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# Structural Analysis of Stratocumulus Convection

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## I. Introduction

In an earlier study (Siems et al, 1989) we found that *explosive* cloudtop entrainment instability (CTEI) is possible only when a parameter defined as $D$ is of order unity, where

$$D = -\Delta\theta_v(\chi^*)/\Delta\theta_v. \tag{1}$$

Here $\chi^*$ is the fraction of environmental air in the exactly saturated mixture of cloudy and environmental air. $\Delta\theta_v(\chi^*)$ is the virtual potential temperature difference of this mixture relative to the unmixed cloud, while $\Delta\theta_v$ is the difference between the unmixed fluids.

Our examination of data from the FIRE project and other data sets leads us to conclude that the enhancement of $D$ is unlikely to ever be sufficient to bring about explosive CTEI under stratocumulus conditions. It therefore appears that cloud breakup occurs via other processes, possibly related to decoupling of the cloud and subcloud layers. To better understand this latter possibility, we have investigated the nature of the turbulent elements and convective motions involved in transport of heat and moisture in cloudtopped boundary layers. We have sought in particular to test the simple conceptual picture of the turbulence which has emerged indirectly or by assumption in previous studies of radiatively driven Sc in which surface fluxes are weak. According to this picture, negatively buoyant thermal or plume like structures descend from the bottom of the radiatively cooled layer near cloudtop, merging to form downdrafts, presumably convective cell edges, within which heat and moisture are transported down. The return flow is broader and pushes up the cloud-clear inversion into hummocks, creating baroclinic torques and rebound momentum at the stratified interface. In the absence of overall shear, these processes should be responsible for entrainment, which is maximum in the intermittent valleys between hummocks. The descending streams are aided in their downward propagation until cloudbase by evaporative cooling, to the extent they remain saturated. Purely evaporatively cooled parcels, however, can proceed downward once they become unsaturated only at the expense of TKE within the layer. This conceptual model has been explored by Nicholls (1989). The situation in the case that shear and/or surface fluxes are important has been documented (Brost et al, 1982) but a similar conceptual picture is not available. Since both were important sources of TKE during the FIRE project, we have investigated the structure of the small scale variability in dynamic and thermodynamic properties in order to construct such a picture. At the time of writing this abstract we have not had time to compare our results to those of Nicholls (1989), but those comparisons will be presented at the FIRE workshop. The emphasis of the work at present has predominantly been on small scale features; however, larger scales are noted throughout.

In this abstract we focus on the following questions:

1) What processes are important in entrainment, where is it maximum and what scales are important? What is the nature of this mixing across the inversion?
2) To what extent are the local dynamics organised by large scale fluctuations in cloud properties? (where here large means greater than ten kilometers or so)
3) Which parcels form the roots of the upward moving plumes/thermals at the top of the lower surface layer, and which form the initial downdrafts at the base of the radiatively cooled layer at cloudtop? What are the roles of radiative cooling, evaporative cooling and surface fluxes relative to mechanical forcing in driving these parcels?
4) Is decoupling evident and to what extent does this affect the circulation?

## II. Research Methods

We have examined 1 and 20 Hz data from the Electra flights made on July 5, 1987. The flight legs consisted of seven horizontal turbulent legs at the inversion, midcloud and below cloud, plus 4 soundings made within the same time period. The cloud deck was thin but solid, for the most part, with three dimensional structure intermittently noted by the flight scientist. Cloudtop was flat, sloping upward to the south west. Cloudbase was quite ragged, with intermittent small cumulus clouds below.

We used the Rosemount temperature sensor and the average of the top and bottom dewpoint sensors, lagged by two seconds, for preliminary temperature and humidity measurements at 1 Hz. The FSSP was working poorly on this day. We therefore used the Johnson-Williams sensor for the 1 Hz liquid water readings. This data was interpolated to 20 Hz data creating a source of error in the liquid water content; however, this error this induces in the total water content and $\theta_v$ is quite small. The noted drift of the JW sensor is also on this order of magnitude. The Lyman-alpha hygrometer was calibrated following the method of Paluch (personal communication 1989) for 20 Hz and corresponding 1 Hz measurements. This gave satisfactory agreement with the dewpoint sensors in cloud, but the calibration is dependent on the relative humidity; extremely dry environmental parcels require special adjustment. Ozone measurements are useful when crossing the inversion but lose importance in the cloud layer as the noise exceeds possible shifts.

## III. Results

### a) Inversion Structure and Entrainment

A typical 20 Hz sounding near the inversion is shown in Figure 1. There is clear evidence of several individually well-mixed regions, of vertical extent h= 50 meters or less, through which $Q_T$ and $O_3$ are quite constant and between which there are very sharp gradients over less than 1 mb. A study of the conserved variables shows that these layers (hereafter referred to as intermediate inversion layers or IILs) are not the product of direct mixing between the cloud and environment at this instant. Interestingly, the rather homogeneous nature of an individual IIL suggests that it did not arise from a uniform or gradient mixing process, but rather from a discrete process similar to that of Broadwell & Breidenthal (1982). Indeed even the transition between IILs is nonuniform. The IILs persist for hours during which they radiatively cool to equilibrium and are sorted by buoyancy. The layers are distinctly subsaturated, which could not arise from the removal of drops alone.

In examining the overall nature of this inversion region, we find that the velocity jump is approximately 8 m/s, $\Delta\theta_v$ about 8 K, and thus the Richardson's number, $Ri=g'h/\Delta U^2$, where $g'=g\Delta\theta_v/\theta_v$, is less than ¼ for $h$ less than 60 m. These regions are thus probably Kelvin Helmholtz vortices forming near the tops of the cloudy hummocks. Note that from vertical soundings it is impossible to distinguish localised Kelvin Helmholtz vortices from horizontally extended layers.

We can roughly estimate the entrainment rate into this shear layer due to these vortices from laboratory and theoretical studies of turbulent mixing in free shear layers (Dimotakis, 1989). These results show that the entrainment into a shear layer of horizontal velocity difference $\Delta U$ is determined by two parameters, namely, $s=\rho_2/\rho_1$ and $r=U_2/U_1$, where the label 2 is associated with the more slowly moving fluid. (i.e., the upper air, in the July 5 case study). In the presence of density stratification one would expect the shear layer thickness to be fully developed near $h_{max}=(\Delta U)^2/g'$. The fraction of fast moving air flowing into the shear layer, according to these studies, is

$$C=s^{1/2}(1+.68(1-r)/(1+r)) \tag{2}$$

Thus for the free shear layer we can estimate an entrainment velocity

$$w_e \simeq U_{ave}h_{max}L^{-1}/(1+C) \tag{3}$$

where L is the distance it takes for the shear layer thickness to grow to saturation. This entrainment rate would be characteristic of those portions of newly created surface over which $h/h_{max}<1$; as the surface ages the shear layer thickness approaches $h_{max}$ and entrainment stops, creating intermittency in the entrainment. Using parameters characteristic of the inversion on July 5 we have $\Delta U=8\ m/s$, $U_{ave}=8\ m/s$, $g'=.2$, $s=.98$, $r=0.33$, $C=1.3$ (i.e., there is 30% more cloudy than noncloudy air in the shear layer). For the laboratory free shear layer the thickness of the molecularly mixed shear layer grows at a rate $h_{max}/L=.075$ at $s$ = 1. Thus we estimate an entrainment velocity of .3 m/s in regions of scale $L$ = 60 / .075 = 800 m. This entrainment velocity would destroy the cloud rapidly, if prolonged; thus the problem is to determine what fraction of the surface is active at any given time and the rate of removal of the lowest IIL. This could occur through the lowest IIL cooling until this layer alone becomes unstable to Kelvin-Helmholtz instability. Entrainment via shear is clearly much more efficient locally than the baroclinic torque mechanism (Breidenthal and Baker, 1985) or the rebound mechanism (Linden, 1973), both of which are proportional to the inverse Richardson's number for the layer, yielding entrainment velocities of several tenths of a centimeter per second.

b) Local Dynamics and Large Scale Forcing

Two flight legs were examined at the inversion, passing in and out of cloud turrets. A two-stream radiative transfer model estimates the cloud turrets on these legs are approximately 40 m deep if we assume uniform liquid water mixing ratio .3 $g/m^3$. This depth is consistent with the lidar measurements. These variations are far greater than can be explained on the basis of turbulent velocities carrying cloudy air into the stratified interface, and must result from a larger scale forcing.

Another symptom of the local effects of larger scale forcing appears to be the presence of upper level fluid below cloudtop in mixed parcels of scales 100 m and more. According to the work of Dimotakis & Brown (1976), and Broadwell & Breidenthal (1982), molecular scale mixing of two fluids in a turbulent eddy occurs only after the two fluids have been in contact over a time comparable to an eddy revolution time. That is, the vortex Richardson's number for eddies responsible for molecular scale mixing must be of order unity. From the observed velocity spectrum it can be shown that for a parcel 100 m in scale to meet this criterion the maximum fraction of upper layer fluid it can contain is on the order of 8%. We have shown earlier that evaporative cooling does not substantially modify this picture. One possible mechanism by which the unbalanced mixing ratios might be created is that small bits of upper level air are drawn down by radiatively cooled cloud parcels, or by the cloud circulations on larger scales, around the edges of the cloud top undulations.

Cloudtop radiative cooling modifies the properties of the upper 50 meters or so of the cloud. If this dominates in driving local dynamics, we expect to see descending, negatively buoyant, liquid water rich parcels whose scales are determined by the requirement that they remain coherent long enough to be substantially cooled. However, the descending parcels are usually relatively dry and tend to be grouped in thinner liquid water regions, indicating significant entrainment is involved in the downdrafts. To understand this better, we note that for a longwave cooling rate,

$$d\theta/dt \approx (F/\rho c_p)\cdot l^{-1} \tag{4}$$

in a parcel of scale $l$, with $F$ the net LW flux from the parcel. Assuming a persistence time $\tau \approx (l^2/\varepsilon)^{1/3}$ (assuming an inertial subrange characterised by TKE dissipation rate $\varepsilon$), we find the cooling possible in a parcel of scale $l$ is

$$\delta\theta/\theta = w_r/w(l) \tag{5}$$

where $w_r \approx F/\rho c_p \theta$ is a measure of the cooling rate and $w(l)=(l\varepsilon)^{1/3}$. For typical values of the cloudtop parameters $F=80\ W/m^2$, $\varepsilon=10^{-3}\ m^2/s^3$ as estimated from the vertical velocity spectrum midcloud, we find that $w_r=10^{-4}\ m/s$, so only very small parcels can cool several tenths of a degree at cloudtop before losing their coherence. Thus the descending parcels which are several hundred meters or more in horizontal scale are not driven directly by their own radiative cooling, but are rather responding to larger scale forcing. This conclusion is supported by the fact that they are not always the coolest parcels, as will be shown below.

c) Convective Elements

There were two flights at midcloud levels; one flying upwind and the other flying cross wind. The downward solar flux ranged from 860 $W/m^2$ to 650 $W/m^2$ during this leg, which, by our simple radiation model, would imply that the plane was between about 100 and 200 m below cloudtop. This is roughly consistent with upward flux observations based on the soundings. The trend is consistent with the observation that cloudtop sloped upward moving out to sea.

We have conditionally sampled the data in the horizontal flight legs at the inversion, midcloud and below cloud, to determine the characteristics of the up- and downdrafts. Figures 2 and 3 show the 20 Hz histograms of $\theta_e$ and $Q_T$ (a) for a 45 second subcloud section; (b) for the parcels for which $w$ is in the upper 10% of the values measured, and c) for those parcels for which $w$ was in the lowest 10% of the values measured. While this is not a sophisticated method to isolate up- and downdrafts, it is a conservative first cut. We see that average values of $\theta_e$ and $Q_T$ are found in all parcels, independent of $w$, whereas the uppermost values of $Q_T$ and $\theta_e$ are found only in updrafts and lowest values of $Q_T$ and $\theta_e$ are found only in the downdrafts. The distribution of values of these parameters is tighter in the updrafts than in the downdraft data in the midcloud segments. We have looked at similar information for all the flight legs, and find broadly similar patterns within and below cloud. We do not see organisation either in the spacing or location of the up- and downdrafts activity in the subcloud legs, whereas there is a suggestion of roughly 5 km spacing in the downdrafts in the midcloud legs, consistent with convective cell geometry. Moreover, the correlations of thermodynamic properties with extremes in vertical velocity are fairly weak suggesting that buoyancy is not dominating the structure. We find the cutoffs defining the up- and downdrafts change markedly on entering cloudbase; that is, the upper ten per cent of the positive velocity excursions are much higher below cloud than in cloud, while the lowest ten per cent of the velocities have small $w$ below cloud and much larger in cloud. Thus buoyancy differences are probably not driving these parcels continuously up to the inversion. An interesting note is that the average velocity is positive in the subcloud layer, contrary to the classical picture of subsidence. Simple parcel calculations show the buoyancy differences existing in this situation are so small that minor excursions in initial vertical velocity (at top or bottom), due to initial forcing, can have substantial impact on velocities of parcels in the middle of the layer.

Horizontal wind variations are correlated with updrafts at low levels, in the sense that the air coming from below has less horizontal momentum than that from above. These correlations are lost above cloudbase suggesting that it should not be used as a horizontal tracer.

d) Decoupling of Cloud and Subcloud

As seen from above, it is not necessarily the warmest or the most buoyant parcels which rise the fastest from low levels to mix with the air above. In fact, the strong updraft regions do not even penetrate the cloud layer. This is seen in the Paluch diagrams (see Figure 4) which show two regions for a given sounding. The first is the from near ocean surface to approximately cloud base. We see a rather uniform mixing line. Note that moist, warm parcels correspond with the updrafts of the previous section. This mixing line can support the notion of mixing with the SST (Boers & Betts, 1988). We next examine the cloud region only. We see that the warm, moist parcels of this section do indeed mix with the air above the inversion but these updrafts do not correspond to the updrafts of the subcloud region. Thus we find that the sounding is decoupled. This height-dependent variation is far greater than has been observed in the course of longer level flights of the plane indicating that horizontal motion is not believed to be accountable for the evident decoupling.

## IV. Discussion

Our data suggest that larger scale forcing, both by shear at cloudtop and by surface fluxes, determine the small scale motions within clouds on July 5. Direct correlation of buoyancy fluctuations and vertical motions on small (100 m to several kilometer) scales is weak. Analysis suggest that shear layer mixing across the inversion dominates the entrainment.

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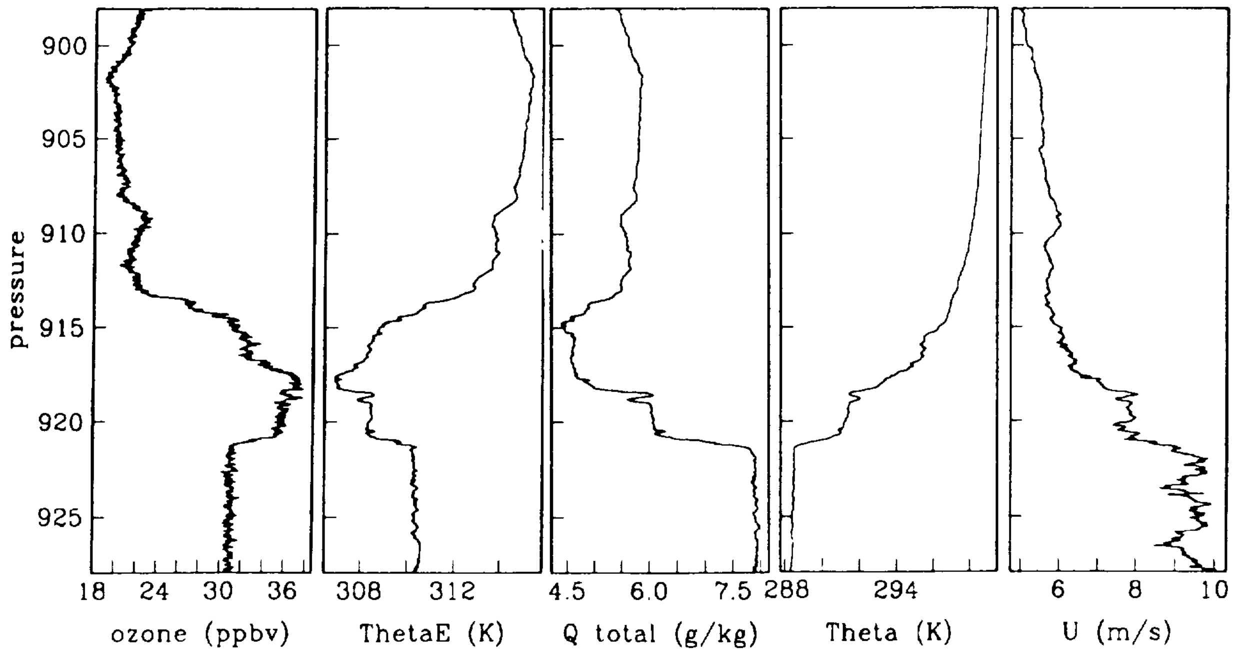


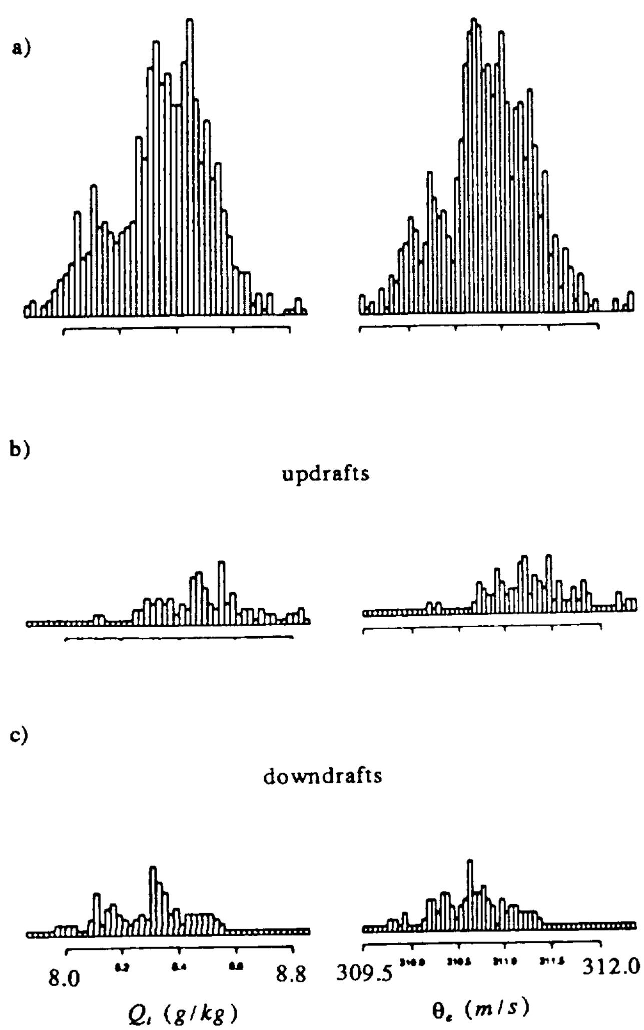


Figure 1. Sounding through cloudtop: 20:16:00-20:17:00.

Figure 2. Histogram for $\theta_e$ and $Q_t$ for (a) all parcels of a 45 second segment at 20 Hz, (b) in updraft parcels (c) and in downdraft parcels.

Figure 3. 20:14:30-20:18:30 sounding denoted by pressure to highlight decoupling. ° - 1000-980 mb; + - 980-960 mb; × - 960-940 mb; ∇ 940-920 mb.