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NOTES AND CORRESPONDENCE

Moistening Processes in the Upper Troposphere by Deep Convection: A Case Study over the Tropical Indian Ocean

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Abstract

Moistening processes in the upper troposphere are examined by relating upper tropospheric humidity (UTH) estimates from SSM/T-2 and Meteosat measurements to convective clouds over the Indian Ocean. Results are compared against NCAR/CCM3 outputs. The analysis separating the tropics into four cloud areas, i.e., deep convective, middle cloud, thin cirrus, and clear/low cloud area, indicates that the upper troposphere above the clear/low cloud area becomes drier (moister) in response to increases (decreases) in convective activity in the tropics. On the other hand, the area between deep convective cloud clusters, and clear/low cloud area, also appears to be moistened by thin cirrus originating from deep convective clouds. Although the CCM3 model reproduces the average number of cloud clusters found in the satellite observations, the model-derived UTH shows significantly different features, i.e., a drier upper troposphere within deep convective clusters, a much higher UTH over the clear/low cloud area, and a slight increase of UTH over the clear/low cloud area with respect to increases in the deep convective area, suggesting that the model needs more accurate physics for better description of the moistening/drying processes.

1. Introduction

Recent climate model estimates suggest that water vapor feedback brings about an increase in climate sensitivity by a factor of 2 (IPCC 2001). Although this is largely explained by the notion that the atmosphere can hold more water vapor at higher temperatures, because of a nearly constant behavior of relative humidity (Manabe and Wetherald 1967), the sensitivity largely depends on the humidity of the upper troposphere under warmer climate conditions. However, it is questionable whether the general circulation model, used for such sensitivity tests, can successfully reproduce the moisture changes found in observational studies, although some progress is apparently being made in this area (e.g., Soden et al. 2002).

There have been studies showing a positive relationship between deep convection and upper tropospheric humidity (UTH)—see Udelhofen and Hartmann (1995) and McCormack et

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al. (2000). In contrast some other studies (e.g., Lindzen 1990) have argued that enhanced deep convection would result in an overall drier upper troposphere through the compensating environmental subsidence. Furthermore, it was argued that water vapor feedback should also be viewed in terms of respective changes in moist and dry areas, in conjunction with convection changes in the tropics (Lindzen et al. 2001). These studies emphasize the importance of moistening processes in the upper troposphere, which are considered to be one of the key elements in understanding the water vapor feedback in the climate system.

For a better understanding of moistening processes in the tropical upper troposphere, we examine the relationship between the convection and UTH within deep convective cloud clusters, and the associated moisture changes in the areas away from the cloud clusters. We do so using satellite measurements of infrared and microwave radiation over the tropical Indian Ocean during January 1999. In addition, in order to examine whether the general circulation model can simulate moistening processes found in satellite observations, we use the National Center for Atmospheric Research (NCAR) Community Climate Model version 3 (CCM3), as a reference case.

2. Datasets and methodology

Satellite data used in this study are from Meteosat-5 and the Special Sensor for Microwave/Temperature-2 (SSM/T-2), onboard the Defense Meteorological Satellite Program (DMSP) F14. Meteosat-5, located at 63°E, provides half-hourly infrared measurements over the Indian Ocean. Brightness temperatures from the infrared window (10.5–12.5 μm), and water vapor (5.7–7.1 μm) channel measurements during January 1999, are used for identifying clouds and estimating UTH over the analysis domain bounded by 25°N–35°S and 30°E–110°E. Since the satellite only measures the radiation input to the detector in terms of a unit (i.e., count), it is necessary to convert the measured count value into the corresponding physical unit (i.e., radiance). In this study, Meteosat measured count values (0.25° gridded data obtained from the Laboratoire de Meteorologie Dynamique (LMD) of France), are converted into brightness temperatures, by applying the calibration coefficients provided by the European Organisation for the Exploitation of Meteorological Satellite (EUMETSAT).

We processed satellite images in two different ways. First, in order to examine UTH variations within the deep convective cloud clusters, SSM/T-2 183.3 ± 1 GHz microwave measurements are used for the UTH retrieval, since infrared measurements are cloud-contaminated in the presence of high clouds. Secondly, to examine the relationship between the total size of the deep convective cloud clusters, and the UTH outside the deep convective region, UTHs are obtained from Meteosat measurements. In order to predict SSM/T-2-like UTH from Meteosat water vapor (WV) channel measurements, a transfer function is applied, relating WV channel brightness temperature to SSM/T-2 183.3 ± 1 GHz brightness temperature, as described in Sohn et al. (2000). To test the credibility of this approach, we compare UTHs from collocated SSM/T-2 and Meteosat-5 measurements. All match-ups are collected if their observation time differences are within 30 minutes, and then data are binned into $2.5^\circ \times 2.5^\circ$ grid values—see Fig. 1. The correlation coefficient is 0.96 with no apparent bias, indicating that UTHs obtained from Meteosat using the transfer function are comparable to SSM/T-2 estimated UTHs.

In order to compare the general circulation model's depiction of moistening processes in the upper troposphere with those revealed from satellite data analysis, we use NCAR CCM3 (version 3.6.6) with a T42 horizontal resolution, 18 vertical levels, and a semi-Lagrangian moisture transport scheme (Kiehl et al. 1998). The model is initialized with National Centers for Environmental Prediction (NCEP) reanalysis, from 1 September 1998 and run through 31 January 1999. The period from 1 September through 31 December 1998 is included only for the model spin-up, and thus it is excluded for the analysis. Observed monthly sea surface temperatures are used for specifying surface boundary conditions. Outputs from a control run are used to determine cloud types and their respective sizes. SSM/T-2 brightness temperatures, are simulated using CCM3 data as input to a microwave transfer model described in Sohn et al. (2003), with the output used for the UTH retrieval.

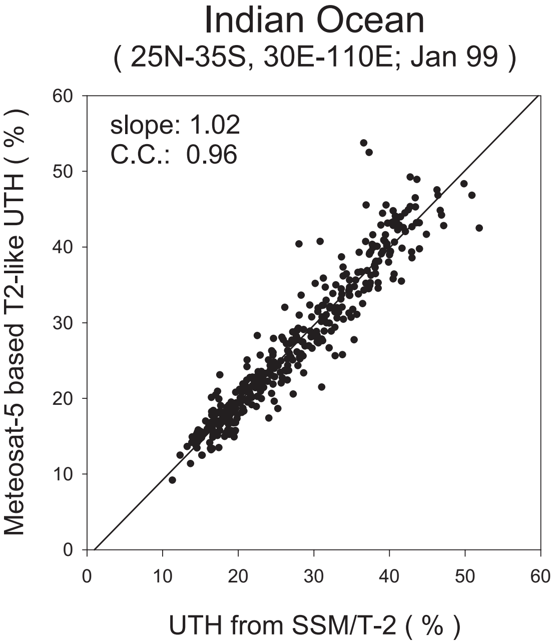

Fig. 1. Scatterplot of monthly mean UTHs from SSM/T-2 183.31 ± 1 GHz brightness temperatures and SSM/T-2-like brightness temperatures converted from Meteosat-5 water vapor channel brightness temperatures for January 1999. Each closed circle represents the value in a 2.5° × 2.5° grid box.

3. Cloud classification

Cloud classification is necessary for examining the moistening processes associated with cloud development. Following Roca and Ramanathan (2000) and Roca et al. (2002), each 0.25° Meteosat grid pixel is labeled as one of four cloud categories, depending on the infrared window brightness temperature (T_{ir}), and the WV channel brightness temperature (T_{wv}). The categories are as follows: (1) if $T_{\mathrm{ir}} \leq 260$ K, then pixels are regarded as convectively-driven clouds, including cirrus anvil clouds detrained from cumulus towers—hereafter referred to as deep convective clouds; (2) pixels with $260 \text{ K} < T_{\mathrm{ir}} \leq 270$ K are regarded as middle clouds; (3) if $T_{\mathrm{ir}} > 270$ K and $T_{\mathrm{wv}} > 246$ K, then pixels are considered as low clouds or clear-sky; (4) lastly, if $T_{\mathrm{ir}} > 270$ K and $T_{\mathrm{wv}} \leq 246$ K, then pixels are labeled as thin cirrus, because the weighting function for the WV channel peaks at a higher altitude than for the IR channel, so that the presence of transparent high clouds results in T_{wv} much colder than T_{ir} (Roca et al. 2002). Thus, type (4) clouds are likely located at altitudes similar to those of type (1).

In order to derive the same cloud quantities as in Meteosat measurements from the CCM3 results, maximum overlapping is used to redistribute CCM3 clouds vertically (Klein and Jakob 1999). Bulk cloud emissivity is calculated for high clouds in the 50∼400 hPa layer, and then clouds are determined to be thin cirrus if the emissivity is less than 0.5 (Jin et al. 1996).

After determining cloud types according to the above criteria, a cloud clustering algorithm is applied to type (1) clouds from both Meteosat-5, and CCM3, to identify deep convective cloud clusters in which adjacent cloud pixels share their boundaries. The total number of cloud clusters thus obtained is about 5000 for the satellite data, and about 1300 for the CCM3 output.

4. Results

To examine UTH dependence on the size of the deep convective cloud clusters, we first calculate the average number of cloud clusters in each Meteosat image, and in the CCM3 output. Also calculated is the number of cloud clusters shown in the SSM/T-2 path, over the analysis domain. Results are given in Fig. 2a. The number of cloud clusters observed in the Meteosat-5 images decreases rapidly with increasing size from isolated small convective clouds to highly organized convective systems, similar to the findings of Roca and Ramanathan (2000). The average number in the SSM/T-2 path is an order of magnitude smaller than for Meteosat, because of the smaller SSM/T-2 coverage. Assuming that SSM/T-2 coverage should not be biased to any particular geographical location in the analysis domain on monthly time scales, such a downscaled number throughout the size spectrum is not surprising. On the other hand, the number of cloud clusters in the CCM3 simulation, shows a pattern similar to that found in Meteosat observations, although the grid size is about ten times larger than in the Meteosat-5 low-resolution image. The similar trend found between Meteosat and CCM3, indicates that both data sets show a wide spectrum of spatial scales for the deep convective cloud clusters over the tropical Indian Ocean.

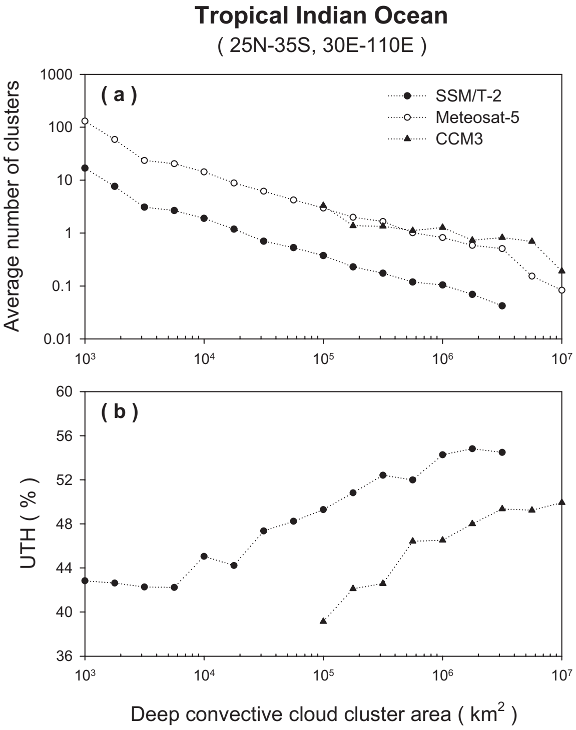

Fig. 2. Distributions of (a) average number of deep convective cloud clusters and (b) mean UTH as a function of the cluster size over the Tropical Indian Ocean. Closed circles represent SSM/T-2 satellite observations for January 1999, while closed triangles represent CCM3 results. Open circles in (a) represent Meteosat-5 measurements.

UTHs from SSM/T-2, and CCM3, are given in Fig. 2b as a function of the size of deep convective cloud clusters. UTHs from Meteosat are not provided because of the cloud contamination of WV channel measurements over the clusters. Since the number of clusters shown in the SSM/T-2 path has the same trend as in the Meteosat data, and there is no reason to expect that the SSM/T-2 coverage is biased by geographical location on monthly time scales, we expect the SSM/T-2 derived UTH to represent the domain average. It is noted that the upper troposphere becomes more humid as the size of cloud clusters increases, i.e., UTH increases from about 43%, at a cluster size of 10^3 km^2 to 54% at 3×10^6 km^2. Since the convection core area increases relative to the cloud cluster area (Roca and Ramanathan 2000), the positive relationship between UTH and cluster size suggests that there may be more hydrometeors detrained from the larger convection core, when the cloud cluster size becomes larger. However, it can be pointed out that more detrainment of hydrometeors should not be singled out as a reason of maintaining such positive relationship, because the amount of detrained hydrometers is highly correlated with other dynamical and physical variables, such as vertical velocity within the convection core or cloud top height.

The CCM3 model also produces a wetter upper troposphere as the cluster size increases, as seen in the satellite observations, despite the simplified treatment of moist convection processes in the model. However, it is clear that CCM3 produces a drier upper troposphere compared to what is suggested from satellite observations.

As the tropical convection is linked to the region outside of the convective area through a large-scale Hadley-type circulation, it is of interest to examine how convection changes over the tropics influence UTH outside the convective area, in particular over the subtropics. In doing so the fractional area of deep convective cloud is compared against the mean UTH over the non-convective areas, using both Meteosat observations and CCM3 outputs (Fig. 3). Meteosat shows an increasing humidity in the upper troposphere, with a slope of 0.12 as the deep convective area increases. Although the scatter is large with a correlation coefficient of 0.26, the apparent positive slope suggests that the non-convective area becomes wetter, as the convective activity is enhanced over the tropics.

CCM3 results show a similar positive relationship, with a correlation coefficient of 0.33, also suggesting that the humidity outside the convective area is positively correlated with the tropical convection area. However, the average humidity is higher than from Meteosat. Considering that the thermally direct Hadley-type circulation connects those two regions, the higher humidity over the non-convective area is consistent with lower humidity over the convective area, shown in Fig. 2b. Since more vigorous updrafts over the tropical convective area induce strengthened sinking motion mainly over the subtropics, the features noted in the

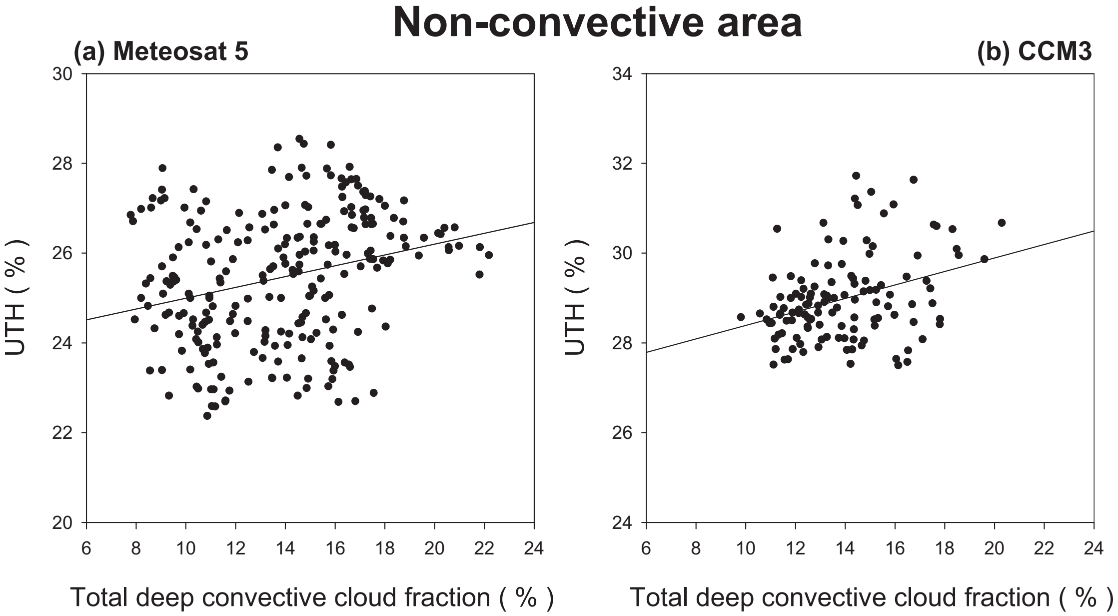

Fig. 3. Scatterplot of mean UTH of the non-convective area with respect to total deep convective cloud fraction over the tropical Indian Ocean. (a) Left panel represents satellite observations and (b) right panel represents CCM3 results for January 1999.

CCM3 results suggest that the Hadley-type circulation in the CCM3 model atmosphere, is weaker than that implied by satellite observations, as noted in moister upper troposphere in the subtropics (Zurovac-Jevtić and Zhang 2003) and as shown in the DJF mean meridional stream function (see Fig. 23 of Hurrell et al. 1998).

We further examine the relationship between the convective area over the tropics, and the UTH over the clear/low cloud area in Fig. 4. Satellite observations indicate a decreasing trend of UTH with respect to the increase of deep convective cloud over the tropics, with a slope of −0.16, suggesting that stronger deep convection results in a drier upper troposphere over the clear/low cloud regions, as also noted in Sohn and Schmetz (2004). By contrast CCM3 exhibits a slightly increasing UTH, with a slope of 0.05 and a much more scattered pattern. Since strengthened downward motion associated with increased convection over the tropics should induce drier subtropics, the near-zero or weak positive slope strongly suggests that the moistening processes in the upper troposphere are not adequately represented by the CCM3 model.

Considering that the difference between Fig. 3 and Fig. 4 is due to middle and thin cirrus clouds, the positive slope shown in Fig. 3a strongly suggests that the upper troposphere is also moistened by middle and thin cirrus clouds. This finding is consistent with other studies by Betts (1990), Soden (1998), and Sherwood (1999) that the upper troposphere can also be moistened in the presence of middle and thin cirrus clouds. By contrast the contribution by middle and thin cirrus to the moistening of the upper troposphere, is not clear in the CCM3 results, because UTH variations in both Fig. 3b and Fig. 4b are positively correlated with the amount of deep convective cloud over the tropics.

5. Conclusions

Satellite analysis shows that the humidity within the convective area increases with the size of deep convective cloud clusters. Outside the convective area, the middle and thin cirrus clouds also moisten the upper troposphere, while the clear/low cloud area dries when convective activity increases in the tropics. It seems that enhanced convection over the tropics will be followed by an expansion of the

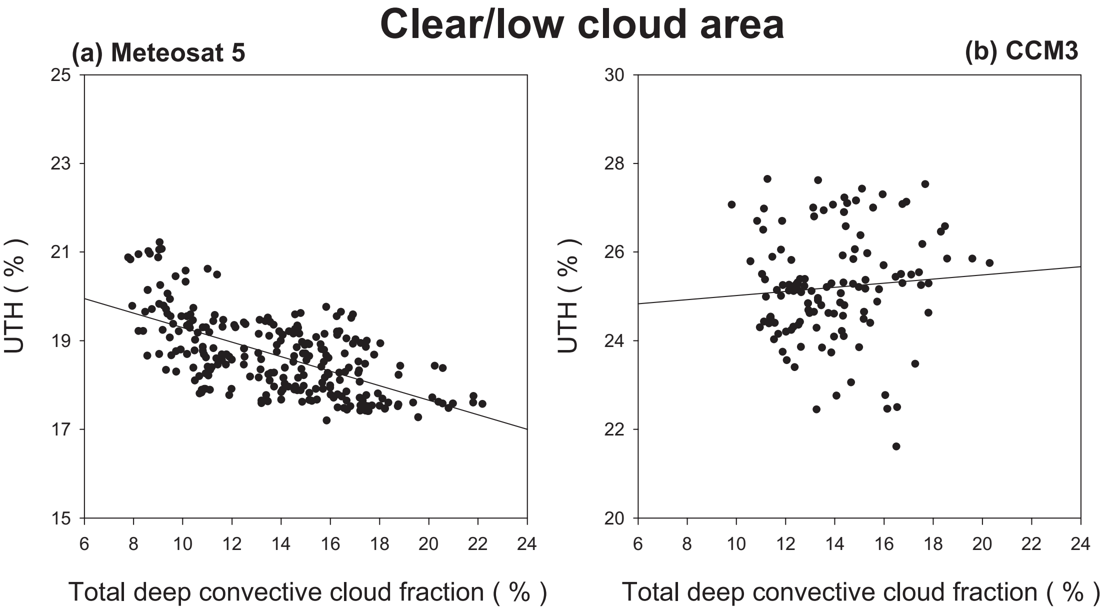

Fig. 4. Scatterplot of mean UTH of clear/low cloud area with respect to total deep convective cloud fraction over the tropical Indian Ocean. (a) Left panel represents satellite observations and (b) right panel represents CCM3 results for January 1999.

moister area, while the optically thin dry area becomes drier in response to the expansion of the moist cloudy area. Compared to those found in satellite analysis, the CCM3 results showed quite different moistening patterns, although the CCM3 UTH also shows an increasing trend with respect to the size of deep convective cloud clusters. In reality, the CCM3 results do not show a clear indication that middle or thin cirrus clouds also moisten the upper troposphere. Furthermore, the CCM3 results fail to depict a drier upper troposphere over the clear/low cloud area in response to increased convective activity over the tropics. It is suggested that CCM3 may have a weaker Hadley circulation in the tropical Indian Ocean, than that inferred from satellite observations.

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