Limiting Factors for Convective Cloud Top Height in the Tropics

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Introduction

Populations of tropical convective clouds are mainly comprised of three types: shallow trade cumulus, mid-level cumulus congestus and deep convective clouds (Johnson et al. 1999). Each of these cloud types has different impacts on the local radiation and water budgets. For climate model applications it is therefore important to understand the factors which determine the type of convective cloud that will occur. In this study, we concentrate on describing the factors that limit the cloud-top heights of mid-level cumulus congestus clouds preventing them from growing into deep convective clouds. Mid-level cumulus congestus clouds are characterized by cloud-base heights near the lifting condensation level, cloud-top heights near the freezing level (~5 km in the tropics), a lack of ice hydrometeors, and measurable precipitation reaching the ground. Previous studies suggest that cumulus congestus cloud-tops are limited by either the entrainment of dry air from above the boundary layer or through the loss of buoyancy of rising parcels as they encounter a weak stable layer near the freezing level.

Convective Cloud Type

We use data from the Nauru99 intensive operational period (IOP) to investigate the role that each of these mechanisms plays in limiting convective cloud-top heights. In order to identify all cases of cumulus congestus and deep convection during Nauru-99 we use the Atmospheric Radiation Measurement (ARM) active remote sensing cloud layer (ARSCL) product (Clothiaux et al. 2000). This product uses a combination of reflectivity measurements from 35 GHz cloud radar and a micropulse lidar to describe the cloud boundaries and radar reflectivity. Figure 1 shows the convective cloud-top heights for the entire Nauru99 IOP from the ARSCL datastream where we have defined convective events as observations with an ARSCL cloud base height less than 2 km. This figure clearly shows the three modes of convective cloud occurrence discussed by Johnson et al. (1999). Boundary layer trade cumulus clouds are present throughout the entire IOP, cumulus congestus clouds (tops near the freezing level ~5 km) are very common while deep convective clouds occur less frequently.

We use the ARSCL product to define mid-level cumulus congestus cases where the cloud base height is below 2 km and the cloud-top height is between 3 and 9 km. Deep convective cases are identified when the cloud-base height is below 2 km and the cloud-top height is above 9 km. The choice of 9 km as the break point allows for the overshooting of the freezing level by cumulus congestus clouds and is

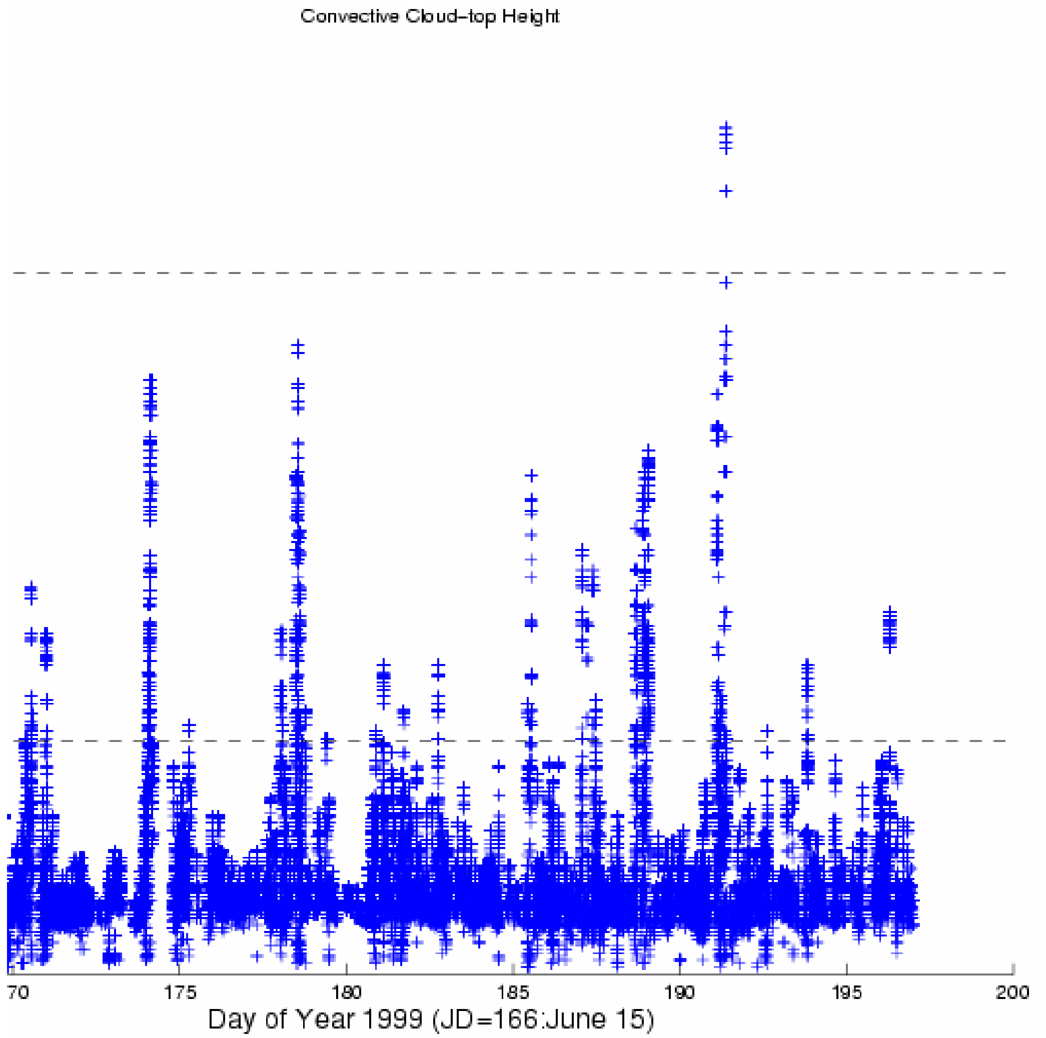

Figure 1. ARSCL convective cloud-top heights during Nauru-99 IOP.

consistent with the criteria used by Johnson et al. (1999). Using these definitions of cumulus congestus and deep convective clouds we define a total of 18 observations of cumulus congestus clouds and one deep convective case during Nauru99. Table 1 lists the times and ARSCL cloud-top heights for each of these cases.

Thermodynamic Analysis

Redelsperger et al. (2002) offer a rather complete summary of the different conditions that have been suggested to explain the limitation of cloud-top height in the case of cumulus congestus clouds. Three main explanations are offered: 1) The difference in cloud depth is a function of the environmental convective available potential energy, 2) that the buoyancy of congestus cloud elements are limited by weak stable layers and/or 3) that congestus cloud tops are limited by entrainment of dry environmental air above the boundary layer. We use the sounding data from the Nauru-99 IOP in order to address each of these conditions.

Table 1. Summary of the characteristics for all mid-level and deep convective cases during the Nauru-99 IOP.

JD-HH (GMT) (nearest sounding)	ARSCL Cloud-Top Height (m)	LNB (m)	Entrainment Rate (%/km)
168-05	5143	15850	19
168-17	5773	15312	8
170-11	4963	13566	17
170-23	3523	13330	29
173-23	7395	9183	4
175-05	3208	13163	25
177-23	4423	13152	5
178-11	6403	13847	4
178-11	8068	13847	4
182-17	5098	13343	24
185-12	3478	13099	31
186-17	5458	14519	11
187-05	5188	13733	20
188-17	5728	14841	17
188-17	4918	14841	18
193-17	3973	14194	10
196-05	4648	14775	23
191-05 deep	9000	14222	10

We have concentrated our analysis to the Nauru99 time period because of the higher frequency of radiosonde profiles during this IOP. During Nauru99 radiosondes were launched approximately once every three hours as opposed to twice per day during routine site operations. This relatively high frequency of radiosonde observations captures some of the evolution of atmospheric thermodynamic profiles on convective time scales.

Figure 2a shows the convective available potential energy (CAPE) as a function of time over the entire Nauru-99 IOP. CAPE is calculated as defined by Moncrieff and Green (1972),

$$\mathrm{CAPE} = \int g \left[(\theta_{v,p} - \theta_{v,\,env}) / \theta_{v,\,env}\right] dz$$

where g is the accelerations of gravity, $\theta_{v,p}$ is the virtual potential temperature of a parcel that is lifted from the surface, $\theta_{v,\,env}$ is the virtual potential temperature of the environmental sounding and the integration is taken from the level of free convection to the equilibrium level of the surface parcel. The observation times of cumulus congestus (X) and deep convective (o) observations are indicated by the symbols on the horizontal axis. The CAPE ranges between approximately 4000 and 8000 Jkg^{-1}, however, there is no obvious correlation between the value of CAPE and the presence (or lack) of cumulus congestus or deep convective clouds. Figure 2b shows a scatter diagram of the ARSCL cloud-top height for the cumulus congestus and deep convective cloud cases and the CAPE from the nearest sounding. There is little or no dependence of the cloud-top heights on the environmental CAPE. This is consistent with the conclusions of Redelsperger et al. (2002) who show similar cloud-top heights resulting in similar environmental CAPE conditions during the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE). Sherwood (1999) showed that although there is a minimum amount of CAPE necessary for convection to occur in the tropics, increased CAPE does not necessarily result in more vigorous convection.

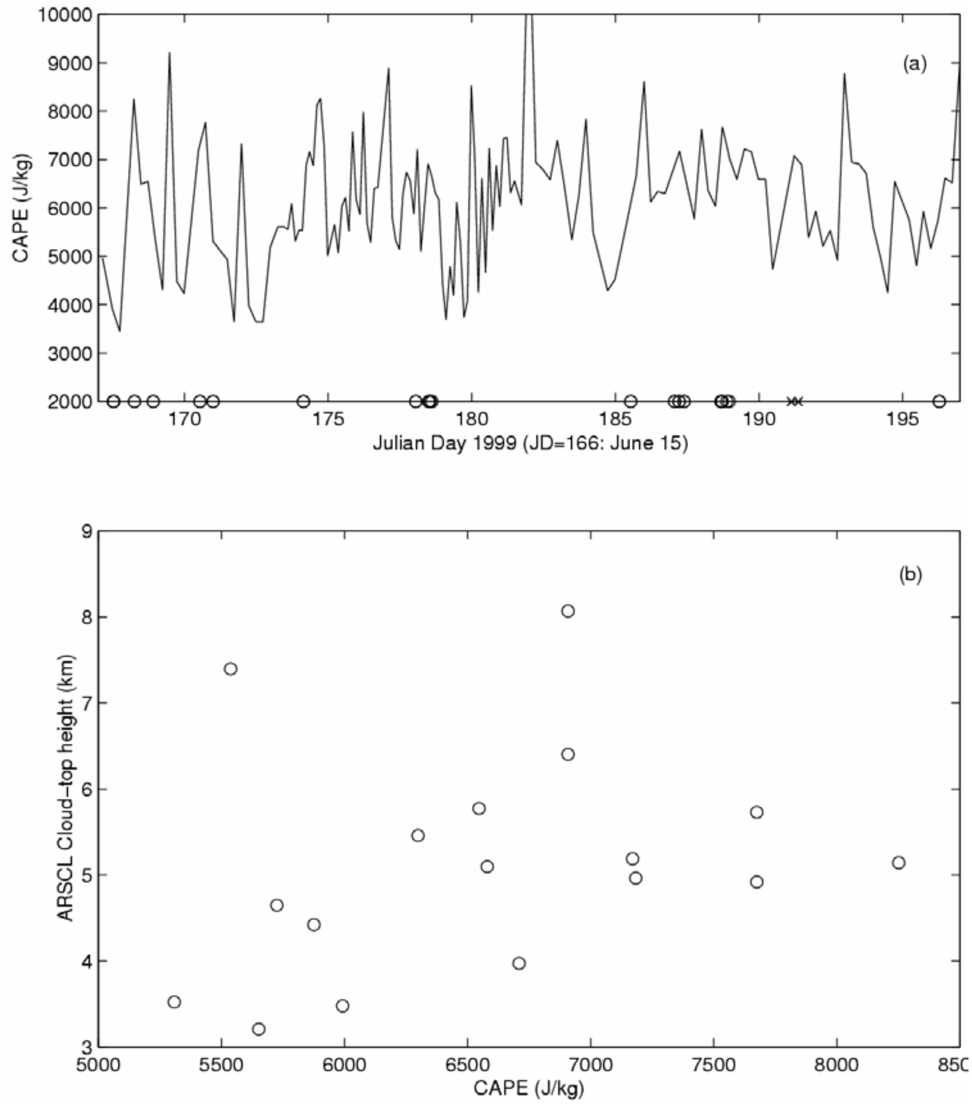

Figure 2. (a) Time series of CAPE during the Nauru99 IOP. (b) CAPE vs. cloud-top height for the 18 cumulus congestus cases summarized in Table 1.

We use modified parcel theory to evaluate the role of the environmental temperature and humidity profiles on cloud-top height. If we consider a case with a parcel rising adiabatically through the tropical environment, we can determine the temperature of the parcel through the conservation of equivalent potential temperature. The equivalent potential temperature is calculated using the approximate relationship derived by Bolton (1980):

$$2_e = 2\exp(2.675w/T_{lcl})$$

where all variables are defined for the parcel and 2 is the potential temperature, w is the water vapor mixing ratio and T_{lcl} is the temperature at the lifting condensation level and is given by:

$$T_{lcl} = 56 + 1/(1/(T_d-56)+\ln(T/T_d)/800)$$

where T and T_d are the temperature and dew point of the parcel respectively. In order to evaluate the buoyancy of the rising parcel, we compare 2_e of the parcel to the saturated equivalent potential temperature of the environment

$$2_{es} = 2\exp(2.675*w_s/T)$$

where w_s is that saturation mixing ratio of the parcel. Generally a parcel begins with $2_e < 2_{es}$ of the environment. As the parcel rises, conserving 2_e, it will eventually have a 2_e equal to the 2_{es} of the environment; this is the level of free convection (LFC). As the parcel rises above the LFC it is positively buoyant and will continue to raise until eventually 2_e is equal to the 2_{es} of the environment again, this is the level of neutral buoyancy (LNB). Above the LNB the parcel becomes negatively buoyant and tends to return to the LNB. Assuming adiabatic ascent, i.e., no mixing of environmental air, we can determine the LNB for any given sounding. The third column in Table 1 contains the LNB determined from the sounding nearest each of the cumulus congestus cases. Neglecting overshooting cloud-tops the LNB is an approximation of convective cloud-top height assuming adiabatic ascent. The LNBs shown in the third column of Table 1 are much higher than the ARSCL cloud-top heights shown in column 2 of Table 1.

Entrainment

In reality, the ascent of a parcel is never adiabatic. The development of convective elements is altered by the entrainment of environmental air. If the rising convective element is near saturated then the entrainment of unsaturated environmental air will decrease the buoyancy of the rising element resulting in a decrease of the LNB (We will designate the level of neutral buoyancy of an entraining parcel as LNB* to distinguish it from the adiabatic case). Entrainment will therefore be a major determining factor of convective cloud-top heights. In order to estimate the entrainment of environmental air for each of the cumulus congestus cases we assume a constant entrainment rate with height (Brown and Zhang 1997) and determine a new profile of

$$2_e = (2_e(\text{parcel}) + F\,)\, z\, 2_e(\text{environment}))/(1+ F)$$

where F is the entrainment rate in km^{-1} and) z is the change in height of the parcel. From this profile of 2_e for the entraining parcel a new level of neutral buoyancy (LNB*) will be determined. We begin with an entrainment rate of 0.1%/km and increase the entrainment rate in steps of 0.1%/km until the new level of neutral buoyancy is approximately equal to the cloud-top height from the ARSCL data product.

We assume that this entrainment rate is correct and investigate the role that environmental thermodynamics play in the determination of convective cloud-top height. If a climatological thermodynamic profile is conducive to the formation of deep convective clouds then substituting the climatological temperature or relative humidity (RH) profile from Nauru-99 for a cumulus congestus profile should result in an increase in the LNB* to deep convective levels. We will use a cloud-top height (i.e., LNB*) of 9 km as the benchmark for deep convective clouds. We also assume that the entrainment rate does not change from our original estimate (a decrease in the entrainment rate in itself will increase the LNB*). The resulting LNB* after substituting the climatological thermodynamic profiles for each of the 18 cumulus congestus cases is shown in Figure 3a. None of the congestus cases show an increase in the level of neutral buoyancy above 9 km when substituting the climatological temperature sounding. Several of the cases show the requisite increase in the level of neutral buoyancy when the climatological MPL is substituted.

In order to better discern which of the mechanisms suggested above may be more important in limiting convective cloud growth we can extend this analysis to consider more extreme cases where the mid-level moisture is very high or where the freezing level is most unstable. For each case we have kept the entrainment rate consistent with the values shown in Table 1. For each cumulus congestus case we first substitute the RH profile from the nauru99 sounding with the highest mid-level (5.5-7.5 km) RH and determine the LNB*. We also determine LNB* after substituting the temperature profile from the Nauru99 sounding that is most unstable (least stable) near the freezing level. Figure 3b summarizes these results showing that for most cases a change to a very moist mid-level results in a change in LNB* to deep convective levels, however, for only a few cases does a change in the temperature profile to a most unstable freezing level result in an appreciable difference in the LNB*. This suggests that for cumulus convective clouds during the Nauru99 experiment, the mid-level humidity plays a more significant role in suppressing the growth of deep convective clouds. This result would suggest that the entrainment of dry air from above the boundary layer is more important than the presence of weak stable layers in limiting convective cloud heights during Nauru-99.

Convective Cloud Depth Parameterization

The results from the analysis above suggest that both the mid-level humidity, affected by intrusions of dry air from the sub-tropics, and freezing level stability, affected by the freezing of tropical anvil clouds play a role in limiting convective cloud depth in the tropics. Figure 4 shows the mid-level humidity plotted versus the stability just below the freezing level for each of the defined cumulus congestus cases. Cumulus congestus cases occur in all four quadrants of the plot except the bottom right where midlevel humidity is high and freezing level stability is low. Although we cannot conclude which physical mechanisms cause the limitation of convective cloud-top height from this plot, we can hypothesize which mechanisms may be responsible for the location of each point on this plot. Points lying in the lower right hand quadrant of this plot would be indicative of deep convection. Points in the upper right hand quadrant are likely congestus limited by the increased stability due to anvil melting. Points in the

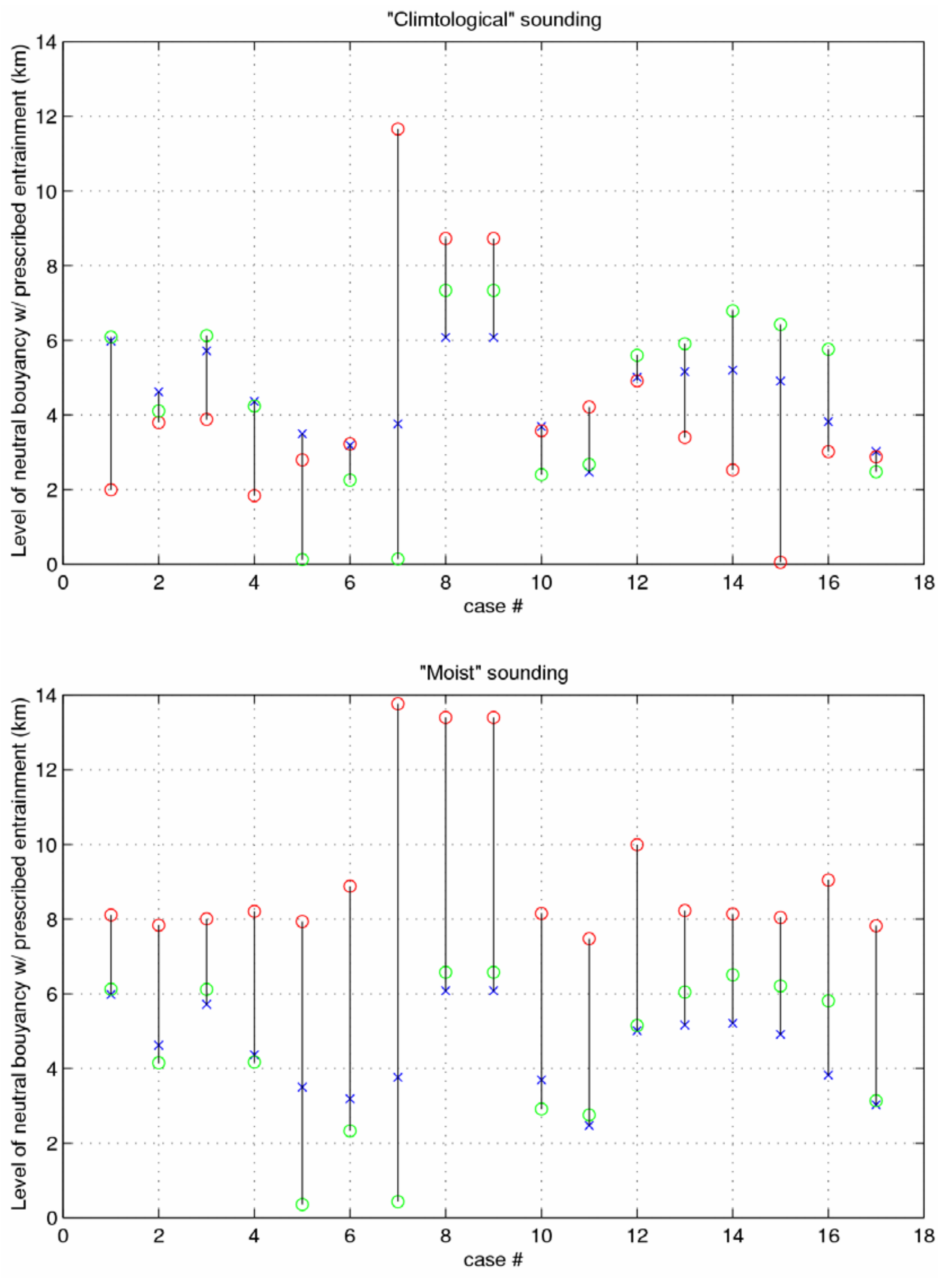

Figure 3. (a) LNB* for cumulus congestus cases summarized in table 1 (X) including the substitution of climatological MPL (red circles) and temperature (green circles) profiles. (b) Same as a, but includes the substitution of the MPL from the sounding with the moistest mid-level during Nauru-99 (red circles) and the temperature from the sounding that is most unstable near the freezing level during Nauru-99 (green circles).

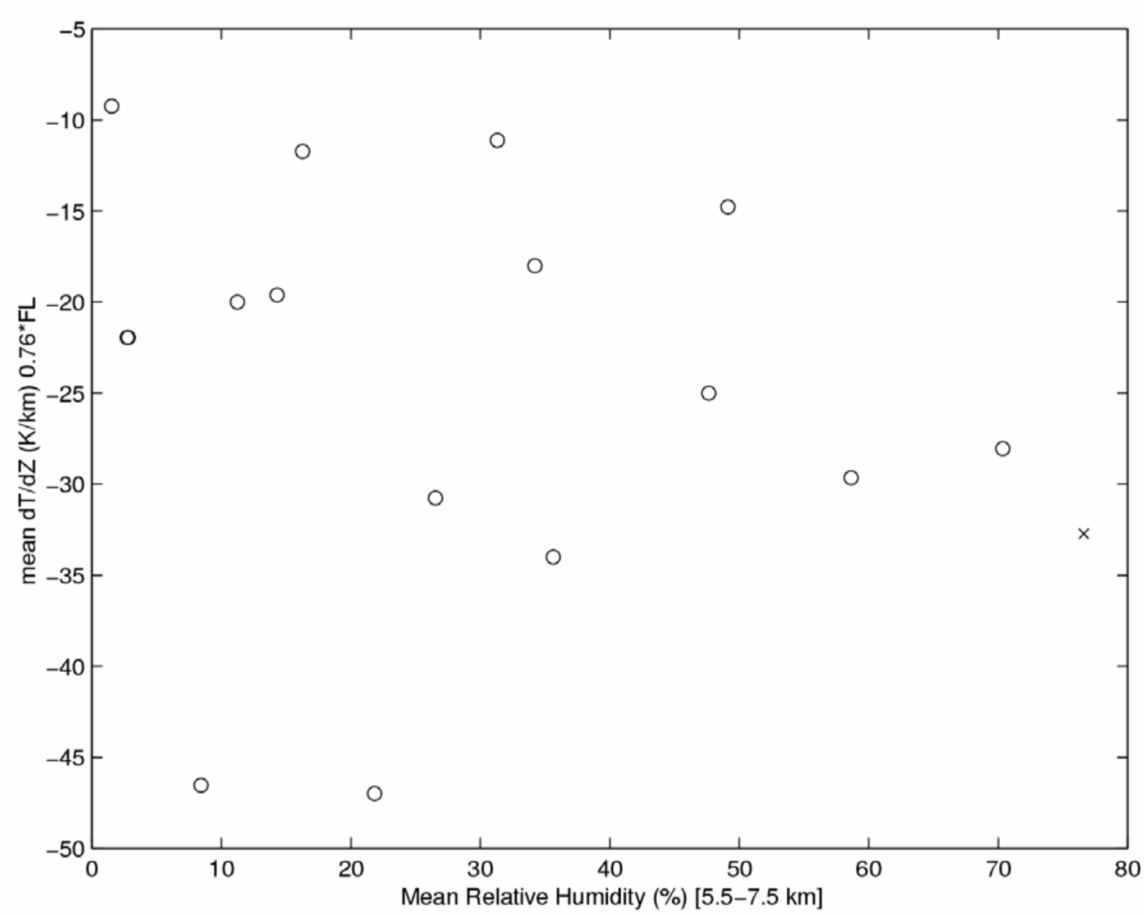

Figure 4. Mean mid-level (5.5-7.5 km) RH vs. vertical temperature gradient at Z = 0.76* freezing height level for the 18 cumulus congestus cases summarized in Table 1. Cumulus congestus cases are indicated by (o), while deep congestus cases are indicated by (x).

lower left hand quadrant are congestus limited by the intrusion of dry air at mid-levels and points in the upper left represent some combination of dry intrusions and anvil melting. These results have implications for the parameterization of convective cloud depth in climate models.

References

Bolton, D., 1980: The computation of equivalent potential temperature. *Mon. Wea. Rev*., **108**, 1046-1053.

Brown, R. G., and C. Zhang, 1997: Variability of mid-tropospheric moisture and its effect on cloud-top height distribution during TOGA-COARE. *J. Atmos. Sci*., **54**, 2760-2774.

Clothiaux, E. E., T. P. Ackerman, G. G. Mace, K. P. Moran, R. T. Marchand, M. A. Miller, and B. E. Martner, 2000: Objective determination of cloud heights and radar reflectivities using a combination of active remote sensors at the ARM CART Sites. *J. Appl. Meteor*. **39,** 645-665.

Johnson, R. H., T. M. Rickenbach, S. A. Rutledge, P. E. Ciesielelki, and W. H. Shubert, 1999: Trimodal characteristics of tropical convection. *J. Climate*, **12**, 2397-2418.

Moncrieff, M. W., and J.S.A. Green, 1972: The propagation and transfer properties of steady convective overturning in shear. *Quart. J. Roy. Meteor. Soc*., **98**, 336-352.

Redelsperger, J. -L., D. B. Parsons, and F. Guichard, 2002: Recovery processes and factors limiting cloud-top height following the arrival of a dry intrusion observed during TOGA COARE. *J. Atmos. Sci*., **59**, 2438-2457.

Sherwood, S. C., 1999: Convective precursors and predictability in the tropical Western Pacific. *Mon. Wea. Rev*., **127**, 2977-2991.