \) (which is a precise measure of buoyancy).

The pressure buoyancy acceleration (term \( B_4 \)) seldom exceeds 1 cm s\(^{-2}\) and therefore is not considered further. An estimate for the maximum magnitude of the subgrid-scale turbulent diffusion (term \( C \)) may be obtained by approximating the term as \( K_M \frac{\partial^2 q}{\partial z^2} \), where \( K_M \) is the momentum eddy diffusion coefficient. On the inner grid, \( K_M \) never exceeds about 7 m\(^2\) s\(^{-1}\) in either simulation, while an upper bound on the velocity gradient is perhaps 2 m s\(^{-1}\) over one grid point. This term therefore never exceeds about 0.6 cm s\(^{-2}\). For the computational mixing (term \( D \)), consider the case of a second-order filter applied at 2\% of the maximum amount for computational stability (see Part I). The computational diffusion coefficient would be a constant 8 m\(^2\) s\(^{-1}\), resulting in mixing comparable to the maximum value of term \( C \). The sixth-order filter used here is much more selective than a second-order filter, however, so that term \( D \) should be no larger than term \( C \). Thus, terms \( C \) and \( D \) are both small and are ignored.

3. Detailed analysis of the 9 August 1987 simulation

We performed trajectory calculations on dozens of groupings of parcels (each containing up to 100 parcels) in the AUG09 simulated cloud in order to understand the processes by which environmental air is entrained into, and mixed air is detrained from, cloud thermals. One such grouping is placed within a strong downdraft and tracked backward and forward in time in order to understand the forces acting upon parcels associated with a representative thermal. Later we examine the role of entrainment near the cloud top by examining the fate of a series of parcels placed in the path of an ascending turret.

We select for analysis a cloud turret 800 m wide that grows rapidly to an altitude above the model surface (\( z \)) of 4.2 km (2.5 km above cloud base). (The visual appearance of the simulated cloud during this period from 320 to 340 min is shown in Fig. 7 of Part I.) Following the collapse of this turret, parameters such as the maximum updraft, downdraft, and cloud water mixing ratio (\( q_w \)), decrease significantly (see Fig. 5 of Part I). A series of parcels is placed within a strong (5 m s\(^{-1}\)) downdraft at 340 min associated with the collapse of the turret; the parcels are then tracked forward and backward in time. Two of these parcels (labeled “A” and “B” in Fig. 1) are selected for discussion because they are representative of the two air masses associated with the turret; although only 50 m apart at 340 min, the parcels have very different histories. Time series of the altitude, vertical speed, and conserved variables (\( Q, \theta \)) of the parcels are shown in Figs. 2 and 3, while Figs. 4 and 5 show the buoyancy and vertical acceleration acting upon them.

Parcel A, which originates in the boundary layer, must overcome a 0.4-K buoyancy deficit upon entering the cloud at 328 min (Fig. 4a; cf. Fig. 8 of Part I); Davies-Jones (1974) and others have noted similar subcloud inversions. The ascending turret containing the parcel is cut off from its source of boundary layer air at 334 min (Fig. 1a), although the air within it remains undilute. The velocity vectors show a classic, if somewhat distorted, circulation commonly associated with idealized thermals. The laterally inward directed wind at \( z = 3.5 \) km is presumably responsible for the notches at both sides of the turret.

Two minutes later (336 min; Fig. 1b), the turret reaches its maximum height of 4.2 km and begins to collapse. Parcel A retains a nearly adiabatic core as it becomes more negatively buoyant (\( \sim 0.8 \) K), suggesting that the collapse of the turret is initially caused by overshooting due to condensate loading (Fig. 4c). Parcel B, initially motionless above the cloud at a height of 4.0 km, is captured by the ascending turret and forced downward. Rather than entering through the side or rear of the thermal, the parcel appears to have been overtaken by the thermal when the thermal was at its maximum altitude, as is often the case for parcels in either cloud (AUG09 or AUG10) that become strong downdrafts. The processes by which the parcel enters the turret are difficult to interpret, as they result from the various model processes of turbulent (subgrid scale) and computational mixing.

The turret has a downdraft of 4 m s\(^{-1}\) on its right side, and the remnant of a vortex is evident in the upper portion of the cloud. A small pocket of nearly undilute boundary-layer air remains in the lower portion of the turret. A penetrative downdraft (3 m s\(^{-1}\)) 300 m wide is evident along the right side of the turret in Figs. 1a,b. Such narrow downdrafts of varying intensity are common in the upper portion of the modeled clouds and form along the edges of ascending cloud turrets as a result of the evaporative cooling of entrained air. (Stronger downdrafts that occurred in the AUG10 case are discussed later.)

It is interesting to note that both parcels are marginally saturated as they descend with the collapse of the turret (339 min; Fig. 1c); such a mixture of air experiences the greatest evaporative cooling and will have the greatest density if buoyancy reversal occurs (e.g., Siems and Bretherton 1992). (Buoyancy reversal is the condition that a mixture of two fluids is denser than either fluid.) Further, the parcels are located on the upper edge of a descending cloud element, where the strongest downdrafts were commonly found. The thermal component (B1) of the buoyancy term dominates the downward acceleration of both parcels, as may be seen by comparing the total buoyancy with the vapor and liquid water drag components in Figs. 4 and 5. Since the par-
The processes acting upon a parcel within the turret may be summarized as follows. A parcel rising within the boundary layer is positively buoyant, although it must overcome a slight inversion near cloud base. As the parcel rises within the cloud, its buoyancy increases because of latent heating, although the parcel eventually overshoots its LNB due to condensate loading. Mixing and evaporative cooling result in strongly negative buoyancy and the parcel plunges downward. After some descent, the parcel finally reaches an equilibrium level and exits the cloud laterally.

In order to further determine the source region for air entrained near cloud top, we place 100 massless tracers in the path of a prominent 800-m-wide rising turret (Fig. 6; not the same turret as discussed earlier). The parcels are spaced 100 m apart within a 1-km horizontal square at a height of 3.9 km at 320 min, which is 200 m above cloud top. (The turret reaches a maximum height of 4.0 km at 327 min.) They are tracked forward in time for 40 min.

Most of the parcels interact with the turret and descend to about $z = 3.0$ km; the maximum descent is 1.5 km. Parcels generally descend in downdrafts during the collapse of overshooting thermals as well as in the...
break of ascending thermals (BCJ88). Most of these parcels remain within the cloud and are at their LNB at 360 min. Thus, detrainment at \( z = 3.0 \) km (and throughout the cloud) is small (again cf. Fig. 2c of Part II).

Parcels A and B in Fig. 1, which compose the strongest downdrafts and are detrained, thus represent a comparatively rare event in the AUG09 cloud.

The bold trajectory in Fig. 6 is interesting in that the environmental parcel is entrained into the edge of the thermal, whereupon it descends a short distance and then ascends in the central region of the thermal. When the thermal collapses it becomes a penetrative downdraft and descends about 900 m into the cloud. The parcel’s downward speed (2 m s\(^{-1}\)) is less than that of parcel B in Fig. 1, which was entrained at the top of the thermal as the thermal began to descend. This parcel therefore represents an event of intermediate intensity between the rapid descent and detrainment of parcel B and the considerably weaker descent of most of the parcels here.

4. Detailed analysis of 10 August 1987 simulation

As noted in Parts I and II, the AUG10 simulated cloud is somewhat more vigorous than the AUG09 cloud, with the cloud top of the former reaching \( z = 5.0 \) km, a peak updraft of 14.5 m s\(^{-1}\), and penetrative downdrafts of up to 9.6 m s\(^{-1}\). Such downdrafts are seen in the model data in the upper portion of the cloud in association with collapsing turrets as in the AUG09 run, although they are stronger and more common in this run. The cloud also produces a prominent detrainment layer about 1.5 km above cloud base, whereas the AUG09 cloud does not. As noted in Part I, this disparity stems in part from the different structure of the buoyancy profiles. As with the AUG09 simulation, the evolution of several cloud thermals was examined using numerous series of trajectory calculations, with the results presented below illustrating the variety of physical behavior.

a. A collapsing turret and penetrative downdrafts

We examine a prominent cloud turret that produced strong penetrative downdrafts upon its collapse. This turret is the most intense (as measured by vertical motion and cloud top height) in the first three hours of the AUG10 run (see Fig. 9 of Part I; Fig. 10a of Part I shows the visual appearance of the simulated cloud at 220 min). The emerging 800-m-wide turret (12 m s\(^{-1}\)), which consists largely of nearly undilute boundary layer air, is visible in the upper portion of the cloud at 219 min (Fig. 7a). The cloud contains multiple thermals, none of which is rooted in the boundary layer at this time. The edges of the cloud mass are characterized by downdrafts of up to 6 m s\(^{-1}\). At higher levels, the gradients in the velocity and other fields are generally

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**Figure 2.** Properties of parcel A. (a) Parcel height (km, solid line). Also shown are the maximum cloud top (dashed line) and minimum cloud base (dotted line). (b) Vertical velocity (m s\(^{-1}\)). (c) Total water mixing ratio (g kg\(^{-1}\), solid line) and cloud water mixing ratio (dotted line). (d) Wet-equivalent potential temperature (K). Bold tick marks denote the times shown in Fig. 1.

**Figure 3.** As in Fig. 2 except for parcel B.
Fig. 4. Time series of buoyancy and other vertical forces acting upon parcel A. (a) Buoyancy (K), determined as the difference between the cloudy virtual temperature of the parcel and that of the near environment. Panels (b), (c) show model vertical acceleration (cm s$^{-2}$): (b) Net acceleration (solid line), vertical pressure gradient force (dashed line), total buoyancy force (dotted line); (c) vapor buoyancy (solid line) and condensate loading (dotted line). Bold tick marks denote the times shown in Fig. 1.

The trajectories of three representative parcels that interact with the turret are also shown in Fig. 7a. They were selected from several massless tracers placed within a penetrative downdraft at 225 min. Parcel A originates in the surface layer and ascends with the turret. Shortly after reaching a height of 4.0 km, it is incorporated into the downdraft. (It later enters another updraft as indicated by the looping trajectory at $x = 4.3$ km.) Parcel B is entrained into the updraft from the buoyancy-sorted turbulent wake region of the cloud at 214 min, while parcel C is nearly motionless initially at a height of 4.0 km.

The turret is at its uppermost extent ($z = 4.4$ km, 3.2 km above cloud base) at 222 min (Fig. 7b), having overshot its LNB by 800 m (see Fig. 12 of Part I). There is little motion in the interior of the turret, and downdrafts are beginning to form along the edges; these descending branches were absent 3 min earlier. The upward motion in the lower half of the plot is from a succeeding thermal. The turret has completely collapsed by 225 min (Fig. 7c), causing most of the upper portion to sharpen, while at lower levels, the updrafts and downdrafts are weaker.

Fig. 5. As in Fig. 4 except for parcel B.

Fig. 6. Vertical cross section showing the starting points (open circles) and ending points (asterisks) of 100 parcels released at $z = 3.9$ km at 320 min and ending at 360 min during experiment AUG09. Three sample trajectories are shown. Shading indicates cloud water within any horizontal column in the y direction at 325 min.
of the cloud to descend. The two downdrafts that were located along the edge of the turret have evolved into strong penetrative downdrafts (9 m s$^{-1}$). All three parcels are ultimately detrained laterally at a height of 2.5 km, which is their LNB.

A horizontal cross section through these downdrafts at 225 min (Fig. 7d) further reveals their narrow size (300 m in diameter) and spatial scarceness. Their structure indicates that the parent turret collapsed in a highly radially asymmetric manner, despite the lack of environmental shear. Although they have a vertical extent of up to 1.0 km (as seen at $x = 5.0$ in Fig. 7c), parcels within them can descend to nearly twice that distance. They are generally not found below about $z = 2.4$ km.

Data from four levels within the cloud and two times are plotted on a conserved variable ($Q, \theta_v$) diagram (Fig. 8a). During the thermal’s ascent phase (220 min), the data lie approximately along a mixing line drawn from cloud base to the region between about 3.3 and 4.0 km. (The shallowness of the cloud has naturally compressed the values toward a single line, thus making it difficult to discern how the source region varies with observation.

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**Fig. 7.** (a) Vertical cross section at 219 min in run AUG10 showing cloud water mixing ratio (greater than 0.01 g kg$^{-1}$ shaded) and vertical velocity (contour interval 2 m s$^{-1}$, zero contour omitted, negative dashed). The trajectories of three parcels are shown, with the starting points (open circles; 190 min), ending points (asterisks; 250 min), and location at the time of the plot (large dots) marked. The box indicates the region plotted in panels (b), (c). (b), (c) Similar to (a), with cloud water mixing ratio, vertical velocity, wind vectors, and parcel locations at the time of the plot (large dots) shown at (b) 222 min and (c) 225 min. (d) As in (c), except a horizontal cross section at $z = 3.3$ km.
Fig. 8. (a) Conserved variable diagram showing model data for saturated parcels from experiment AUG10 at 220–225 min at several heights (labeled). The abscissa is wet-equivalent potential temperature ($\theta_e$, K) and the ordinate is total water mixing ratio ($Q$, g kg$^{-1}$). The solid line represents the near environment (defined by horizontal averages of unsaturated points within the inner grid), with heights (in km) labeled. Model-derived cloud-base conditions are marked with a large cross, the extent of which roughly represents the variability in cloud-base conditions. Cloud-top conditions are indicated on the sounding by an open circle at the observation time, with the range of cloud top during the preceding and succeeding 10 min marked by a bold curve. Arrows indicate the presence of nearly undiluted cloud-base air just below cloud top (see text). (b) As in (a), except saturated and unsaturated points at 220 min and 3.0 km are plotted. Labeled are the saturation curve, below which points are saturated; and the neutral buoyancy isopleth, to the left of which points are negatively buoyant compared to the environment at that level.
level. The problem is even more severe for the AUG09 cloud.) Points at higher levels tend to lie along a slightly steeper mixing line than those at lower levels, suggesting mixing with air from higher altitudes, as found by BCJ88. Nearly undilute cloud-base air (indicated by arrows) is found in the uppermost region of the cloud (3.8 km, or 0.3 km below cloud top). Five minutes later, when the turret is collapsing, the source region of the entrained air is as high as \( z = 4.2 \) km, consistent with the trajectories of parcels within the penetrative downdrafts (Fig. 7b).

A plot of only those points at the 3.0-km level at 220 min (Fig. 8b) more clearly reveals that the source region is 200–500 m above the observation level; BCJ88 observed similar characteristics in Montanan cumulus clouds. Many of the updrafts, and nearly all of the downdrafts, are negatively buoyant, consistent with buoyancy sorting (Taylor and Baker 1991). At still higher levels (not shown), the updrafts tend to entrain air from slightly below the observation level.

b. An isolated turret and the detrainment layer

Following the collapse of the aforementioned turret, the AUG10 cloud was markedly quiescent from 250 to 270 min. During this time the environment was sufficiently capped so that large masses of boundary layer air failed to reach their level of free convection (LFC: cf. Fig. 12 of Part I). From 270 to 300 min, a series of narrow turrets began to push above this level. Here we examine in detail the first of these turrets, which achieves a maximum vertical velocity of 10 m s\(^{-1}\) and rises to 3.7 km (2.4 km above cloud base). (The visual appearance of the turret emerging at 272 min through the cap of the thermal (e.g., at \( z = 2.8 \) km represents the level of maximum detrainment, as discussed in Part II.) Several groupings of trajectories were run, and we have selected two parcels for further study.

Continued surface heating finally produces a coherent mass of buoyant air large enough to rise a significant distance above the LFC before eroding. The turret is fueled by a strong, spatially continuous updraft that extends from near the surface through cloud base at 266 min (Fig 9a). The peak upward velocity is 5 m s\(^{-1}\), with most of the air below the cloud moving upward at speeds greater than 2 m s\(^{-1}\). Time series of various parcel properties are shown in Figs. 10–13. Parcel A is neutrally buoyant during most of its rise through the boundary layer, but becomes negatively buoyant (−0.5 K) as it enters the cloud (Fig. 12a). (This was also noted for the AUG09 cloud.) [The large but opposing pressure gradient and buoyancy forces (Fig. 12b) result from the model’s partitioning of vertical forcing into buoyancy and pressure gradient terms (section 2), as well as the time evolution of the mean conditions. This pattern is also seen in Fig. 4b and was noted by Reuter and Yau (1987b).]

By 270 min (Fig. 9b), the broad (1.7 km) updraft present in the upper portion of the subcloud layer narrows to 800 m as it feeds into the bottom of the cloud, reflecting the increased static stability there. Contours of total water content clearly show that the emerging turret is an extension of the boundary layer. By 273 min (Fig. 9c) the turret is about 600 m wide and has grown to a height of 3.2 km. It is interesting to note that the turret ascends to a height above cloud base of approximately four times this diameter, in general agreement with laboratory studies of Sánchez et al. (1989). The upper portion of the turret remains undilute and contains a strong updraft of 9 m s\(^{-1}\), although it is becoming cut off from the boundary layer.

As with parcel A in the AUG09 cloud (Fig. 4c), condensate loading contributes to the initial deceleration of parcel A here (Fig. 12c). Later, evaporative cooling of the cloudy air due to entrainment and mixing dominates, although another factor is the entrainment and lifting of stable environmental air. Parcel B originates in the environment above the cloud at a height of 3.2 km. Rather than entering through the side or rear of the thermal, it appears to have been overtaken by the thermal and rises with it.

Three minutes later (276 min; Fig. 9d) the turret has attained a height of 3.5 km and has fully developed at its top a toroidal circulation characteristic of a self-similar thermal. [It is interesting to note that a well-developed toroidal circulation was absent in the previously examined AUG10 cloud turret (Fig. 7b). This is perhaps because of the larger diameter of that turret, as well as the fact that the latter is ascending through existing cloud.] Parcel B, along with other parcels (not shown), loops through this cyclostrophically balanced circulation in less than two minutes. At its midpoint the turret is only about 400 m across and is becoming cut off from the lower portion of the cloud; small amounts of undilute air (\( Q = 10 \) g kg\(^{-1}\)) remain, however. The dilute air and low wind speeds (2 m s\(^{-1}\)) found immediately below the cap of the thermal (e.g., at \( z = 3.0 \) km) suggest that the thermal is behaving as a shedding thermal (Scorer and Ronne 1956).

Finally, at 279 min (Fig. 9e) the turret is collapsing (5 m s\(^{-1}\)). Parcels A and B descend and become nearly neutrally buoyant after 290 min, as they are ejected at about 2.8 km into the previously mentioned detrainment layer; we consider this height to be representative of the LNB of actual boundary layer parcels. It is considerably lower than that of hypothetical undilute parcels (about 3.7–4.0 km; see Fig. 12 of Part I). It is interesting to note that, although the maximum height of the turret (3.7 km) agrees well with the equilibrium level of a parcel rising reversibly from cloud base (Fig. 12 of Part I), the agreement is fortuitous. The turret actually becomes diluted by environmental air long before reaching its maximum height and is in fact negatively buoyant at its maximum altitude. It reaches that height only because of the momentum generated during its ascent.
In order to further determine both the origin and fate of parcels within the detrainment layer, we performed trajectory experiments similar to that illustrated in Fig. 6. In one case, 25 parcels are distributed within the cloud at the 2.8-km level and then “released” at 270 min. They are tracked backward and forward for 60 min (Fig. 14). The parcels most commonly originate either below cloud base (1.3 km) or above 2.4 km (Table 2; cf. Fig. 2b of Part II); the maximum height of origination was 3.6 km. This distribution is consistent with mixing between undilute updrafts and environmental air at or near the cloud top. Most of the parcels end up near the 2.8-km level and are ejected laterally from the cloud; the remainder are deposited into a low-velocity turbulent wake region at lower levels in or near the cloud.

5. Discussion

We simulated cumulus congestus clouds using a three-dimensional nested grid model having a 50-m uniform grid spacing. The prescribed environment was that associated with nonprecipitating New Mexican cumulus clouds observed on 9 and 10 August 1987 (Part I). We conducted a detailed parcel trajectory and conserved
variable analysis of modeled clouds, with the principal goal of understanding the mechanisms associated with entrainment and detrainment. Our findings are summarized below and are illustrated schematically in Fig. 15.

Each of the modeled clouds contained multiple thermals at any point in its lifetime. This is consistent with observations of New Mexican clouds (e.g. Blyth and Latham 1993), and indeed animations of the modeled clouds bears strong resemblance to time-lapse photography of actual clouds. Figures 1a and 9c, for example, clearly show evidence of the classic thermal circulation (e.g., Woodward 1959).

Undilute regions of subcloud air were found to occur within the simulated clouds at all levels up to the cloud top. In the upper portion of the clouds, such air was found within small (compared with the overall width of the cloud) thermals that were continually eroding yet vigorously ascending, consistent with the observations of Heymsfield et al. (1978), Jensen et al. (1985), BCJ88, and others. Such thermals were responsible for most of the entrainment and detrainment in the simulated clouds. The thermals formed in the boundary layer as masses of buoyant air became large enough to overcome a slight inversion at cloud base and became detached from the boundary layer as they ascended (Fig. 15a).

Entrainment occurred in these clouds as environmental air was engulfed by ascending turrets (Fig. 15b). The model results suggest that this air entered the thermal by a variety of means: through the ascending cap, through lateral mixing, and through the rear of the thermal after having been swept downward along the lateral edges. Much of the latter appeared to be shed in the
Fig. 12. As in Fig. 4 for parcel A in Fig. 9. Bold tick marks denote the times shown in Fig. 9.

Fig. 13. As in Fig. 4 except for parcel B in Fig. 9. Bold tick marks denote the times shown in Fig. 9.

Fig. 14. Vertical cross section showing the starting points (open circles) and ending points (asterisks) of 25 parcels released at \( z = 2.8 \) km at 270 min and tracked backward and forward for 60 min during experiment AUG10. Two sample trajectories are shown. Shading indicates cloud water content within any horizontal column in the \( y \) direction at 270 min.

Table 2. Height distribution of 25 parcels released at \( t = 270 \) min, \( z = 2.8 \) km, and tracked backward and forward for 60 min during experiment AUG10.

<table>
<thead>
<tr>
<th>Height (km)</th>
<th>Number at beginning</th>
<th>Number at end</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1.3</td>
<td>9 (36%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>1.3–2.4</td>
<td>1 (4%)</td>
<td>8 (32%)</td>
</tr>
<tr>
<td>2.4–3.2</td>
<td>6 (24%)</td>
<td>17 (68%)</td>
</tr>
<tr>
<td>&gt;3.2</td>
<td>9 (36%)</td>
<td>0 (0%)</td>
</tr>
</tbody>
</table>

Wake of the thermal, which contained dilute cloud-base air moving at low velocities ascending through the remnants of their predecessors as a favored means for new cloud growth (Ludlam 1958; Mason and Jonas 1974).

Undilute clouds turrets overshot their level of neutral buoyancy (LNB) by a considerable distance in the AUG10 simulation, while such turrets in the AUG09 cloud failed to reach that level. Thus, there is no correspondence between cloud-top height and the LNB of undilute parcels. Condensate loading triggered the collapse of individual turrets, with additional reductions in buoyancy resulting from the evaporative cooling due to entrainment as well as the transport of entrained environmental air upward; it was difficult to discern the relative importance of these factors, however.

Our results generally agree with experimental and observational evidence that environmental fluid is transported down alongside a thermal in thin sheets, with mixing occurring as the environmental fluid enters the
FIG. 15. Schematic diagram of the life cycle of a modeled cloud turret. (a) Convection begins when a boundary layer updraft becomes organized and penetrates a weak inversion near cloud base. (b) A toroidal circulation develops as the turret ascends and accelerates. Environmental air entrained in this manner is deposited in a trailing wake. Strong downdrafts associated with the turret’s collapse originate either near the top of the turret or in the descending branch of the toroidal circulation (open circles). (c) Downdrafts develop in response to overshooting and are further fueled by evaporative cooling. They descend to their level of neutral buoyancy, which is typically located at mid levels within the cloud. Parcels within strong downdrafts are detrained away from the cloud in a narrow layer.

rear of the thermal (Johari 1992; Stith 1992). The model resolution used here was not sufficient to determine whether mixing might occur along the front of the thermal, however, although examples were seen where environmental parcels were engulfed by the rising cloud top. Our results also agree with the findings of Sánchez et al. (1989), namely, that thermals starting from rest entrain at a small rate, which helps explain how relatively narrow thermals can retain undilute cores. Further, the thermals typically ascended a distance of four diameters and were approaching a self-similar state, with the associated higher entrainment rates, as they neared their uppermost extent (e.g., Figs. 9c,d).

Conserved variable analysis suggests that the composition of most parcels within the clouds can be explained by a single mixing event. The source of entrained air within both updrafts and downdrafts was typically a few hundred meters above the observation level (although there was a tendency for updrafts at the highest levels to entrain air from just below that level). This is in agreement with the notion that the toroidal circulation of ascending thermals is a primary means for entrainment, with the observations by Blyth et al. (1988), and with the 1D modeling results of Raymond and Blyth (1986) and Blyth and Raymond (1988).

Penetrative downdrafts (Squires 1958) formed in the upper portion of the modeled clouds as a result of collapsing turrets (Figs. 1c and 7c,d). The narrowest and strongest of these developed along the edges of ascending turrets that were overshooting their LNB; the intensification of these downdrafts marked the collapse of such turrets (Fig. 15c). Similar structures were observed by Austin et al. (1985) and were modeled by Reuter and Yau (1987b). These downdrafts were stronger than those along the edge of ascending thermals and existed over a greater vertical depth, particularly in the AUG10 cloud. Other strong downdrafts that were not as narrow resulted when environmental parcels were incorporated into the top of turrets that had reached their uppermost extent (Figs. 1b, 9c). Such downdrafts tended to be marginally saturated (which would be the most dense mixture of two air masses) and appear to have developed primarily in response to overshooting (negative buoyancy). This may be compared with Grabowski’s (1993) conclusion that buoyancy reversal is a result, rather than cause, of entrainment.

Parcels within the strong downdrafts were composed of a mixture of cloud-base and cloud-top air. They descended to mid levels within the modeled clouds before being detrained laterally, as predicted by Fraser (1968) and Raymond and Blyth (1986). (The LNB of most mixed parcels was more than 1 km below that of undilute parcels.) The height of the detrainment layer was related to the level at which parcel buoyancy decreased most rapidly with height (Bretherton and Smolarkiewicz 1989). Downdrafts in the AUG10 cloud were stronger, penetrated deeper, and were more frequent than in the AUG09 cloud, resulting in significant downward transport and lateral detrainment in a narrow layer at mid-levels within the cloud; the AUG09 cloud produced a much weaker detrainment layer (Part II). This is perhaps because turrets in the AUG10 case overshot their LNB by a greater amount, resulting in more rapid descent and hence a greater tendency to be laterally detrained.
The presence and strength of detrainment layers was quite sensitive to the buoyancy profile.

The results reported in this three-part series have shed new light on the entrainment and detrainment processes within cumulus clouds. In particular, they have helped to establish that undulate boundary layer air, contained within ascending thermals, is generally found at all vertical levels within cumulus cloud. The shedding thermal model (Scorer and Ronne 1956; Blyth et al. 1988), in which such thermals are responsible for driving the entrainment process, is also largely confirmed. Such thermals erode as they ascend, depositing entrained air in a low-velocity trailing wake. Strong, narrow penetrative downdrafts associated with the collapse of overshooting turrets are also responsible for much of the mixing as well as the lateral detrainment of mass and moisture occurring in narrow layers (Part II).

Many unanswered questions regarding cumulus convection could best be answered by further statistical analysis of modeling results such as these. For instance, the relative contribution to entrainment by shedding thermals (ascent phase) and penetrative downdrafts (collapse phase) is not clear, and the role of strong downdrafts in producing lateral detrainment needs to be quantified. The favored location of entrainment relative to an ascending thermal (e.g., through the leading edge or during transport along the side) could similarly be determined, although higher resolution than was used here would likely be required.

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