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# FACTORS RESPONSIBLE FOR THE VERTICAL DEVELOPMENT OF TROPICAL OCEANIC CUMULUS CONVECTION

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## 1 INTRODUCTION

Cumulus convection over the warm pool region in the tropical western Pacific (TWP) plays an important role in driving the global atmospheric circulation and heat transport. Recent studies on tropical convection have been focused on the various types of cumulus clouds: not only shallow trade cumulus and deep cumulonimbus, but also cumulus congestus. It has been known that congestus clouds exhibit a significant part of tropical convection over the TWP warm pool region (e.g., Johnson et al. 1999). For the development of cumulus convection, Johnson et al. (1999) suggested that the mid-level stable layer is relevant to the heights of cumulus clouds, while Brown and Zhang (1997) showed that the mid- to upper-level dryness limit their tops. Redelsperger et al. (2002) examined the factors that control the height of tropical convection by cloud-resolving simulations and found that mid-level inversions and dry-air entrainment into clouds both limit the vertical extent of convection. Their simulations were carried out in realistic TOGA-COARE settings including the effects of large-scale circulation. The numerical experiments in rather idealized settings, however, would be more useful in order to elucidate the mechanisms of the interaction between cumulus convection and its environment.

This study investigates the factors responsible for the development of cumulus convection by use of observational data over TWP and cloud-resolving simulations in idealized settings.

## 2 OBSERVATIONAL EVIDENCE

The radiosonde data obtained by a Japanese research vessel called *Mirai* in TWP areas are used in order to classify the characteristic temperature and moisture profiles depending on precipitation amounts. The total observation periods were divided into three types: DRY1 (almost no rain, little cloud appearance); DRY2 (little rain, occasionally some cloud appearance); and RAINY (a lot of rain).

In each environmental condition, cumulus-type clouds are identified from multi-band infrared brightness temperature data from a Japanese satellite GMS with the use of cloud-classification algorithm of Inoue (1987) and Tokuno and Tsuchiya (1994). Figure 1 shows the frequency distribution of infrared data (at 11 $\mu$m wavelength, denoted as IR1) as well as cumulus-type clouds surrounding the *Mirai* location in the DRY1, DRY2, and RAINY periods. Comparing the three IR1 distributions, the distribution shifts toward cold temperatures from DRY1 to RAINY. Figure 1 clearly indicates that in DRY1 the most frequent cloud type is shallow cumulus, while in DRY2 and RAINY middle-topped congestus clouds can be identified and in RAINY a pronounced cold peak (cumulonimbus clouds) is also found. The analysis clearly reveals the existence of three modes of tropical cumulus convection.

Analyses of radiosonde data indicated that in DRY2 and RAINY the middle and upper levels are in a moist condition, while in DRY1 those levels are quite drier that those in the other two. On the other hand, temperature profiles showed the difference among the three periods seems not to be significant and, comparing the frequency of the appearance of stable layers ($> -4$ K/km), no significant difference among the three periods was identified in middle levels. Therefore, the development of the type of cumulus convection seems to be more relevant to moisture profile, especially at mid- to upper levels, than to temperature profile.

## 3 NUMERICAL EXPERIMENTS

Numerical experiments with a cloud-resolving model, the Advanced Regional Prediction System (ARPS), are performed to investigate in an idealized fashion the sensitivity of the vertical development of cumulus convection to moisture profile and stability.

The model is configured in a two-dimensional domain of 200 km (horizontal) by 25 km (vertical) with cyclic lateral boundaries with the grid sizes of 1 km (horizontal) and 50-950 m (vertical, stretched). Physics processes in our simulations include cold-rain microphysics, subgrid-scale turbulence, atmospheric radiative transfer, and surface physics. The initial temperature and moisture profiles are set based on the observations, but the initial atmosphere is assumed to be at rest. Time integrations are conducted for five days in order for the simulations to reach their equilibrium states, and the results during the last two days are analyzed.

As a control, we have conducted simulations initialized with the temperature and moisture profiles in the DRY1, DRY2, and RAINY periods and

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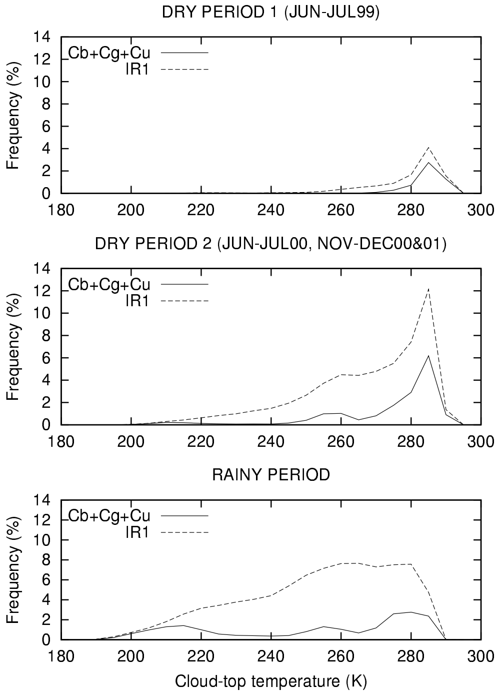
DRY PERIOD 1 (JUN-JUL99)

DRY PERIOD 2 (JUN-JUL00, NOV-DEC00&01)

RAINY PERIOD

FIG. 1: Cloud-top height distributions as the frequency of the IR1 and cloud-classified data.

confirmed the appearances of the basic features in the three periods even in rather idealized settings.

After the control simulations, two series of sensitivity experiments, i.e., sensitivities to moisture and temperature profiles are carried out. In all the following sensitivity experiments, temperature profiles are based on the DRY1 profile. In the first series, the moisture profiles are given by setting a humid layer from the surface to the height $H$ (which is taken from the RAINY moisture profile) and a dry layer above $H$ (which is taken from the DRY1 profile). The height $H$ is gradually increased from 1 km to 12 km at 1-km interval.

In the second series, the temperature lapse rate is varied from $-5.7$ (K/km) to $-3.7$ in the 4.5-5.5 km layer. The moisture profile used in this series of experiments is the same with the case of $H = 6$.

Figure 2 shows the vertical profiles of total water condensates mixing ratio averaged over the computational domain for the last two days. Results from the cases of DRY1 and $H = 1$, 4, 5, 6, and 8 km are chosen in the figure. Although the lowest 1 km is moistened (the case $H = 1$ km), cloud development is limited below the 6-km level. When $H$ is increased over 4 km, cloud development can be seen in middle and upper levels. Further increase in $H$ above 6 km results in pronounced frequency of condensation above the 10-km level.

Furthermore, our close examinations of the results indicated that the development of cumulus clouds was suppressed due to the entrainment of dry air in mid- to upper levels.

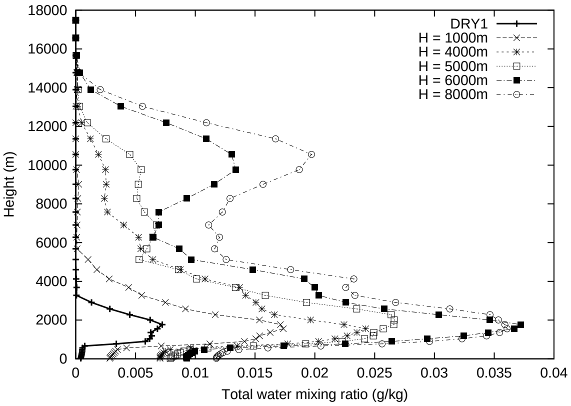

FIG. 2: Vertical profiles of water condensate mixing ratio (g/kg) averaged over the computational domain for the last two days in the moisture-sensitivity experiments.

From the sensitivity experiments changing the mid-level stability, it was shown that as the stability increases above $-4.5$ (K/km), middle-topped clouds become more and more significant. The observational evidence shows that the standard deviations of temperature lapse rates at the 4.5-5.5 levels are 1-2 (K/km), and thus the value of $-4.5$ seems to be a significantly stable state.

## 4 SUMMARY

Moisture profiles at mid- to upper levels play an important role in the vertical development of tropical convective clouds, and mid-level moist layer is favorable for the development of cumulus congestus and cumulonimbus clouds. The entrainment processes around cloud tops is a vital mechanism for the vertical development of convective clouds, and thus dry-air entrainment seems to be unfavorable for that development.

## ACKNOWLEDGMENT

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