Modeling and Physics of Cloud-Top Entrainment Instability

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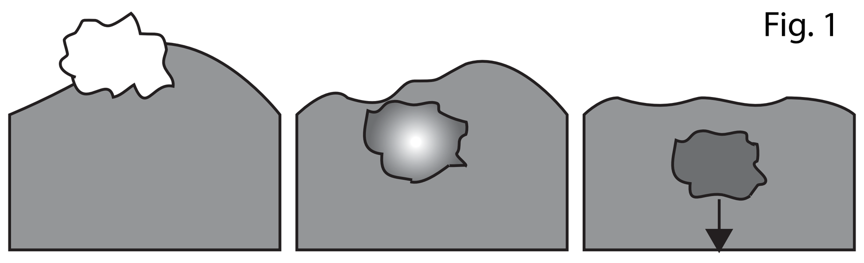
Cloud-Top Entrainment Instability

Fig. 1



The cloud-top entrainment instability (CTEI, Lilly 1968, Deardorff 1980, Randall 1980) is a hypothesized positive feedback between cloud-top entrainment and enhanced turbulence associated with buoyancy reversal shown in Fig. 1 (BR, Siems et al. 1990). CTEI would result in cloud breakup. CTEI is expected with the Randall-Deardorff criterion, $\Delta_{RD}=\Delta s_v-(\Delta s_v)_{crit}=f(\Delta h,\Delta r)<0$. Δh, Δr are jump values at cloud top of moist static energy and total mixing ratio, respectively.

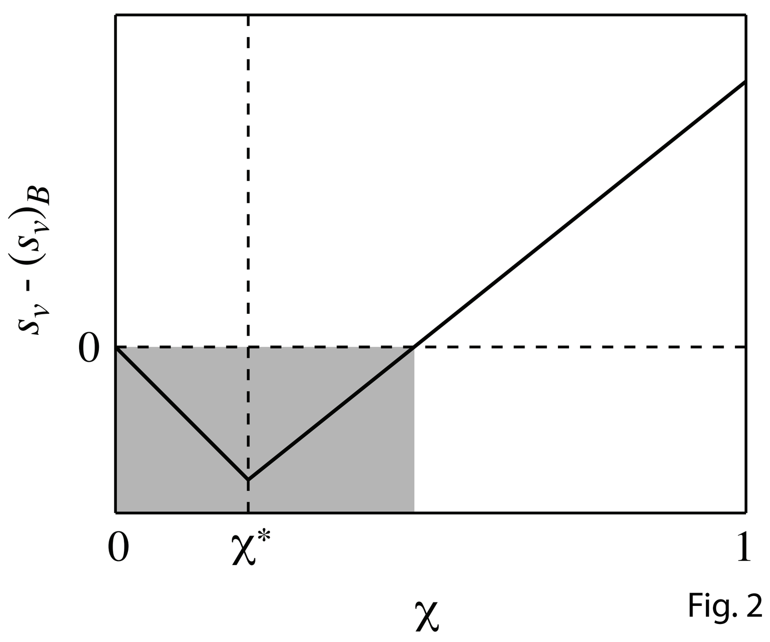


Fig. 2

CTEI has been controversial. Cloud breakup has been seen in large-eddy simulations (LESs) (e.g., Moeng et al. 1995). On the other hand, studies such as Albrecht et al. (1985) and Kuo and Schubert (1988) do not support CTEI. The former argue that instantaneous cloud dissipation by entrained air is unlikely because of small liquid water amount (Fig. 2). The latter showed observed uniform cloudiness under $\Delta_{RD}<0$.

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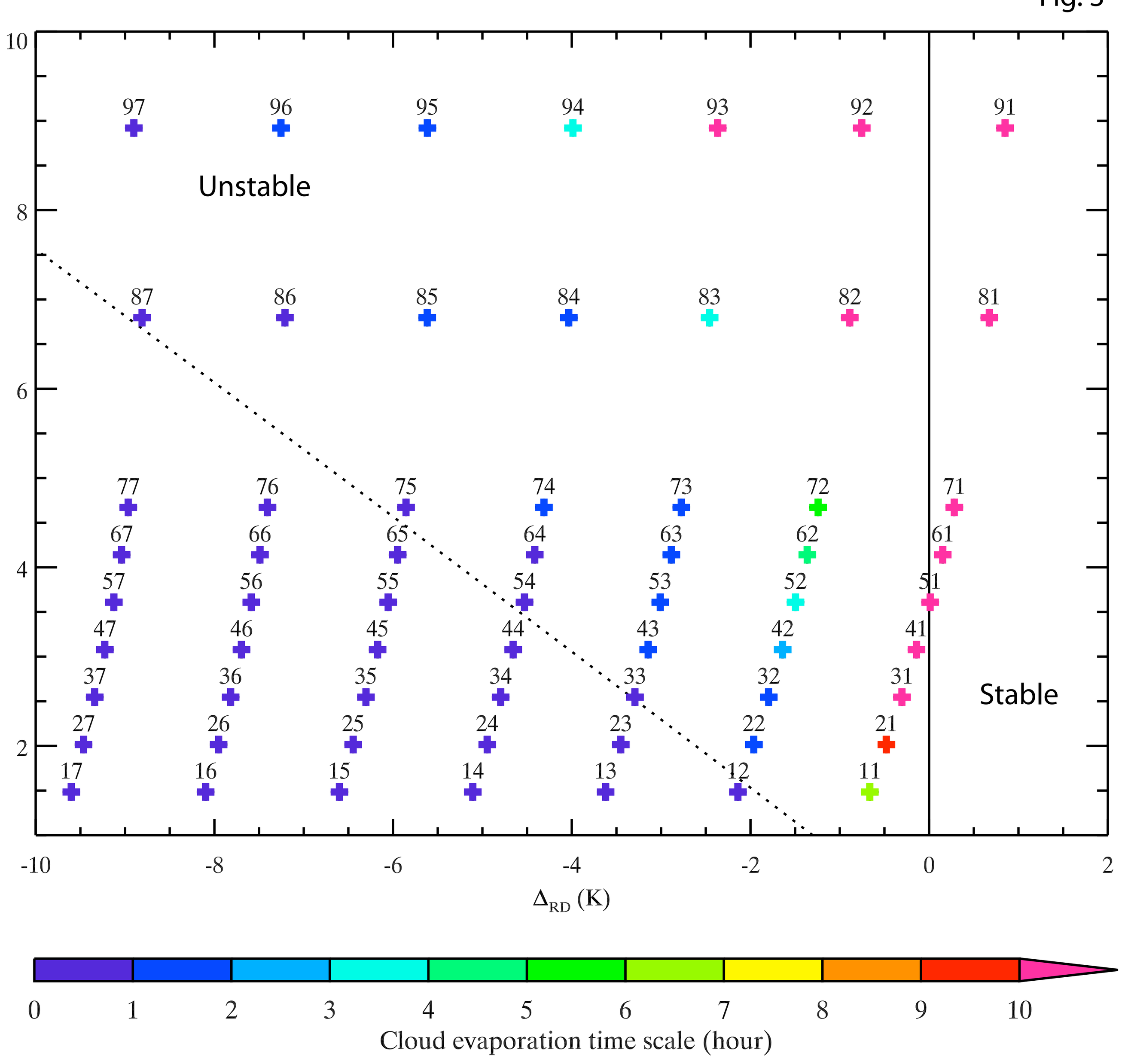
Idealized LES experiments with BR are designed so as not to have any source of turbulent kinetic energy production except for entrainment due to evaporative cooling.

Fig. 3

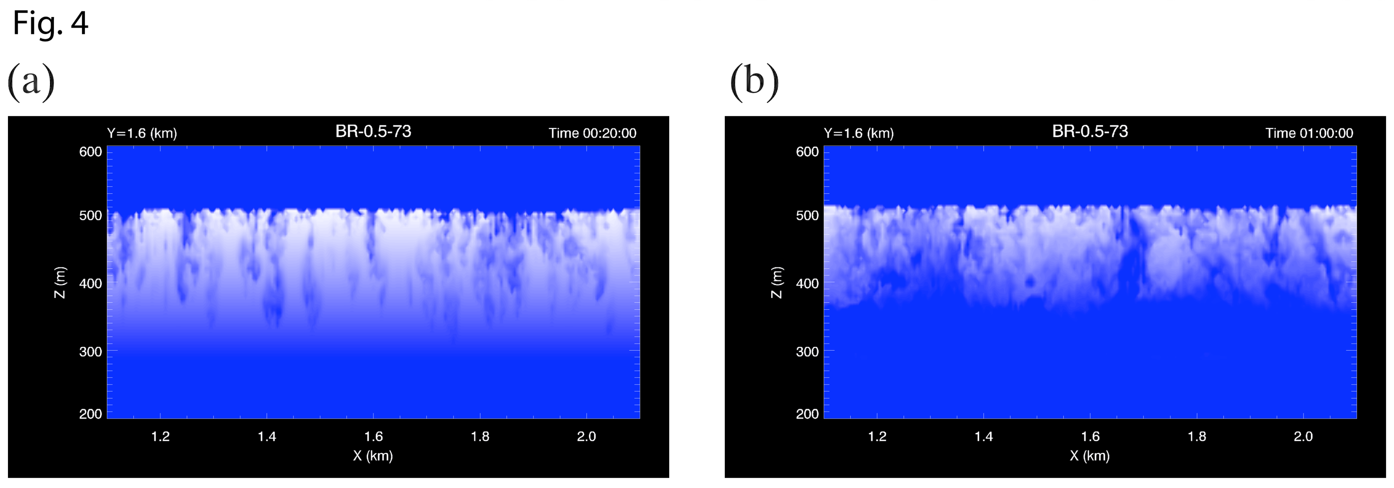


The results suggest that CTEI does exist and occurs when and only when the RD criterion is satisfied (Fig. 3). The criteria proposed by Siems et al. (1990, dotted line) and MacVean and Mason (1990, not shown) are inadequate.

Further analysis and additional simulations with longwave radiation, surface latent heat flux, or both suggest that CTEI is a weak process for typical marine stratocumulus clouds, and can be masked. This line of reasoning offers a good explanation for the persisting cloud decks observed under CTEI conditions.

An Idealized CTEI Run with 5 m Isotropic Grid

Fig. 4



YR08 used 50 m horizontal grid space. Comparing with 5 m vertical grid space, it may not be appropriate for simulating CTEI. For example, small scale turbulence in the entrainment region may be comparably important for vertical and horizontal directions. The all-or-nothing assumption for microphysics model is suggested to be valid for smaller than 10 m horizontal grid space (e.g., Grabowski 2007).

We performed a CTEI run, (case 73 in Fig. 3) with 5 m isotropic grid. Fig. 4 shows a cross sectional view of the cloud liquid water at 20 minutes for (a), and 60 minutes for (b), when integrated TKE is maximum (Fig. 5). In Fig. 5, solid line is for the Δx=5 m case, and dashed line is for the Δx=50 m case. The cloud of the Δx=5 m case dissipates within three hours, slightly faster than the Δx=50 m case. Entrainment rate and TKE are almost same for both cases, but slightly stronger for the Δx=5 m case. Further comparison suggests that the effect of horizontal grid to the statistics for these two case are generally small.

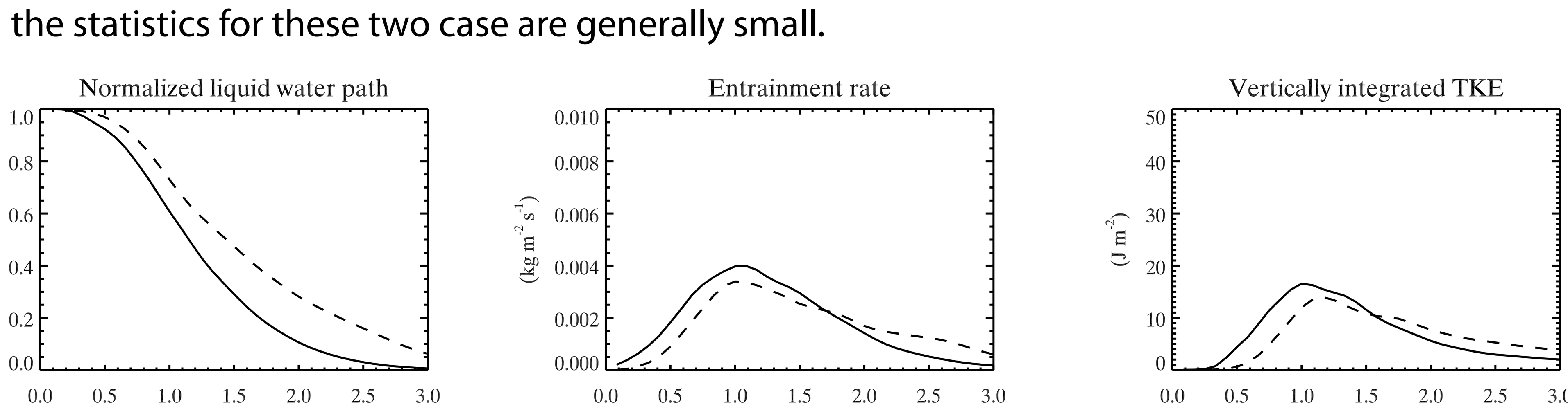


Fig. 5

Mixing line

Mixing line (Fig. 2) is reproduced with the joint PDF of mixing fraction and virtual potential temperature with both Δx=5 and 50 m cases (Fig. 6). Fig. 6 also shows PDF of mixing fraction. Time series of PDF and JPDF are computed at the initial inversion top height until 40 % of LWP is evaporated. During this time, the height becomes cloud layer.

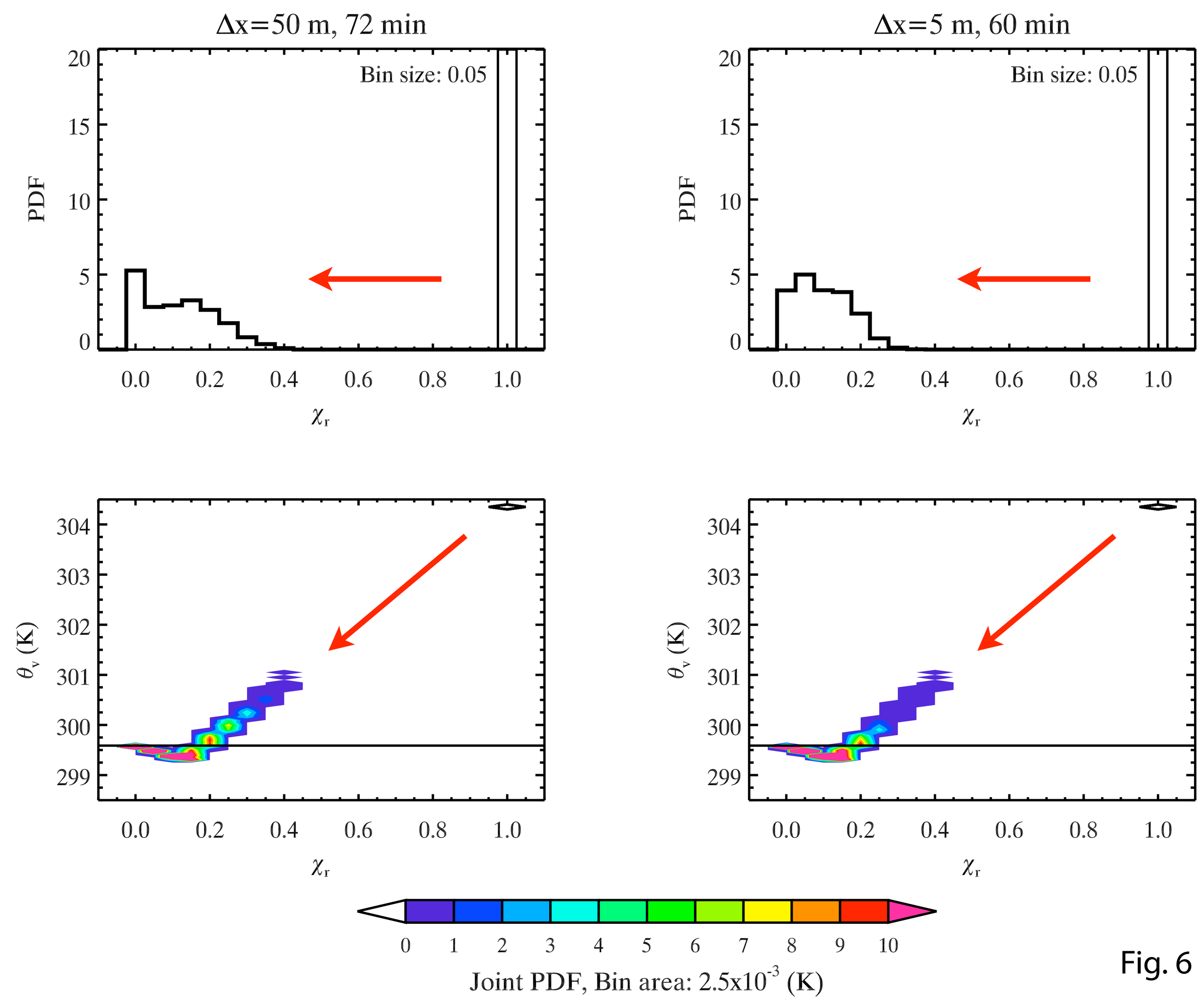


Fig. 6

Animating these PDF and JPDF shows that the PDF moves left spreading its distribution with tail at the right end, and JPDF moves along with the mixing line. There is no noticeable difference between two runs. Buoyancy reversal is taken place for both simulations.

CTEI Thermal Size

Analysis of the data obtained during DYCOMS-II observation, Gerber et al. (2005) reported the width of holes in marine stratocumulus cloud is about 5 m. With the application of the spatial statistics, the width of CTEI parcel can be estimated. Spatial autocorrelation and covariance of vertical velocity at hour 1 are presented in Fig. 7. These figures suggest that the width of entrained air parcel is about 10-15 m around cloud top (white arrows in the figures). Does this mean horizontal grid space should be smaller than 10 m for CTEI study with current SGS and microphysics models?

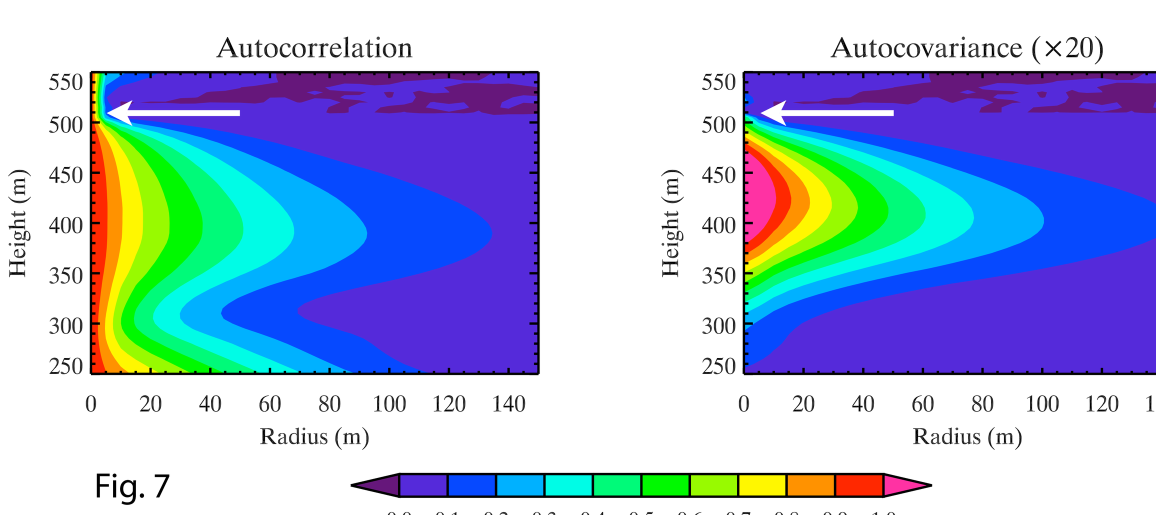
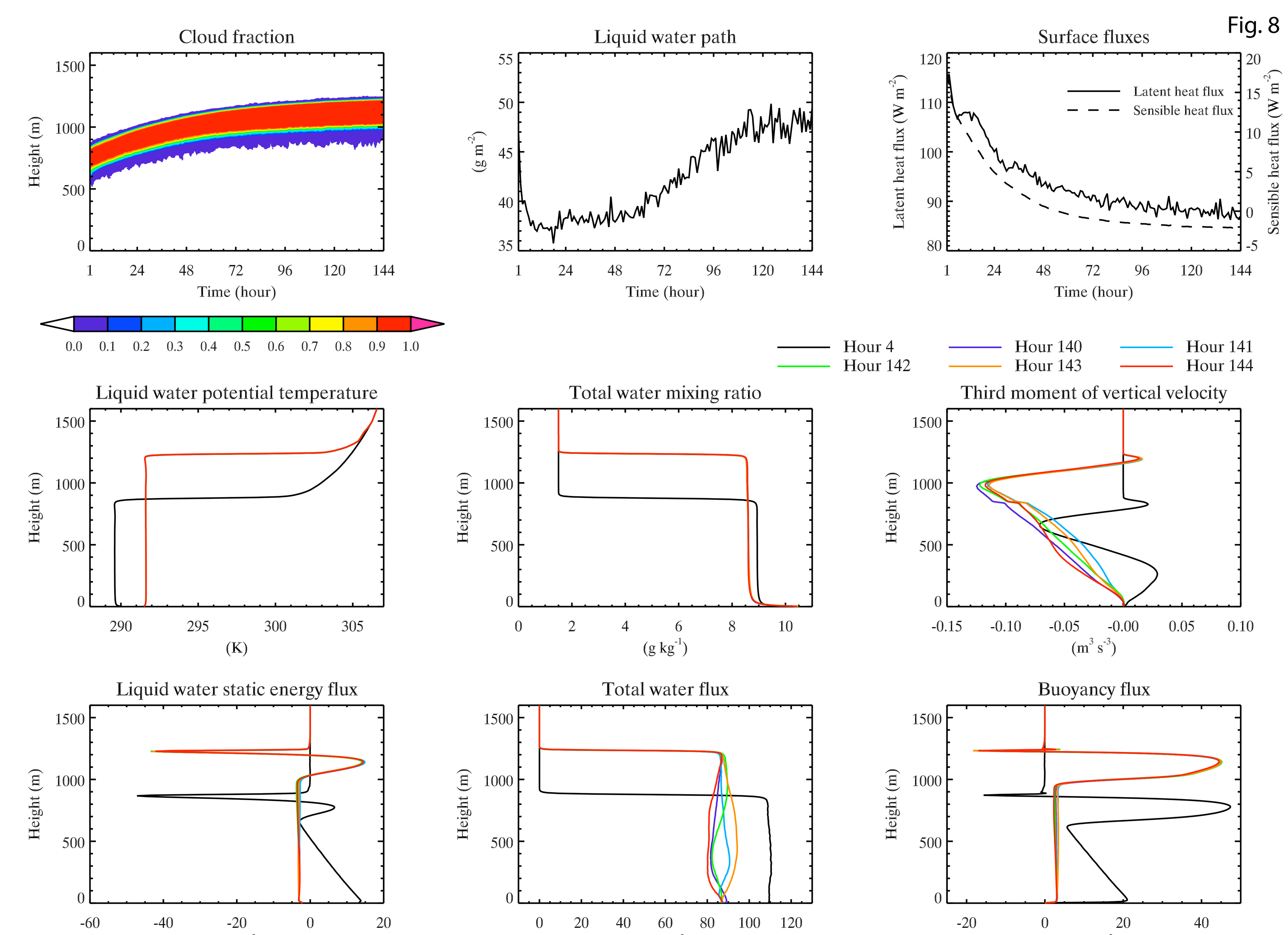


Fig. 7

Designing New Experiment

We have been designing new experiment to investigate the interaction between CTEI and cloud-top radiative cooling. DYCOMS-II LES (Stevens et al. 2008) is chosen because of the realistic model setup based on the observation. After six days, the PBL reaches a quasi-steady state (QSS), or radiative convective equilibrium (Fig. 8). The QSS is required for our experiment. Our target horizontal grid size is 8.75 m, which is four times smaller than the current Δx. After changing the resolution, we will restart the run until new QSS is reached with new mesh.

Fig. 8



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