

Large-Eddy Simulation of Cloud-Top Entrainment Instability

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Introduction

Cloud-top entrainment instability (CTEI, Lilly 1968, Deardorff 1980, Randall 1980) is a hypothesized cloud destructive phenomenon onto stratocumulus cloud through buoyancy reversal (Siems et al. 1990) as illustrated in Fig. 1. Unlike a negative feedback of entrainment by radiative cooling, buoyancy reversal could lead a positive feedback (Fig. 2), when the Randall-Deardorff CTEI criterion, $\Delta = \Delta s_v - (\Delta s_v)_{crit} = f(\Delta h, \Delta r) < 0$ is satisfied. $\Delta h, \Delta r$ are jump values at cloud top of moist static energy and total mixing ratio, respectively.

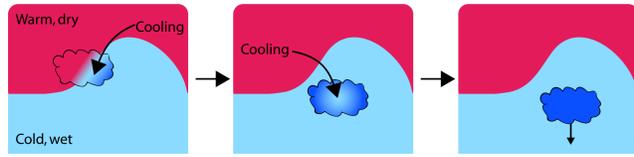


FIG. 1: Buoyancy reversal = Entrainment by evaporative cooling.

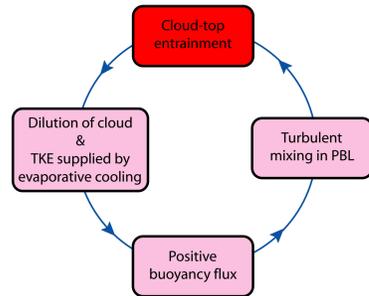


FIG. 2: Hypothesized CTEI positive loop.

CTEI hypothesis has been controversial since it appeared. Cloud destruction has been seen in large-eddy simulations (LESs) (e.g., Moeng et al. 1995, MacVean and Bretherton personal communication, unpublished manuscript). On the other hand, theoretical and observational studies such as Albrecht et al. (1985, hereafter APS) and Kuo and Schubert (1988, hereafter KS) do not support CTEI. APS argue that instantaneous cloud dissipation by entrained air is unlikely because of small liquid water mixing ratio. KS showed that observed uniform cloudiness under the CTEI criterion is satisfied.

Objectives and Method

CTEI hypothesis proposes that there can be a positive feedback involving the *enhancement of turbulence* by buoyancy reversal *when the criterion is satisfied*. Thus, we address following two questions to investigate:

1. Does the Randall-Deardorff CTEI criterion work?
2. How much convection (i.e., buoyancy flux) is generated only by buoyancy reversal?

For this purpose, large amount of LESs were conducted. The System for Atmospheric Modeling (SAM, Khairoutdinov and Randall 2003) was set up so as not to have any source of convection except buoyancy reversal. MacVean and Bretherton (unpublished manuscript) was referred to create soundings. First BR (Buoyancy Reversal) experiment consists of 49 different conditions to make a possible CTEI map shown in Fig. 3. The area on the right side of the boundary is unstable according to the Randall-Deardorff criterion. All 49 cases have same initial maximum liquid water mixing ratio 0.5 g kg^{-1} .

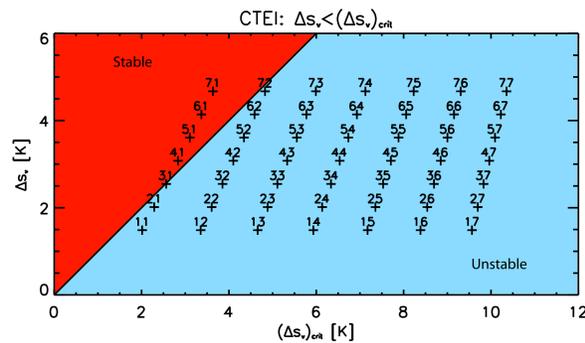


FIG. 3: CTEI map. Solid line is a theoretical boundary for CTEI.

We performed two more series of simulations. BR-1 and BR-2 have maximum liquid waters of 1 and 2 g kg^{-1} , respectively. With these liquid water mixing ratio, the PBL sounding for each index for both cases was created so as to have the same $\Delta = \Delta s_v - (\Delta s_v)_{crit}$ for each index of BR. Same free tropospheric sounding for each index of BR was used, too. Because of this experimental design, BR, BR-1 and BR-2 have same CTEI map.

Preceding this BR experiment, SAM simulated real marine stratocumulus cloud (MSC) cases such as FIRE (Moeng et al. 1996), ASTEX (Khairoutdinov and Kogan 1999) and DYCOMS-II (Stevens et al. 2004). Smoke cloud case (SMOKE, Bretherton et al. 1999) was also performed by SAM. We followed referred papers to set up SAM. All four cases were performed for 10 hours longer than the previous studies.

CTEI Maps

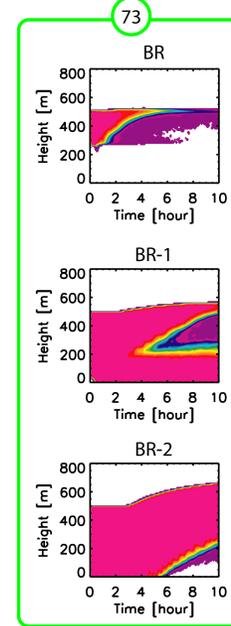
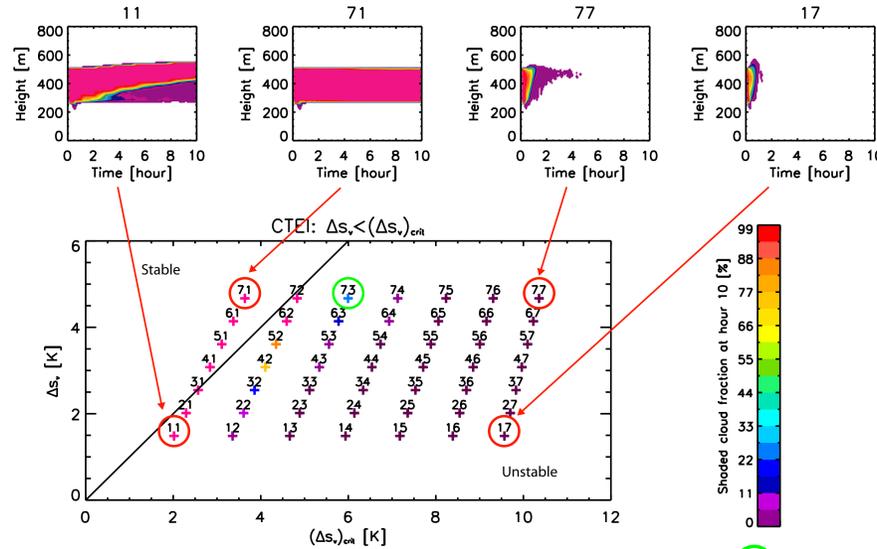


FIG. 4: CTEI maps generated by use of shaded cloud fraction at hour 10. Dark purple means zero fraction. Time evolutions of cloud fraction of selected cases are also presented.

Buoyancy Flux

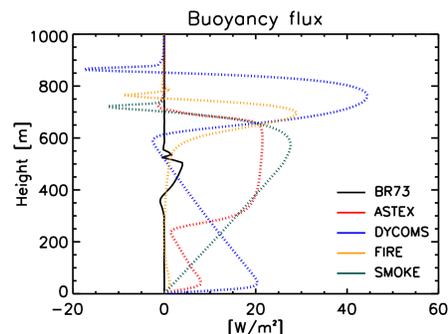


FIG. 5: Vertical profiles of the buoyancy flux. Fluxes are time-averaged between hour two and three except case 73 of BR which is a snapshot at hour 2.

The maximum value of the buoyancy flux of BR73 is much smaller than that of any cases. Effect of the CTEI may not be seen if cloud building processes (radiative cooling and surface flux) are strong enough to compensate for the cloud-destroying effects of CTEI.

Our correlation analysis between vertical velocity and the perturbations of the virtual dry static energy (not shown) reveals that the correlation of BR73 is as large as MSCs (~ 0.7), which tells that buoyancy generation by turbulence is very efficient. Covariance of two variables of BR73 is very small. It comes from small variances because of lack of processes to promote turbulence besides evaporative cooling.

Dependency of Liquid Water Amount

Their theoretical study by APS tells that under typical stratocumulus conditions, buoyancy reversal is weak because of the small liquid water mixing ratio ($< 1 \text{ g kg}^{-1}$). The APS theory also suggests that if cloud has a lot of water, negative buoyancy is relatively easy to generate.

Fig. 6 is a comparison of the maximum buoyancy flux of BR, BR-1 and BR-2. Three cases have initial maximum liquid water content 0.5, 1, 2 g kg^{-1} . As APS suggest, there is the dependency of liquid water amount for the buoyancy flux generation. Compare the maximum value of MSCs and SMOKE in Fig. 5. Both BR-1 and BR-2 have values that are comparable to those produced by other processes.

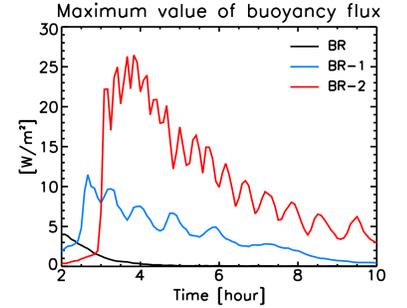


FIG. 6: Time series of maximum buoyancy flux for case 73 of BR, BR-1 and BR-2.

CTEI of MSCs

DYCOMS-II and FIRE are unstable for CTEI for entire integration. Very small rising cloud top ($\sim 50 \text{ m}$) is observed for both cases, but clouds persist. Both cases have small liquid water mixing ratio ($\sim 0.2 \text{ g kg}^{-1}$). They agree with KS.

ASTEX is stable initially, then around hour 5, the transition occurs (Fig. 7). Corresponding cloud field is shown in Fig. 8. Cloud gets thinner and thinner after the condition shifts to unstable, and many halls appear at the end of the simulation. Liquid water mixing ratio and buoyancy flux are shown in Fig. 9. Extreme drying takes place after CTEI occurs with rapid cloud-top rising, and large buoyancy flux generation is there.

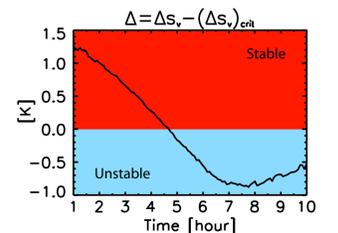


FIG. 7: Time evolution of Δ .

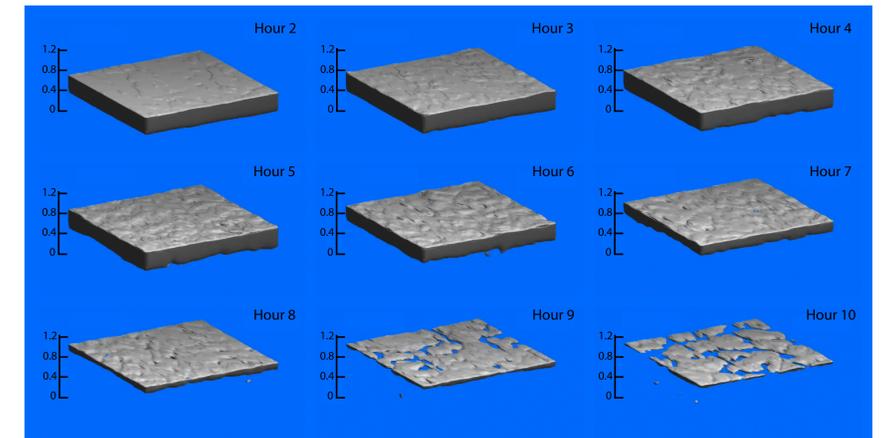


FIG. 8: Time evolution of cloud.

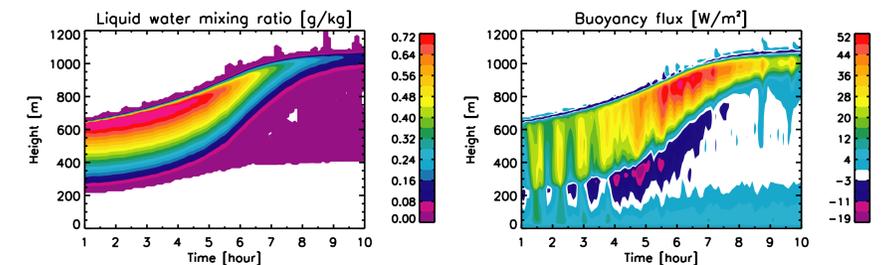


FIG. 9: Time evolutions of liquid water mixing ratio and buoyancy flux.

Conclusions

1. Does the Randall-Deardorff CTEI criterion work?

The Randall-Deardorff CTEI criterion works. In the absence of cloud-building processes, CTEI eventually dissipates the clouds. KS result is understandable if cloud-building processes are suppressing the effect of CTEI. Cloud destruction by CTEI is possible for real MSCs as demonstrated by ASTEX.

2. How much convection (i.e., buoyancy flux) is generated only by buoyancy reversal?

For typical MSC, buoyancy flux production by CTEI is weak. APS theory is valid. Strength of convection depends on the liquid water amount.