On the warming in the tropical upper troposphere: Models versus observations

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[1] IPCC (Intergovernmental Panel on Climate Change) AR4 (Fourth Assessment Report) GCMs (General Circulation Models) predict a tropical tropospheric warming that increases with height, reaches its maximum at ~200 hPa, and decreases to zero near the tropical tropopause. This study examines the GCM-predicted maximum warming in the tropical upper troposphere using satellite MSU (microwave sounding unit)-derived deep-layer temperatures in the tropical upper- and lower-middle troposphere for 1979–2010. While satellite MSU/AMSU observations generally support GCM results with tropical deep-layer tropospheric warming faster than surface, it is evident that the AR4 GCMs exaggerate the increase in static stability between tropical middle and upper troposphere during the last three decades. **Citation:** Fu, Q., S. Manabe, and C. M. Johanson (2011), On the warming in the tropical upper troposphere: Models versus observations, *Geophys. Res. Lett.*, *38*, L15704, doi:10.1029/2011GL048101.

1. Introduction

[2] One pronounced feature in GCM (general circulation model)-predicted climate change in the 21st century is the much enhanced maximum warming in the tropical upper troposphere near ~200 hPa [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. This feature has important implications to the climate sensitivity because of its impact on water vapor, lapse rate, and cloud feedbacks [e.g., *Colman*, 2001; *Hartmann and Larson*, 2002] and to the change of atmospheric circulations [e.g., *Held*, 1993; *Butler et al.*, 2010]. It is therefore critically important to observationally test the GCM-simulated maximum warming in the tropical upper troposphere.

[3] There have been extensive research activities to examine tropical tropospheric versus surface temperature trends [*Karl et al.*, 2006; *IPCC*, 2007]. Strong observational evidence indicates that the tropical tropospheric temperature changes more than the surface on the multi-decadal time scale [e.g., *Fu et al.*, 2004; *Fu and Johanson*, 2005; *Santer et al.*, 2005, 2008] although some analyses still suggest the opposite [e.g., *Christy et al.*, 2007]. But there is little observational study, to date, to examine the temperature trend difference between tropical upper- and lower-middle troposphere [*Fu and Johanson*, 2005].

[4] Early GCMs [e.g., *Manabe and Wetherald*, 1975] also predicted larger warming in tropical upper-troposphere than in lower- troposphere, but not as much as that from the recent IPCC (Intergovernmental Panel on Climate Change) AR4 (Fourth Assessment Report) GCMs [*IPCC*, 2007]. It is also evident that the lapse rate feedback of the IPCC AR4 GCMs [*Soden and Held*, 2006] is larger than the older GCMs [*Colman*, 2003]. In this note, we examine the trends of temperature differences between tropical upper- and lower-middle troposphere based on satellite microwave sounding unit (MSU) observations and compare them with the AR4 GCM simulations for 1979–2010. It is shown that these trends from observations are significantly smaller than those from AR4 GCMs, a direct consequence of the much enhanced simulated warming in the tropical upper troposphere. The MSU data sets and GCM simulations used in this study are described in section 2. Section 3 shows the comparison of GCM results with the observations. The causes of the discrepancy between models and observations are discussed in section 4. Summary and conclusions are given in section 5.

2. MSU Data Sets and GCM Simulations

[5] The MSU, since 1979, and its successor, the Advanced MSU (AMSU), from 1998, provide global coverage of temperature for several atmospheric deep layers from NOAA polar-orbiting satellites. A continuing community effort of MSU/AMSU data-analyses has been made since 1990s to satisfy the climate research requirements of temporal homogeneity and calibration [*Karl et al.*, 2006; *IPCC*, 2007]. Several important non-climatic influences have been identified and removed, including diurnal temperature biases related to local sampling times of the satellite and their changes over its lifetime, warm target related errors in the MSU/AMSU calibration, and biases due to decay of the satellite orbits [e.g., *Wentz and Schabel*, 1998; *Christy et al.*, 2003; *Fu and Johanson*, 2005; *Mears and Wentz*, 2005; *Zou et al.*, 2006]. Although atmospheric deep-layer temperature time series derived from different research groups still give diverse trend results, the MSU/AMSU atmospheric deep-layer temperatures represent one of the most reliable data sets for the trend analyses.

[6] The nadir brightness temperatures measured by MSU channels 2 (T_2) and 4 (T_4) are widely used for monitoring temperature changes in the troposphere and stratosphere, respectively. Although the T_2 signal is mainly from the troposphere, the stratospheric contribution in the T_2 trend is significant [*Fu et al.*, 2004; *Fu and Johanson*, 2005]. To correct for the stratospheric influence, the University of

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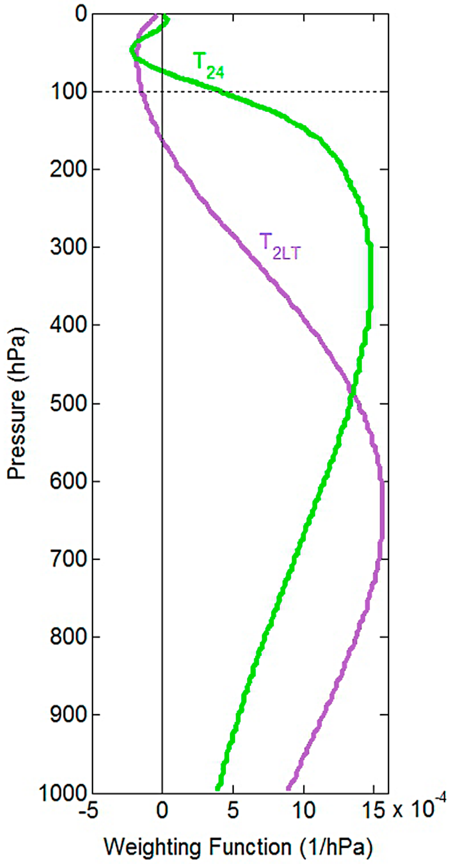

Figure 1. The effective weighting function of T_{24} and T_{2LT}. The tropical tropopause is set at 100 hPa.

Alabama at Huntsville (UAH) team created a synthetic channel called T_{2LT}, where LT means "lower-middle troposphere", by subtracting signals at different view-angles of MSU Channel 2 [*Spencer and Christy*, 1992]. *Fu et al.* [2004] developed a simple technique to derive the tropospheric temperature based on a linear combination of T_2 and T_4. In the tropics, the tropospheric temperature can be derived from $T_{24} = 1.1T_2 - 0.1T_4$ [*Fu et al.*, 2004; *Fu and Johanson*, 2005]. The effective weighting functions for T_{24} and T_{2LT} are shown in Figure 1 in units of 1/hPa, which reach the maximum at the tropical upper- (~300 hPa) and lower- (600 hPa) middle troposphere, respectively. Therefore, T_{24} and T_{2LT} derived from MSU/AMSU observations provide an ideal product to examine the GCM-predicted much enhanced warming in the tropical upper troposphere.

[7] We will employ T_2, T_4, and T_{2LT} monthly brightness temperature from both UAH [*Christy et al.*, 2003] (version 5.4) (http://www.ssmi.com/msu/msu_data_description.html) and the Remote Sensing System (RSS) (http://www.nsstc.uah.edu/data/msu/) [*Mears and Wentz*, 2009a, 2009b] (version 3.3) teams. We will also use T_2 and T_4 from the NOAA team [*Zou et al.*, 2006] (version 2.0) (http://www.star.nesdis.noaa.gov/smcd/emb/mscat/mscatmain.htm). (There is no T_{2LT} product from the NOAA team.) They are all gridded (2.5° × 2.5°) data sets from 1979 to 2010. The tropical region from 20°N–20°S is considered.

[8] The surface temperature data will be from HadCrut3v [*Brohan et al.*, 2006], GISTEMP [*Hansen et al.*, 2010], and NCDC [*Peterson and Vose*, 1997]. The NCDC data is based on blended GHCN v3 (Global Historical Climate Network) land surface temperature data with SSTs from ERSST v3b [*Smith et al.*, 2008]. The most up to date version of ERSST (v3b) does not incorporate satellite data due to a residual cool bias that was identified in the SST trends.

[9] Model simulations of the 20th and 21st centuries from a collection of GCMs are used. They are from the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model data set [*Meehl et al.*, 2007] which are used by *IPCC* [2007] AR4. The 20C experiments in many of these GCMs terminated in either 1999 or 2000 but the observations that we use extend until 2010. For a comparison with observations, the 20C simulations are extended by appending model simulations from the start of the SRES A1B scenario to the end of each model's 20C data. Only 20C runs with branches to A1B runs are used to create the model data for 1979–2010. The time series have been examined closely and there are no discontinuities at the splicing points. For a direct comparison with observations, T_2, T_4, and T_{2LT} are produced by applying the weighting functions to the GCM simulated temperature profiles.

3. Temperature Trend Difference Between Tropical Upper- and Lower-Middle Troposphere

[10] Figure 2 shows the trends of temperature differences between tropical upper- and lower-middle troposphere (i.e., T_{24}-T_{2LT}) from both observations and models for 1979–2010. The error bars of 95% confidence intervals are given by considering the effects of temporal auto-correlation [e.g., *Santer et al.*, 2008]. The results from each model ensemble member and the multi-model ensemble mean are shown. For the latter, we first derive the individual model ensemble mean and the multi-model ensemble mean is obtained by averaging the individual model ensemble means.

[11] The trends of T_{24}-T_{2LT} from both observations and models are all positive (Figure 2), indicating that the tropical upper-middle troposphere is warming faster than lower-middle troposphere [*Fu and Johanson*, 2005]. But the positive trends are only about 0.014 ± 0.017 K/decade from RSS and 0.005 ± 0.016 K/decade from UAH, which are not significantly different from zero. In contrast, the T_{24}-T_{2LT} trend from multi-model ensemble mean is 0.051 ± 0.007 K/decade, which is significantly larger than zero. The trends from observations and multi-model ensemble mean do not fall within each other's 95% confidence intervals, suggesting that they are significantly different from each other. Note that 30 out of 36 model ensemble members have the T_{24}-T_{2LT} trends significantly larger than zero. Four of the six ensemble members that have insignificant trends greatly overestimate the interannual variability (comparing the error bars of these ensemble members with observations in Figure 2), which leads to insignificant T_{24}-T_{2LT} trends. Furthermore, the trends from RSS (UAH) fall within 95% confidence intervals of only 8 (6) ensemble members while the trends from only two realizations fall within 95% intervals of observed trends. The trend in T_{24}-T_{2LT} has much less error bars than trends in T_{24} or T_{2LT} alone because the subtraction removes much of the common variability in tropical upper- and lower-tropospheric temperatures. Thus tests using trends in

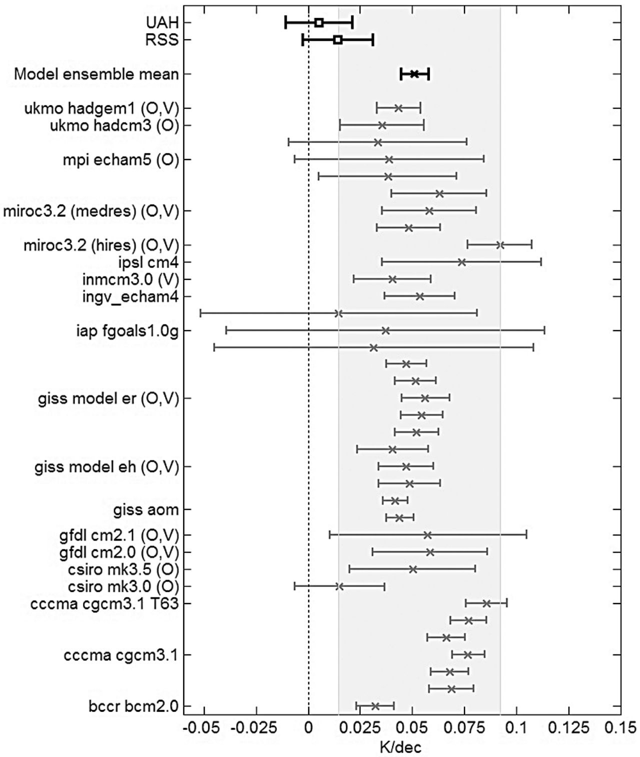

Figure 2. Trends of T_{24}-T_{2LT} for 1979–2010 with error bars of 95% confidence intervals with consideration of auto-correlation. The observational results are given by thick black squares and lines while model results are given by the light black crosses and lines for each model ensemble member. Multi-model ensemble mean result is in thick black crosses and lines. The gray shading encompasses the range of the individual model ensemble member trends. O and V in the parentheses after the model names indicate that the model considers the stratospheric ozone depletion/volcanic eruptions.

T_{24}-T_{2LT} are more stringent to identify significant trend discrepancies between models and observations.

[12] We further examine statistical significance of the differences between model results and observations in T_{24}-T_{2LT} trends using the two-sample tests [*Lanzante*, 2005]. It is found that the trends of $(T_{24}\text{-}T_{2LT})_{model}\text{-}(T_{24}\text{-}T_{2LT})_{obs.}$ time series based on RSS (UAH) is significantly larger than zero at 95% confidence intervals (considering auto-correlations) for 27 (29) out of 36 model ensemble members. Among the 9 (7) ensemble members that did not show significant differences from observations, seven of them (including ensembles from MPI ECHAM5, IAP FGOALS1.0g, and GFDL CM2.1) largely overestimate the interannual variability, causing insignificant differences from observations. We conclude that the T_{24}-T_{2LT} trends from AR4 GCMs for 1970–2010 are significantly larger than observations and that significant positive T_{24}-T_{2LT} trends from AR4 GCMs are not supported by the observations.

[13] Figure 3 shows the difference time series between T_{24} and T_{2LT} from observations and multi-model ensemble mean. The time series from RSS and UAH agrees well with each other. The interannual variability in observations is largely driven by ENSO (El Nino–Southern Oscillation). There are much smaller variability in the multi-model ensemble mean time series (Figure 3) and thus much smaller error bar in its trend (Figure 2). This is because the interannual variability is largely smoothed out by multi-model ensemble averaging. We can see a steady positive trend from simulations but little trend from observations. Figure 3 indicates that our results should not be sensitive to the starting/ending points considered although a long period of time from 1979 to 2010 does help obtain a statistically meaningful comparison between model simulations and observations.

4. Discussion

[14] The trend discrepancies between model simulations and observations in T_{24}-T_{2LT} (Figure 2) may be due to biases in the MSU/AMSU data, common errors among models, or a combination of both. Table 1 shows that the T_{24} trends over tropics for 1979–2010 are 0.160 K/decade from RSS but 0.089 K/decade from UAH, which are, respectively, larger and smaller than the averaged observed surface temperature trend of ~0.122 K/decade. [The T_{24} trend from NOAA MSU/AMSU data set is 0.196 K/decade.] The discrepancies in tropical tropospheric temperature trends from various teams are caused by both uncertainty internal to the data set due to measurement and construction errors [*Mears et al.*, 2011] and the structural uncertainty due to applying a different set of reasonable processing choices [*Thorne et al.*,

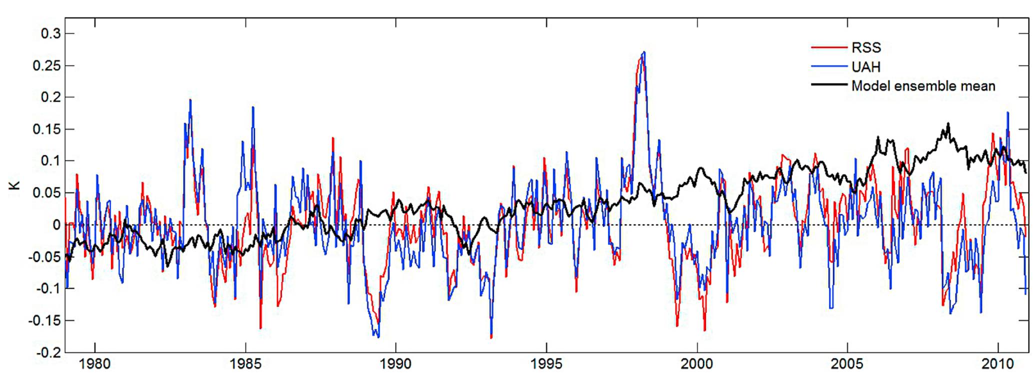

Figure 3. Difference time series between T_{24} and T_{2LT} over tropics (20°N–20°S) from observations based on RSS (thin red line) and UAH (thin blue line) data sets, and from multi-model ensemble mean (thick black line).

Table 1. Temperature Trends (K/dec) at the Surface (T_s), in the Lower-Middle Troposphere (T_{2LT}), and in the Upper-Middle Troposphere (T_{24}) over the Tropics (20°N–20°S) for 1979–2010 from Observations and the CMIP3 Multi-model Ensemble Mean[a]

T_s	T_{2LT}	T_{24}
	Observations	
0.130 ± 0.083 (NCDC)	0.145 ± 0.118 (RSS)	0.160 ± 0.133 (RSS)
0.115 ± 0.100 (GISTEMP)	0.084 ± 0.124 (UAH)	0.089 ± 0.134 (UAH)
0.122 ± 0.105 (HadCrut3v)		0.196 ± 0.138 (NOAA)
	Model Ensemble Mean	
0.192 ± 0.058	0.257 ± 0.075	0.309 ± 0.082

[a]The 95% confidence intervals are given with consideration of auto-correlation.

2005]. It is beyond the scope of this paper to reconcile the discrepancies among various MSU/AMSU data sets although it is worth noting that the residual errors in the data were judged to be the most likely explanation for smaller UAH tropical tropospheric warming than the surface [*Karl et al.*, 2006; *IPCC*, 2007; *Santer et al.*, 2008]. However note that the T_{24}-T_{2LT} trends from RSS and UAH are both significantly smaller than the AR4 GCM simulations, indicating that this result may be robust because of the cancellation of systematic errors related to data uncertainties. We may not be able to fully exclude the possibility that the errors in the satellite data are the explanation for the discrepancies between model and observations in T_{24}-T_{2LT} trends. It would be a useful future study to examine the dependence of T_{24}-T_{2LT} trend on the internal uncertainty following *Mears et al.* [2011]. The construction of T_{2LT} by the NOAA team would also provide a further check on the structural uncertainty. In addition, an accurate MSU weighting function in the tropics, which should be a function of location and time and atmospheric conditions, may also be needed to derive the T_{24} and T_{2LT} from the GCM simulations for a precise comparison with observations.

[15] Significantly smaller T_{24}-T_{2LT} trends from both RSS and UAH than the simulations indicate possible common errors among AR4 GCMs. In order to gain some insight into the issue, we derived the ratio of T_{24} to T_{2LT} trends from both GCMs and observations. Despite large differences in the simulated tropical temperature trends from various model ensemble members (not shown here), all simulated T_{24} trend are ~20% consistently larger than T_{2LT} trends. Different from GCM simulations, the T_{24} trend from RSS (UAH) is only about 10% (6%) larger than T_{2LT} trends. Therefore in terms of trends, we have $T_{24} = 1.2{*}T_{2LT}$ from all model ensemble members, but $T_{24} = 1.1{*}T_{2LT}$ from RSS or $T_{24} = 1.06{*}T_{2LT}$ from UAH. We may also write T_{24}-T_{2LT} = $c{*}T_{2LT}$ where c is 0.2 for AR4 GCMs but 0.10 (0.06) for RSS (UAH). It can be seen that larger T_{24}-T_{2LT} trends can be not only caused by larger c but also by larger T_{2LT} trends.

[16] Tropical surface temperature trend from multi-model ensemble mean is more than 60% larger than those from observations (Table 1), indicating that AR4 GCMs overestimate the warming in the tropics for 1979–2010. Thus larger T_{24}-T_{2LT} trends from AR4 GCMs are partly caused by GCM overestimation of tropical temperature trends. Note that T_{24}-T_{2LT} trends are 0.014 ± 0.017 (0.005 ± 0.016) K/decade from RSS (UAH) but 0.051 ± 0.007 K/decade from multi-model ensemble mean (Figure 2). It is important to point out that differences in both tropospheric temperature trends and the factor c determine the significance of the discrepancies between model and observations in T_{24}-T_{2LT} trends. On one hand, by using T_{2LT} trend from multi-model ensemble mean (Table 1) along with the c of 0.1 from RSS as an example, we obtain a T_{24}-T_{2LT} trend of 0.026 (±0.016) K/decade that is significantly larger than zero. On the other hand, using the T_{2LT} trend from RSS but the c of 0.2 from AR4 GCMs, we have a T_{24}-T_{2LT} trend of 0.029 (±0.016) K/decade that is also significantly larger than zero. An important point here is that significant trends in T_{24}-T_{2LT} from AR4 GCMs are not only caused by larger simulated tropospheric temperature trends but also caused by a larger vertical amplification from T_{2LT} to T_{24} and the two contribute about equally.

[17] The tropical tropospheric warming from AR4 GCMs increases with height, reaches its maximum at ~200 hPa, and decreases to zero near tropical tropopause [*IPCC*, 2007]. The trend ratios of T_{2LT} to T_s and T_{24} to T_s from AR4 GCMs are 1.34 and 1.61, respectively (Table 1), while the corresponding trend ratios from RSS are 1.19 and 1.31 (the trend ratio of T_{24} to T_s from NOAA is 1.61), using an averaged T_s trend of 0.122 K/decade from observations. Thus the satellite MSU/AMSU data from RSS and NOAA support the GCM results that the tropical deep-layer troposphere warms faster than the surface [*Fu et al.*, 2004; *Fu and Johanson*, 2005; *Zou et al.*, 2006; *Santer et al.*, 2008]. Such positive trend in static stability in terms of tropical deep-layer troposphere relative to the surface from both models and observations is not inconsistent with the present study. The later indicates that the AR4 GCM-simulated warming in the tropical upper troposphere relative to the lower-middle troposphere is larger than observations.

[18] The AR4 GCM simulations vary by the forcing included [*Karl et al.*, 2006; *IPCC*, 2007], which may affect both the amount of overall warming as well as its vertical structure. For the radiative forcing associated with stratospheric ozone depletion and volcanic eruptions (see Figure 2), 15, 6, 1, and 14 ensemble members consider, respectively, both of these forcings, only stratospheric ozone depletion, only volcanic eruptions, and none of the two. Whether and how these forcings are considered in the GCMs may be especially relevant to the change of the temperature vertical structure [*Forster et al.*, 2007; *Free and Lanzante*, 2009]. By considering the 15 model ensemble members that include both stratospheric ozone depletion and volcanic eruptions, we have a T_{24}-T_{2LT} trend of 0.055 K/decade versus 0.051 K/decade from the entire ensembles. The two-sample tests show that T_{24}-T_{2LT} trends in 14 (15) of these 15 ensemble members are significantly larger than observations based on RSS (UAH). Note that the GCM simulations including both stratospheric ozone depletion and volcanic eruptions are more accurate in terms of external radiative forcing. The stratospheric ozone depletion decreases the T_{24}-T_{2LT} trend [*Forster et al.*, 2007] while the volcanic eruptions that occurred in the first half of the 1979–2010 increase the T_{24}-T_{2LT} trend [*Free and Lanzante*, 2009].

[19] It is also noticed that there have been more El Nino activities during the first half of the satellite era but more La Nina during the second half. This change of the ENSO

activities may lead to a cooling of the surface and the enhanced cooling in the tropical upper troposphere [*Free and Lanzante*, 2009]. We performed sensitivity study by removing ENSO from the RSS and UAH time series with the Nino 3.4 index using a time-lagged regression method [e.g., *Mass and Portman*, 1989]. It is found that this effect on the T_{24}-T_{2LT} trend is small (only about 0.001 K/decade).

5. Summary and Conclusions

[20] One of the striking features in GCM-predicted climate change due to the increase of greenhouse gases is the much enhanced warming in the tropical upper troposphere. Here we examine this feature by using satellite MSU/AMSU-derived deep-layer temperatures in the tropical upper- (T_{24}) and lower- (T_{2LT}) middle troposphere for 1979–2010. It is shown that T_{24}-T_{2LT} trends from both RSS and UAH are significantly smaller than those from AR4 GCMs. This indicates possible common errors among GCMs although we cannot exclude the possibility that the discrepancy between models and observations is partly caused by biases in satellite data.

[21] IPCC AR4 GCMs overestimate the warming in the tropics for 1979–2010, which is partly responsible for the larger T_{24}-T_{2LT} trends in GCMs. It is found that the discrepancy between model and observations is also caused by the trend ratio of T_{24} to T_{2LT}, which is ~1.2 from models but ~1.1 from observations. While strong observational evidence indicates that tropical deep-layer troposphere warms faster than surface, this study suggests that the AR4 GCMs may exaggerate the increase in static stability between tropical middle and upper troposphere in the last three decades. In view of the importance of the enhanced tropical upper tropospheric warming to the climate sensitivity and to the change of atmospheric circulations, it is critically important to understand the causes responsible for the discrepancy between the models and observations.

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