# Turbulent mixing processes around the top of the boundary-layer stratocumulus cloud in large-eddy simulations

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## 1. Introduction

Cloud top entrainment instability (CTEI; Randall 1980; Deardorff 1980) is an interesting concept in understanding interaction between cloud and turbulence as well as in clarifying mechanisms of the decay of stratocumulus clouds. The CTEI theory says that stratocumulus clouds start to decay once the condition, $k > k_0$, is satisfied, where $k\,(=(C_p / L)\Delta\theta_e / \Delta q_t)$ is a CTEI parameter. $k_0$ is a constant, and recognized to be 0.2−0.7. $\theta_e$ and $q_t$ are equivalent potential temperature and total water mixing ratio, respectively, and $\Delta$ means a jump across an entrainment interface layer; *i.e.*, $\Delta \equiv \Phi_+ - \Phi_m$, where $\Phi_+$ and $\Phi_m$ are horizontal means for any conservative scalars. Scientists have however debated its roles in the real atmosphere (Kuo and Schubert 1988; Moeng 2000 (M00); Yamaguchi and Randall 2008 (YR08)), because we can expect that the rapid growth of the turbulence and subsequent dissipation of cloud deck would occur just across the CTEI condition, which are not observed features even in idealized LESs in M00 and YR08. We focus especially on the early stage of simulation results, and investigate how the turbulent mixing changes depending on *k*.

## 2. Model setup

We apply the DYCOMS-II environment (Ackerman et al. 2009, Fig. 1) to our LES study. To investigate cloud responses to the change of *k*, we conduct a control experiment (CTL) and 7 sensitivity experiments; vapor just above $z_i$ is increased/decreased at a 1 g kg$^{-1}$ interval against CTL. We define $z_i$ as the horizontal mean of cloud-top heights of each cloudy column. The sensitivity experiments are referred to as $R_{m1}$, $R_{m2}$, $R_{m3}$ and $R_{m4}$ ($R_{p1}$, $R_{p2}$ and $R_{p3}$) to the left (right) of CTL (Fig. 1a). Note that *k* increases with $q_{t+}$ decreases. The horizontal and vertical grid sizes are 50 m and 5 m, respectively. The size of the domain is 6.5 km x 6.5 km x 1.5 km. The objective of this study is to understand interaction between cloud and turbulence under a simplified condition; we leave other issues regarding a radiation process, heating from the earth's surface, and detailed microphysics processes such as an aerosol and cloud sedimentation effects, for future study.

## 3. Results and conclusion

Simulated liquid water paths (LWP) negatively correlated with *k* (Fig. 2), which agrees well with past LES studies (e.g., M00). For example, $R_{m4}$, which has the largest *k* value among them, experiences the most intense turbulent mixing across $z_i$, and its LWP decreases from 180 g m$^{-2}$ to less than 40 g m$^{-2}$. The rapid decays of LWP especially in $R_{m4}$−$R_{m1}$ occur in an early stage of the simulations (~3600 s), and their LWP values become in a nearly quasi-equilibrium state after then (not shown). To understand how the intense turbulent mixing occurs, we choose $R_{m4}$, and compute 1800-s backward trajectories of 100 air parcels that are put uniformly on the height of $z_i$ (800 m) after 3600 s. The result showed that the air parcels originated from the well-mixed cloudy layer (300~700 m) and from a dry layer just above $z_i$. On average, the former comes from the region more apart from $z_i$ (~0.77 $z_i$) due to the mixing by large eddies in the cloudy layer than the latter does. The latter originates very near $z_i$ (~1.01 $z_i$) (not shown).

A $q_t - \theta_l$ diagram (Fig. 3) indicates that the mean values of the air parcels at 3600 s (initial locations) (circle) are produced by the mixing between the former (square) and the latter (triangle) air parcels. To understand the mixing processes quantitatively, it is useful to introduce an idea of the mixing fraction (Albrecht 1985), $M_\Phi \left(\equiv \left(\Phi_{zi} - \Phi_m\right) / \left(\Phi_+ - \Phi_m\right)\right)$. We computed $M_q$ and $M_\theta$, and the results were about 0.15, which are values similar to previous studies (e.g., Kurowski et al. 2009). Figure 4 shows theoretically-expected buoyancy due to the mixing of two airs, $\left(q_{t+}, \theta_{l+}\right)$ and $\left(q_{tm}, \theta_{lm}\right)$. Buoyancy decreases until $M \approx 0.14$, because of evaporation of clouds, and it switches to increase across the value. It is interesting that the turbulent mixing across $z_i$ in LES occurs to make the resultant negative buoyancy maximum.

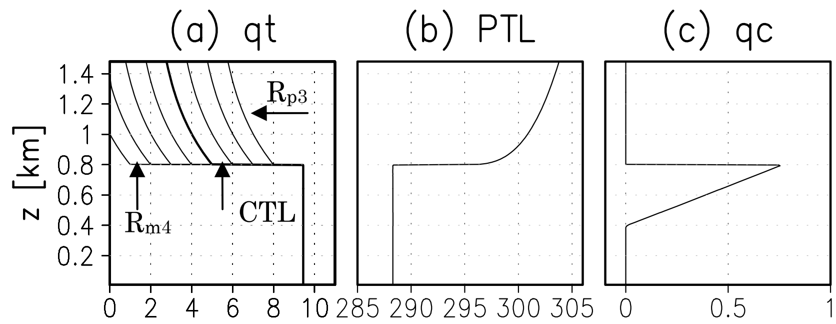
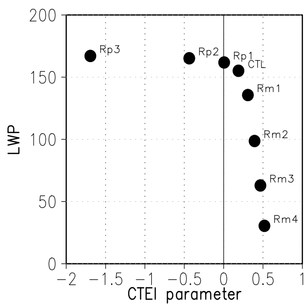
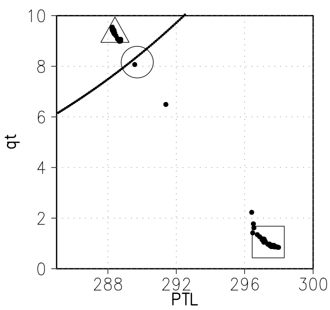



Fig. 1: Initial conditions for LESs of the stratocumulus-topped boundary-layer. (a) $q_t$ (g kg$^{-1}$), (b) $\theta_l$ (K) and (c) cloud water mixing ratio (g kg$^{-1}$). CTL (thick line) denoted in Fig. 1a is the one used in the DYCOMS-II study (Ackerman et al. 2009), and others for the present sensitivity study.



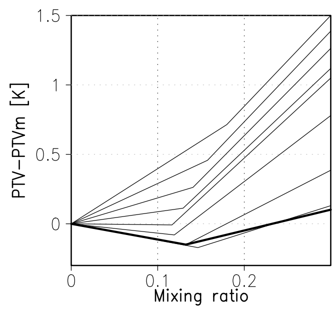




Fig. 2 (left): $k$–LWP diagram computed based on snap shots of horizontal means after 6 hrs. Lower to upper dots show the results of $R_{m4}$ to $R_{p3}$.

Fig. 3 (middle): $q_t - \theta_l$ diagram calculated based on the backward trajectories of $R_{m4}$. Dots show values at air parcels of $t = 1800$ s. Saturation mixing line at $z_i$ is drawn in the left upper. See text for the meanings of triangle, circle and square.

Fig. 4 (right): Theoretically-expected buoyancy generated by the mixing of unsaturated and saturated two air parcels. Lower to upper lines show the results for $R_{m4}$ to $R_{p3}$ (the result of $R_{m4}$ is bolded), and are estimated by horizontal means at $z_m = 0.77 z_i$ and $z_+ = 1.01 z_i$ of $t = 2700$ s.

## References

Ackerman, A. S., and coauthors, 2009: Large-eddy simulations of a drizzling, stratocumulus-topped marine boundary layer. *Mon. Wea. Rev.*, **137**, 1083-1110.

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

Deardorff, J. W., 1980: Stratocumulus-capped mixed layer derived from a three-dimensional model. *Boundary-Layer Meteor.*,**18**, 495-527.

Kurowski, M. J., S. P. Malinowski, and W. W. Grabowski, 2009: A numerical investigation of entrainment and transport within a stratocumulus-topped boundary layer. *Quart. J. Roy. Meteor. Soc.*, **135**, 77-92.

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

Randall, D. A., 1980: Conditional instability of the first kind upside-down. *J. Atmos. Sci.*, **37**, 125-130.

Yamaguchi, T., and D. A. Randall, 2008: Large-eddy simulation of evaporatively driven entrainment in cloud-topped mixed layers. *J. Atmos. Sci.*, **65**, 1482-1504.