5.1 ENTRAINMENT IN NOCTURNAL STRATOCUMULUS

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1. INTRODUCTION

Two of the chief obstacles in our attempts to rationalize the role of the stratocumulus-topped boundary layer (STBL) in the climate system are our uncertainty about how the STBL couples to the free-troposphere and what processes regulate its transition to a cumulus-coupled layer. The coupling to the free-troposphere can be expressed in terms of an entrainment rate, E. Attempts to estimate E observationally have been frustrated by our use of sub-optimal tracers, and by an experimental emphasis on daytime conditions, in which the evolution of the cloud layer is most pronounced. Attempts to estimate E using large-eddy simulation (LES) are frustrated by the very strong stratification typical of the capping inversion atop the STBL. This strong stratification significantly reduces the turbulent lengthscales which makes the STBL particularly challenging to simulate numerically. Because of these difficulties the fidelity of entrainment laws which have been derived on the basis of LES is open to question. To address these issues a field program, DYCOMS-II, was conducted in nocturnal stratocumulus well offshore of Southern California. In what follows we describe the basic strategies of DYCOMS-II, and preliminary estimates of E as estimated during the first research flight (RF01). These estimates suggest the stratocumulus entrain less efficiently than previous work has led us to expect. They also indicate that cloud-top entrainment instability (CTEI) is not an important process in regulating the lifetime of stratocumulus.

2. ESTIMATING E

As reviewed by Stevens et al., (2002) there are essentially two distinct methods, the ratio and difference methods respectively, for estimating E from data. The ratio method is based on the budget of tracers which are either adiabatically conserved or which have sources which can be accurately characterized. In such a method the entrainment velocity for thin entrainment interfacial layers can be estimated as $E = -\overline{w'c'}/\Delta C$, where for some tracer C, ΔC is the difference across the interfacial layer and $\overline{w'c'}$ is the turbulent flux of C at the base of the interfacial layer (top of the STBL). In principle independent estimates of E can be made for independent scalars. In contrast, the difference method is based on the evolution of cloud top height. Because E essentially represents the diabatic contribution to boundary layer growth, it can be estimated as the difference between the adiabatic growth rate (given by W_{ls} the large-scale subsidence velocity valid at $z = h$ where h is the depth of the STBL) and the actual growth rate of the layer, i.e., $E = dh/dt - W_{ls}$.

During DYCOMS-II flight patterns were predominantly nocturnal and were crafted to facilitate the use of both the difference and ratio methods. Thirty minute circular flight legs allowed for estimates of the divergence D of the large-scale wind, which is central in estimating W_{ls} (see paper P1.20 for further discussion of these points). These flight legs also enabled estimation of vertical profiles of the flux $\overline{w'c'}$ at various heights within and above the STBL, from which both ΔC and $\overline{w'c'}$ at $z = h$ could be estimated, the latter by either eddy-correlation or budget residuals. In all, four different tracers were used to estimate E by the ratio method: temperature, ozone, water-mass and dimethyl sulfide (DMS). One of the innovations of DYCOMS-II was the deployment of a fast DMS measurement capability. Because the only known source of DMS is at the surface and because it has lifetimes of order a few days it is thought to be an optimal tracer for estimation of E. The focus on nocturnal measurements also greatly simplifies the analysis of the layer energetics and hence the relationship between estimates of E and the external forcing.

3. RF01

In Fig. 1 we show profiles of total-water mixing ratio, q_t, liquid water potential temperature θ_l, and liquid water as measured from soundings and level legs during RF01. The profiles are typical, except in so far as the free-tropospheric humidity profiles are free of significant variability. The layering of scalar profiles above the top of the STBL often frustrates attempts to estimate ΔC and hence E using the ratio method. Clearly evident in the profiles is the sharpness of the transition between

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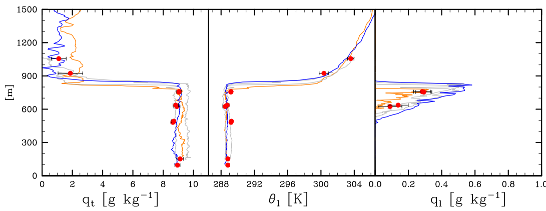

Figure 1: Vertical structure of boundary layer as observed during RF01.

the STBL and the free-troposphere. The cloud cover was solid for the entire time in the experimental area. Although individual soundings indicate some variability in q_l profiles, this variability represents a steady thickening of the layer with time, something which is perhaps better illustrated by Fig. 2, which shows that the thickening of the layer was predominantly associated with a lowering of cloud base. This evolution places perhaps the strongest constraints on the entrainment velocity. Calculations with a mixed layer model suggest that entrainment rates larger than 0.5 cm/s would lead to a thinning, rather than a thickening of the cloud layer. It turns out that such estimates are also consistent with the flux data which leads to estimates of E which range from 0.4-0.6 cm/s.

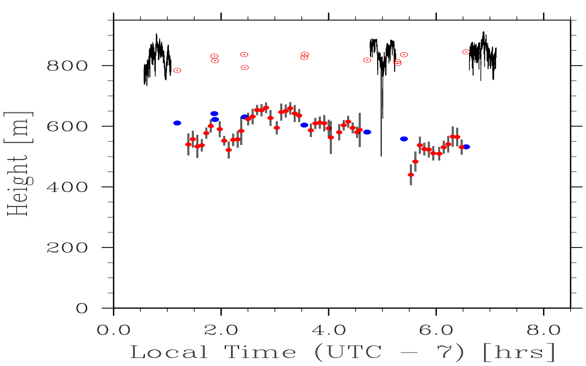

Figure 2: Cloud top derived from lidar and radar (lines) and penetrations (dots in circles) and cloud based derived from penetrations (filled dots) and LCL from 5 min thermodynamic state data during RF01.

Because entrainment rules generally formulate E as a function of the radiative forcing ΔF and the interfacial stability as measured by Δq_t, $\Delta\theta_l$ and $q_{l,max}$, these quantities must also be estimated from data. While Δq_t and $\Delta\theta_l$ can be directly estimated from Fig. 1 mixing diagrams, e.g., Fig. 3, constructed from high-rate data collected during cloud top penetrations provide an alternative estimate. These penetrations suggest that over most of the region $\Delta\theta_l \approx 10$ K and $\Delta q_t \approx 7.5$ gkg^{-1}. Using values of $q_{l,max}$ typical of a mixed layer with the thermodynamic properties of RF01 (i.e., approx 0.5 gkg^{-1}) and values of the radiative forcing of approximately 70 Wm^{-2} (which was characteristic of both the measured fluxes and predictions from a radiative transfer model) allows us to estimate E as predicted by a number of entrainment laws as summarized in (Stevens, 2002). Although there is considerable variability in the predictions of various entrainment laws, all predict substantially more entrainment, with E ranging from ≈ 0.7 cm/s to much, much larger values, all of which would produce progressive cloud thinning.

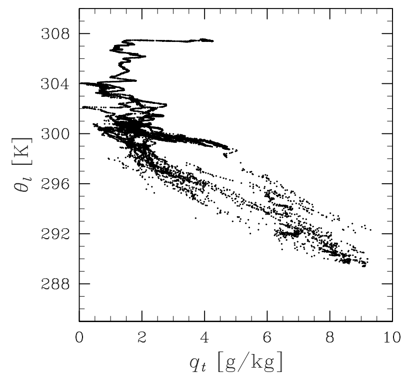

Figure 3: θ_l versus q_t mixing line diagram from high-rate cloud-top penetration data during RF01.

One of the reasons many of the entrainment rules predict values of E much larger than observed is their sensitivity to buoyancy reversal as measured by the CTEI parameter $\Delta_2 \approx 0.5\Delta\theta_l + 950\Delta q_t$. For $\Delta_2 < 0$ buoyancy reversal is possible and many theories predict the cloud layer to be unstable to entrainment and thus predict much larger values of E. Depending on how one estimates the jumps, during RF01 Δ_2 varies between about -1 and -2.5. The tendency of LES to produce a thinning of the cloud layer for $\Delta_2 < 0$ (e.g., Moeng, 2000) and the apparently negligible impact of buoyancy reversal in enhancing entrainment during RF01 suggests that buoyancy reversal does not play an important role in regulating either entrainment or the lifetime of the STBL.

Acknowledgments: This project was supported by NSF grant # ATM-0097053.

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