7.6 ON THE ENTRAINMENT PROCESS IN STRATOCUMULUS CLOUDS

H. Gerber*
Gerber Scientific, Reston, VA, USA

Szymon P. Malinowski
Warsaw University, Poland

Jean-Louis Brenguier and Frederic Burnet
Meteo-France, Tolouse, France

1. INTRODUCTION

Entrainment in stratocumulus clouds (Sc) is thought to be a key process in the breakup of the large maritime Sc sheets and in their evolution into trade-wind Cu. While the basic physical processes, including cloudtop radiative cooling, cloudtop cooling due to liquid-water evaporation, and mechanically induced mixing, are understood in a qualitative sense, their interactions and quantitative behavior are not sufficiently known. This lack appears to be a significant factor in our inability to successfully predict the evolution and breakup of Sc. This situation exists for two reasons: The interfacial layer between Sc top and the free atmosphere, where entrainment processes occur, is thin and undulating, thus making it difficult to measure the pertinent physical phenomena with typical aircraft probes with insufficient response times. The second reason is that modeling efforts of the Sc with large-eddy simulation (LES), while having much advanced in recent years in sophistication and spatial resolution, have not yet been able to identify entrainment structures near cloud top (e.g., Lock and MacVean, 1999; Stevens et al, 1999).

The Dynamics and Chemistry of Marine Stratocumulus study (DYCOMS-II; Stevens et al, 2001) held off the southern coast of California in July, 2000 provided the first opportunity to fly nearly co-located on a research aircraft (NCAR C-130) the following three probes with greatly enhanced response times: Fast Forward Scattering Spectrometer (FFSSP; Brenguier et al, 1998), Ultra-Fast Temperature Sensor (UFT, Haman et al, 2001), and the Particle Volume Monitor (PVM; Gerber et al, 1994) measuring, respectively, droplet spectra and concentration, temperature, and liquid water content and effective droplet radius at rates up to and exceeding 1000 Hz. The 1000-Hz rate corresponds to an incloud distance of 10 cm at an aircraft speed of 100 m/s, which holds promise of including scales potentially important in the entrainment process.

* Corresponding author address: H. Gerber, Gerber Scientific Inc., 1643 Bentana Way, Reston, VA 20190; e-mail: hgerber6@comcast.net

We describe measurements made with the three fast probes in the Sc on Flight 3 of DYCOMS starting near midnight on 12 July and lasting until after daybreak; and we present preliminary analyses and results relating measured microphysics and thermodynamics to the entrainment process. The 12-July Sc was unbroken, about 350-m thick, and contained light drizzle. We concentrate here on the "porpoising " section of this flight, where the aircraft flew at a shallow slope ratio of about 1/20 between 50-m above and 50-m below cloud top a dozen times over a period of 1200 s (120 Km horizontal distance).

2. ENTRAINMENT STRUCTURES

Figure 1 shows the altitude of the aircraft and the PVM, UTF, and FFSSP measurements during the aircraft's descent into the top of the Sc for a small segment of the porpoising section of Flight 3. The PVM and UFT data were measured at 1000 Hz, and the droplet size spectra was measured by the FFSSP at 50-Hz.

The LWC data in Fig. 1 show maximum values that are relatively constant in time, with fine scale fluctuations that are interpreted as being a result of Poissonian sampling noise. These maximum values are close to the predicted adiabatic LWC for this Sc. Dispersed within the LWC data are narrow regions in the cloud with much less than adiabatic LWC (e.g., see #1 in Fig, 1; also see Fig. 2). These depleted LWC regions are assumed to be a result of the entrainment process. The temperatures measured by the UFT in these regions show virtually no change from adjacent cloud portions that have quasi-adiabatic LWC. The droplet spectra measured by the FFSSP and the effective radius (Re) measured by the PVM in these regions also show little change, unless LWC is depleted close to totally (e.g., see # 2 and #4 in Fig. 1).

Given these measurements, which are representative of the rest of the porpoising on Flight 3, the entrainment structures near cloud top can be described as having the following properties: they are demarcated by sharp LWC changes from background LWC, they vary in horizontal size from 10's of m to a maximum of about 200 m, and their formation reflects the effects of an inhomogeneous mixing process.

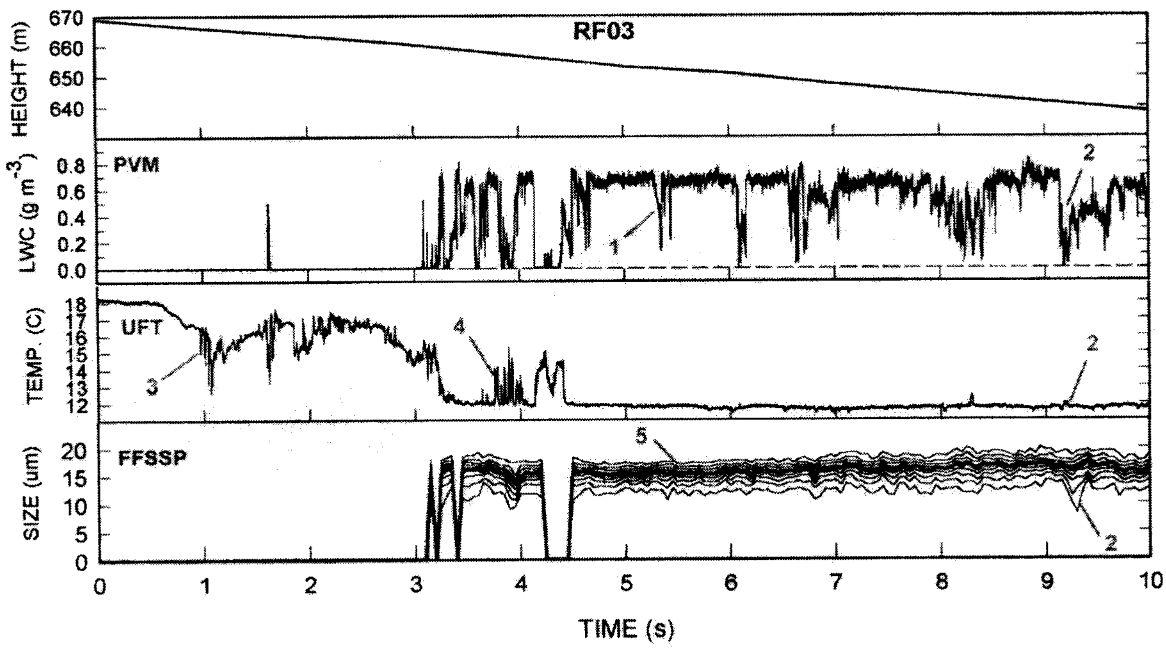

Fig 1 - High rate measurements of liquid water content (LWC), temperature, and droplet size spectrum as the NCAR C-130 aircraft descends into the top of the stratocumulus cloud on Flight 3 of the DYCOMS study. Entrainment structures are indicated by (1), structured where LWC has nearly evaporated by (2), (3) points to the cloud-free inversion layer with temperatures cooled below the free atmosphere above, (4) indicates the location of a mixing event where meter and sub-meter scales are involved, and (5) shows the droplet spectra (diameter) which are nearly unchanging even in places where entrainment structures exist (the thin lines indicate 10% percentiles of the concentration, and the thick line shows the mass-median diameter). Each second corresponds to about 100 m.

In fact, an isobaric mixing calculation between cloudtop quasi-adiabatic air (T=12.25 C) and the air from the top of the inversion layer (T=20 C; RH=30%), shows that mixed parcels with liquid water cannot contain more than 14% of free tropospheric air. At larger mixing proportions all the cloud LWC is evaporated, thus increasing RH in the inversion layer air. Such a calculation also implies that mixed parcels containing liquid water cannot be cooler than the quasi-adiabatic cloudy air by more than 0.15C, due to evaporation of all the existing LWC (0.7 gm^{-3}). When the proportion of free tropospheric air is larger, the final temperature of mixtures lie between the cloudtop temperature and temperature at the top of the inversion. The first 3 seconds of measurements in Fig. 1 illustrate such transient mixing states.

The entrainment structures shown in Fig. 1 and 2 appear passive from a mixing standpoint. Only rarely does the porpoising data show what appears to be mixing in progress between cloudy air and dryer air above the cloud. Figure 3 shows a closeup of such an event (see also #4 in Fig. 1). Here the 10-cm resolution data of the PVM and UFT show fine scale structures on the order of meters and smaller that are difficult to interpret, because these two probes were separated on the aircraft wing by 6.2 m. Nevertheless, it suggests that the active mixing process occurs not with temperature changes equivalent to the entire temperature jump between the cloud and the free atmosphere, which is of the order of 7.75 C for this Sc, but with only a fraction of the jump. This infers that multiple mixing events between the cloud and overlying air must occur where early stages cool and moisten the inversion, while final stages are characterized by LWC smaller than the adiabatic value, but with droplet spectra and temperature almost equal to the quasi-adiabatic reference.

In other portions of the porpoising leg shown in Fig. 1, a rather different relationship exists between the high rate LWC and UFT temperature data. Figure 4 shows temperature fluctuations on the order of 0.4C over horizontal scales ranging from about 1 m to 10m, but with a LWC record that in this case shows no significant variability. This observation may be showing narrow filaments of subsiding cloudy air near cloudtop cooled by i.r. flux divergence; although, it is puzzling that in the filaments small increases of LWC are not seen. There appears to be no correlation between these filaments

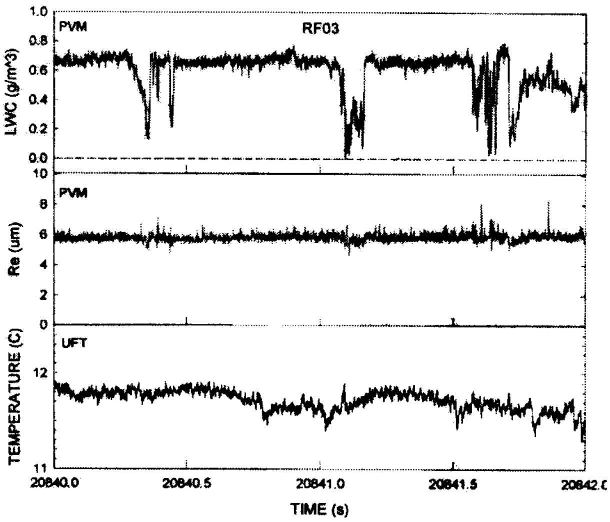

Fig. 2 - Expanded section of Fig. 1 (5.5s - 7.5 s) showing LWC, effective radius (Re) and temperature.

and the depleted LWC regions associated with entrainment.

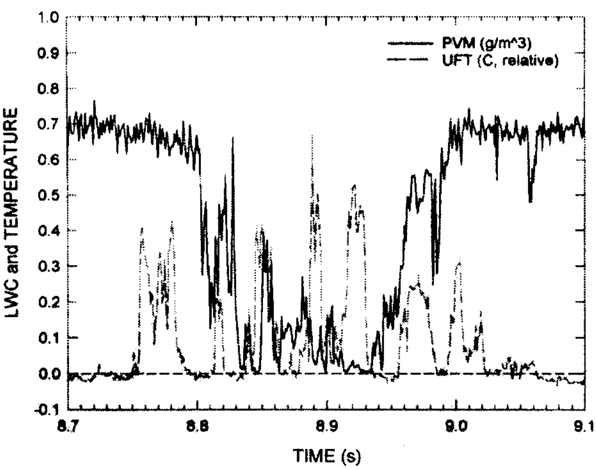

Fig. 3 - 1000-Hz LWC and temperature data in a narrow region undergoing mixing; 0.1 s is equivalent to 10 m.

3. INVERSION LAYER

The layer between cloudtop and the free atmosphere above, unaffected by boundary-layer processes, has a variety of different descriptions. The early work of Lilly (1968) used for the sake of modeling simplicity a discontinuous interface of zero thickness between cloud and free atmosphere, which has been called a zeroeth-order interface jump in the more recent literature (VanZanten et al, 1999). It has been realized that this description does not necessarily reflect the nature of the layer just above cloud top, and that the layer is rather of the 1st-order interface type where a finite thickness exists between cloud top and the free atmosphere. It is observed that cloudtop coincides with the base of the temperature inversion that extends on the average over a narrow layer up to the free atmosphere. It has been suggested by Gerber (1996), Brenguier et al (2000) that this layer is moistened and cooled by mixing with cloudy air, thus affecting parcels entrained into the cloud.

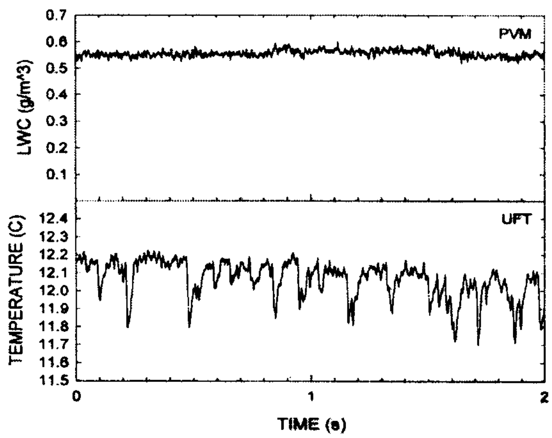

Fig 4 - 50-cm resolution LWC and temperature measurements in a region near cloudtop where radiative cooling may be occurring.

Here we will call the 1st-order interface layer the inversion layer or conditioned layer, a layer with three dimensions. It has been taken into account in LES literature (e.g., Moeng, 2000) that the height of Sc cloudtop varies significantly in the horizontal direction, while the interface layer might still consist of a sharp interface. Figure 5 looks at the distribution of cloudtop heights and inversion-top heights for the porpoising section of Flight 3. This shows again that cloudtop varies significantly in height, but also shows that the inversion layer can not be considered a sharp interface, but one which has a finite thickness at least for this Sc. For this data the inversion thickness has a mean value of about 22 m (difference between inversion top and cloudtop). Only occasionally does the cloudtop coincide with the inversion top. Here the inversion top is chosen as the height during the ascent and descent of the aircraft where the UFT sees initially rapid fluctuations in temperature that are also reduced from free atmospheric values. Similar choices can be made using the Lyman-alpha mixing ratio data.

The UFT temperatures in the inversion layer range between the free atmospheric value and the incloud value that differ by about 7.5 C (see Fig. 1). This cooled cloud-free inversion air results from the

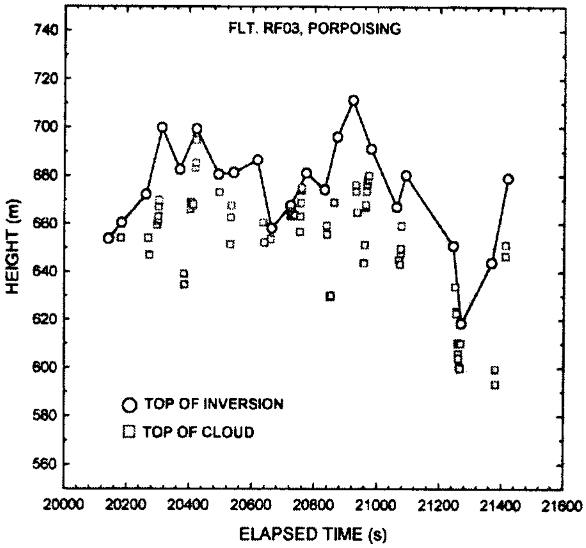

Fig. 5 - Locations of inversion and cloudtop determined during aircraft porpoising through cloudtop.

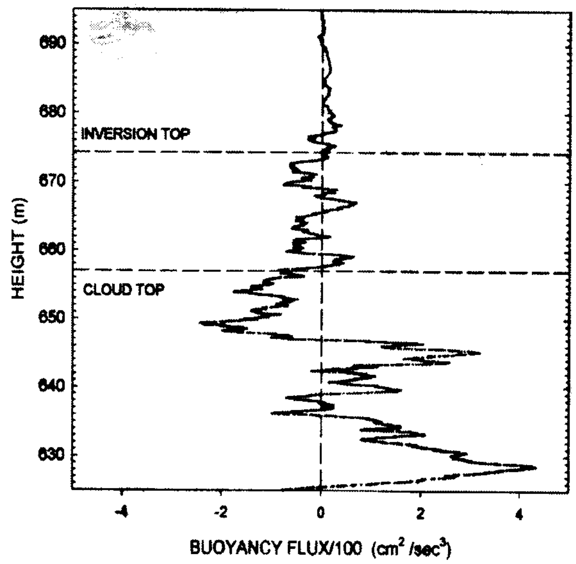

Fig 6 - Mean buoyancy flux calculated for the porpoising interval shown in Fig. 5

evaporation of cloudy air upon mixing with the warmer and dryer air higher up. If cloudtop is chosen as the reference level, it can be said that cloudy air detrains to condition the inversion layer. It appears that the mixing associated with this conditioning process is not a one-step process between free-atmospheric air above the inversion and the cloudy air. Rather, the mixing seems to consist of a series of mixing events that gradually condition the inversion layer to the point where some air parcels approach the buoyancy of the cloud. This mixing mechanism would be consistent with the lack of a temperature difference between the depleted-LWC entrainment structures and the rest of the cloud, as well as with the predominance of the inhomogeneous mixing mechanism reflected in the droplet spectra.

Figure 6 shows the mean buoyancy flux calculated for the porpoising section of flight 3. The flux is given by the product of the buoyancy referenced to the virtual potential temperature at the top of the inversion (300 K). While the curve in Fig. 6 includes large uncertainties as a result of the relatively small data sample corresponding to the porpoising section, several features stand out. The flux in the inversion layer is small including at the base of the inversion, a layer of negative buoyancy exists just below cloud top, and areas of large positive flux are found lower down. The small flux value at the base of the inversion is consistent with the description of the entrainment structures that appear buoyancy neutral with respect to the rest of the cloud; and the negative layer of buoyancy flux just below cloud top may reflect the effects of radiative cooling.

4. CTEI

Cloud-top entrainment instability (CTEI) criterion has been a topic of many papers over the years. It is based on the zeroeth-order interface assumption, and predicts that under certain conditions evaporative cooling at cloudtop due to entrainment causes negative buoyancy that destabilizes the Sc. The criterion for this instability is given by

$$\Delta\Theta_e < k\ L / c_p\ \ \Delta q_T$$

where $\Delta\Theta_e$ is the equivalent potential temperature jump and Δq_T the total water mixing ratio jump across the interface, L is the latent heat of evaporation, c_p is the specific heat, and k is usually given a value of 0.23.

Observations that tested the CTEI criterion (e.g., Kuo and Schubert, 1988; Siems et al, 1990) have not supported this concept. Albrecht et al (1985) suggested CTEI would not hold if entrainment caused the entire liquid water to evaporate; and Siems et al (1990) and Wang and Albrecht (1994) indicated that only specific, and possibly rare, mixing fractions caused buoyancy reversal that would lead to potential de-stabilization.

Flight 3 Sc in DYCOMS showed a significant potential for entrainment de-stabilization given that the CTEI criterion gave a value of k = 0.5 . This k value would, according to some recent LES modeling, cause an unstable cloudtop interface leading to fractional cloudiness of the Sc (Lewellen and Lewellen, 1998; Moeng, 2000).

The Flight 3 Sc were unbroken, and showed essentially no signs near cloudtop that CTEI was playing any role. The entrainment in this Sc was in effect nearly isothermal with respect to the rest of the cloud, showing no evaporative cooling that would relate to buoyancy reversal and CTEI. A potential explanation for the lack of observed buoyancy reversal may be the observations that the inversion layer has finite thickness, and that the mixing associated with entrainment proceeds over multiple events rather than a single event such as for a zeroeth-order interface.

5. CONCLUSIONS

The analysis of high rate temperature (UFT), LWC (PVM), and droplet spectra (FFSSP) measurements made during DYCOMS Flight 3 in a short porpoising interval near Sc top suggests the following preliminary conclusion related to the entrainment process:

a. A finite-thickness cloud-free inversion layer overlaying cloudtop is the site of mixing of detrained cloudy air with dryer inversion air and occasionally with air from above the inversion.

b. The conditioning of the inversion layer caused by cooling and moistening of detrained cloud results in the buoyancy reduction of air parcels in the layer that are ultimately entrained into cloudtop with little, if any, buoyancy difference from the unaffected cloudtop. The latent heat of evaporation may provide the mechanism that causes the equalization of the buoyancies.

c. Buoyancy reversal due to evaporative cooling is not observed in the entrainment structures near cloudtop, even though, it is predicted for the Flight 3 Sc conditions by the CTEI criterion.

d. The measurements described here do not answer the question, how does air enter the cloud to form the entrainment structures? Possibilities are that residual buoyancy reversal or dynamic effects cause inversion air to enter the cloud.

e. Narrow cloud filaments with depressed temperature observed sometimes near cloudtop may be a signature of radiative cooling. The filaments are unrelated to the entrainment process.

f. The effect of the entrainment structures on the cloudtop microphysics is essentially one of inhomogenous mixing, where droplet concentrations are diluted in the structures rather than droplets being reduced in size.

g. The scales of mixing events in the inversion layer are too small to be observed in current LES studies of Sc entrainment.

6. REFERENCES

Abrecht, B.A., R.S. Penc, and W.H. Schubert,1985: An observational study of cloud-topped mixed layers., *J. Atmos. Sci., 42*, 800-822.

Brenguier, J.-L., et al., 1998: Improvements of droplet size distribution measurements with the Fast-FSSP (Forward Scattering Spectrometer Probe), *J. Atmos. Oceanic Technol., 15*, 1077-1090.

Brenguier, J.-L., H. Pawlowska, L. Schueller, R. Preusker, J. Fischer, and Y. Fouquart., 2000: Radiative properties of boundary layer clouds: Droplet effective radius versus number concentration. *J. Atmos. Sci., 57*, 803-821.

Gerber, H., B.G. Arends, and A.S. Ackerman, 1994: New microphysics sensor for aircraft use. *Atmos. Res., 31,* 235-252.

Gerber, H., 1996: Microphysics and modeling of layer clouds. *Proc. ETL/CSU Modeling and Measurement Workshop*, Boulder, CO,23-25 Oct., 1995, 175-187.

Haman, K. E., S.P. Malinowski, B. Strus, R. Busen, and A. Stefko, 2001: Two new types of ultra-fast aircraft thermometer. *J. Atmos. Oceanic. Technol., 18,* 117-134.

Kuo, H.-C., and W.H. Schubert, 1988: Stability of cloud-topped layers. *Quart. J. Roy. Meteor. Soc., 114*, 887-916.

Lewellen, D., and W. Lewellen, 1998: Large-eddy boundary layer entrainment. *J. Atmos. Sci., 55,* 2645-2665.

Lilly, D.K., 1968: Models of cloud-topped layers under a strong inversion. *Quart. J. Roy. Meteor. Soc., 94*, 292-309.

Lock A.P., and M.K. MacVean, 1999: The parameterization of entrainment driven by surface heating and clout-top cooling. *Quart. J. Roy. Meteor. Soc., 125,* 271-299.

Moeng, C.-H., 2000: Entrainment rate, cloud fraction, and liquid water path of PBL Stratocumulus clouds. *J. Atmos. Res., 57*, 3627-3643.

Siems, S.T., et al, 1990: Buoyancy reversal and cloud-top entrainment instability. *Quart. J. Roy. Meteor. Soc., 116,* 705-739.

Stevens, B., C.-H. Moeng, and P. Sullivan, 1999: Large-eddy simulation of radiatively driven convection: Sensitivities to the representation of small scales. *J. Atmos. Sci., 56*, 3963-3984.

Stevens, B.,et al, 2001: Dynamics and chemistry of marine stratocumulus - *DYCOMS-II. Bull. Amer. Meteor. Soc.*, in print.

VanZanten, M.C., P.G. Duynkerke, and J.W.M. Cuijpers, 1999: Entrainment parameterization in convective boundary layers. *J. Atmos. Sci., 56,* 813-828.

Wang, Q., and B.A. Albrecht, 1994: Observations of cloud-top entrainment in marine stratocumulus clouds. *J. Atmos. Sci., 51*, 1530-1547.

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