P1.6

EFFECTS OF MOISTURE PROFILES ON THE MODE OF 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), and that these clouds can have a role in contributing to moistening and preconditioning the tropical atmosphere for deep organized convection. They suggested that the mid-level stable layer is relevant to the height of cumulus clouds. On the other hand, Brown and Zhang (1997) showed that the mid- to upper-level dryness limit the vertical development of cumulus convection. Redelsperger et al. (2002) examined the factors that control the height of tropical convection by using a cloud-resolving model 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 relationship between tropical cumulus convection and environmental temperature and moisture profiles by use of observational data over TWP and conducts a series of numerical experiments with a cloud-resolving model to examine the sensitivity of tropical convection to temperature and moisture profiles in idealized conditions.

2. OBSERVATIONAL ANALYSIS

2.1 Data

The observational data used in this study were obtained by a Japanese research vessel called *Mirai* at stationary locations in TWP area during four cruises in 1999-2001. R/V *Mirai* has many capabilities for carrying out meteorological and oceanographic observations, and this study uses data obtained by radiosonde, ceilometer, and surface air observations. Radiosonde observations were carried out every three hours. The ceilometer and surface meteorological data were obtained every one minute.

The duration time of the each observation was two to four weeks, and the four observation periods are listed in Table 1. These periods are classified into three categories considering rainfall amount: DRY1 (almost no rain, little cloud appearance); DRY2 (little rain, occasionally some cloud appearance); and RAINY (a lot of rain). The whole period of the 1999 observation is classified as DRY1, and the other periods are classified both into DRY2 and RAINY depending on the rainfall amount.

In addition to these in-situ data, multi-band infrared brightness temperature data from the Japanese Geostationary Meteorological Satellite (GMS) are used. The spatial resolutions of these data are 0.1 degree, and the data are obtained every one hour.

TABLE 1: List of the observation periods.

Year	Location	Period
1999	0°N, 165°E	20 Jun-5 Jul
2000	7°N, 140°E	19 Jun-1 Jul
2000	2°N, 138°E	27 Nov-11 Dec
2001	2°N, 138°E	9 Nov-9 Dec

2.2 Cumulus cloud distribution

Multiple infrared-channel data (at 11, 12, and 6.7 μm wavelengths) are useful in classifying cloud types. We use the techniques of Inoue (1987) and Tokuno and Tsuchiya (1994) to diagnose and classify cumulus-type clouds, i.e., cumulus, cumulus congestus, and cumulonimbus, and examine the cumulus distribution in TWP. In the each observation period, the analysis area extends 10 degrees by 10 degrees centered at the R/V *Mirai* location. Figure 1 shows the frequency distribution

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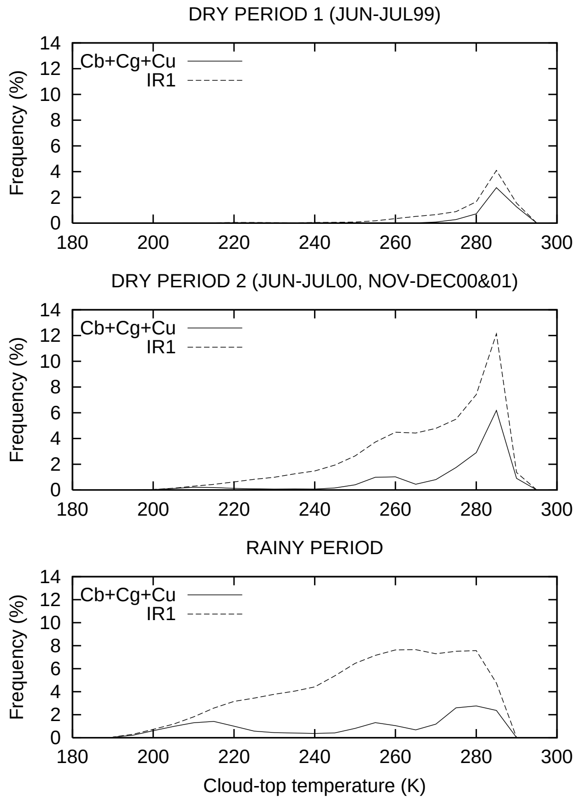

FIG. 1: Cloud-top height distributions as the frequency of the IR1 and cloud-classified data.

of infrared data (at 11 μm wavelength, denoted as IR1) as well as cumulus-type clouds in the DRY1, DRY2, and RAINY periods. Comparing the three IR1 distributions, the distribution shifts toward cold temperatures from DRY1 to RAINY, which demonstrates a similar feature found in the previous studies (e.g., Brown and Zhang 1997).

The cumulus-cloud distribution feature appears to be more remarkable if a cloud-classification scheme is used for the satellite data. 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.

This analysis clearly reveals the existence of three modes of tropical cumulus convection and suggests that the development of these cumulus clouds is related to dry or rainy conditions of tropical atmosphere.

2.3 *Environmental variability*

In this section the analysis of the sounding data is presented.

Figure 2 shows the vertical profiles of relative humidity averaged over the each category of the periods. In DRY2 and RAINY the middle to upper levels are in a moist condition, while in DRY1 those levels are quite drier that those in the other two. Comparing the time series of the vertical profiles of relative humidity in the DRY1, DRY2, and RAINY periods with the time variation of IR temperatures (figure not shown), good correlation between cloud-top height and mid- to upper-level relative humidity can be identified.

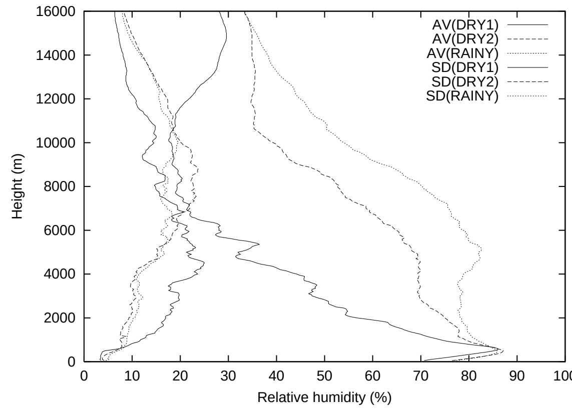

FIG. 2: The vertical profiles of the averaged relative humidity and its standard deviation in the DRY1, DRY2, and RAINY periods. AV denotes the averages, and SD the standard deviations.

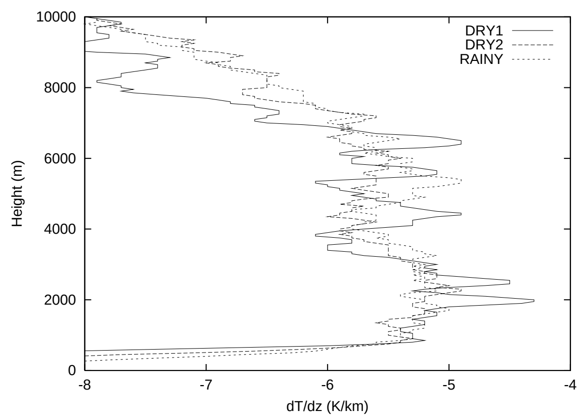

FIG. 3: The same as Fig. 2, except for stability (dT/dz).

Figure 3 shows the temperature profiles averaged over the three periods. At the heights of around 2 and 6 km, layers of high stability are found; however, the difference among the three periods seems not to be significant, except at the 2-km level in the DRY1 case. Comparing the frequency of the appearance of stable layers (> -4 K/km), no significant difference among the three periods was identified in the middle levels at around 5-6 km heights.

Comparing Figs. 2 and 3, the most significant difference among the DRY1, DRY2, and RAINY periods is the variance of mid- to upper-level humidity. Thus, 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

3.1 Model setup and experimental design

Numerical experiments with a cloud-resolving model are performed to investigate in an idealized fashion the sensitivity of the vertical development of cumulus convection to moisture profile and stability. The model used here is the Advanced Regional Prediction System (ARPS). The model is configured in a two-dimensional domain of 200 km (horizontal) by 25 km (vertical) with cyclic lateral boundaries. Physics processes in our simulations include cold-rain microphysics, subgrid-scale turbulence parameterization, atmospheric short-wave and long-wave radiation scheme, and surface physics. For simplicity, Coriolis effect is not included. The grid resolutions are 1 km in the horizontal and 50-950 m (stretched) in the vertical. The initial temperature and moisture profiles are set based on the observations, but the initial atmosphere is assumed to be at rest due to our philosophy of the idealized simulations. 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.

First, in order to check the performance of the model we have conducted simulations initialized with the temperature and moisture profiles in the DRY1, DRY2, and RAINY periods and confirmed that the basic features in the three periods were well-represented even in rather idealized conditions of resting atmosphere.

After these basic 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 given by the DRY1 profile with some modifications for the stability-sensitivity experiments. In the moisture-sensitivity experiments 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 (see Fig. 4 for the initial profiles).

In the stability-sensitivity experiments 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 RAINY profile in the lowest 6 km and the DRY1 profile in the above (i.e., $H = 6$ km).

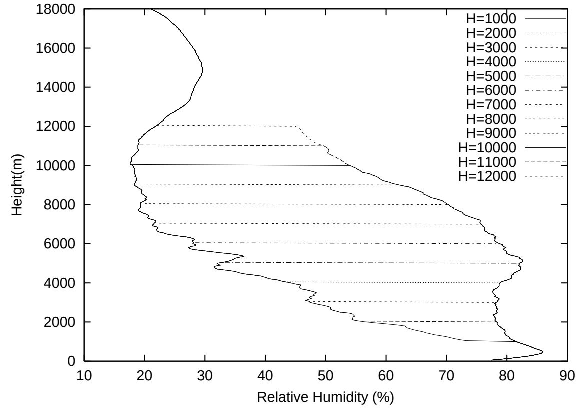

FIG. 4: The initial vertical profiles of relative humidity for the moisture-sensitivity experiments. H denotes the top height of the lower moist layer.

3.2 Sensitivities to moisture profiles

Figure 5 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.

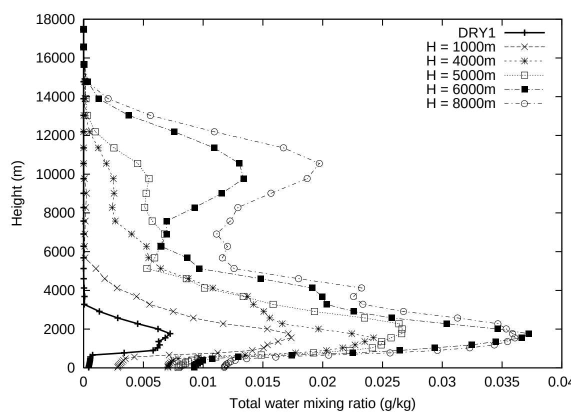

FIG. 5: Vertical profiles of water condensate mixing ratio (g/kg) averaged over the computational domain for the last two days in the moisture-sensitivity experiments.

The features shown in Fig. 5, however, may not account well for thin clouds near cloud tops, because in this figure high cloud mixing ratio within the main body of cloud would be highlighted. Thus, we examine the cloud-top distribution by

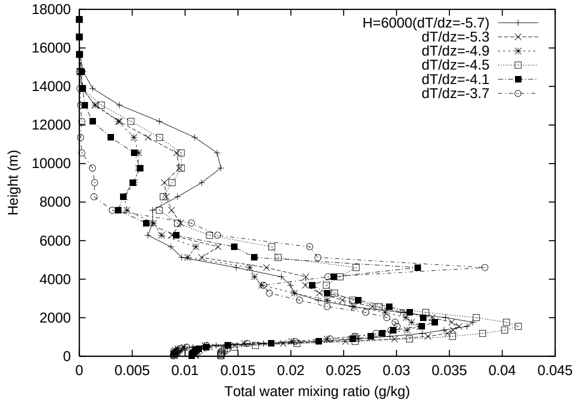

FIG. 6: The same as Fig. 5, except for the stability-sensitivity experiments.

defining clouds as total water mixing ratio exceeding 0.1 g/kg, and verified the existence of the three major cumulus peaks.

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.

One might argue that increasing moisture results in the increase in precipitable water content and so the increase in cloud formation, and therefore the feature of the vertical cloud development in increasing H shown in Fig. 5 seems to be taken for granted and only a reflection of increased precipitable water content. However, examining the relationship between the environmental precipitable water content and the simulated total precipitation, it was demonstrated that in the cases of $H \geq 6$ km total precipitation amount remarkably increases as compared to the cases of $H \leq 5$ km in which nearly linear correlations between precipitable water and precipitation can be identified. Therefore, the results shown in the moisture-sensitivity experiments take into account the effects of moisture profile on the mode of cumulus development.

3.3 Sensitivities to mid-level stability

Figure 6 shows the vertical profiles of water condensate amount for the stability-sensitivity experiments. As the stability in the mid-layer increases, the upper-level peak corresponding to deep cumulus clouds disappears. 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.

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