Interannual co-variability of tropical temperature and humidity: A comparison of model, reanalysis data and satellite observation

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[1] We use a 20-year record of HIRS radiance measurements to evaluate the fidelity of interannual co-variability of tropical humidity and temperature in the reanalyses and GFDL AM2 simulations. Large inconsistencies between the NCEP and ECMWF reanalyses are found as are disagreements between the reanalyses and AM2 simulations. The largest discrepancies occur in the middle and upper troposphere where the NCEP and ECMWF tropical-mean relative humidity anomalies are found to be negatively correlated. When compared to HIRS dataset, NCEP is found to have unrealistically large interannual variablity in both the upper (6.7 μm) and middle (7.3 μm) tropospheric humidity channels. The radiance anomalies simulated from AM2 model output are shown to agree well with those observed by HIRS. These results support the validity of the strong coupling between temperature and humidity variations simulated in the GFDL AM2 and highlight the need to improve the representation of interannual variations of humidity in the reanalyses. **Citation:** Huang, X., B. J. Soden, and D. L. Jackson (2005), Interannual co-variability of tropical temperature and humidity: A comparison of model, reanalysis data and satellite observation, *Geophys. Res. Lett.*, *32*, L17808, doi:10.1029/2005GL023375.

1. Introduction

[2] Water vapor is the dominant greenhouse gas in our atmosphere. Its feedback to the surface warming has been one of the central topics in climate studies for several decades [*Held and Soden*, 2000, and references therein]. However, despite its importance there remains considerable debate regarding the relationships between temperature and water vapor, particularly in the tropical free troposphere where the distribution of water vapor is closely related to convection, a process poorly resolved in the GCMs.

[3] Previous studies in this area have focused primarily on radiosonde observations. *Sun and Held* [1996] and *Sun et al.* [2001] examined the temperature-humidity relationships on the interannual time scale from radiosonde observations as well as several GCM simulations. Their results imply that the observed coupling between tropical free tropospheric humidity and surface temperature variations are significantly weaker than those simulated by the GCMs. A study by *Bauer et al.* [2002] suggests that such discrepancy may, in part, be attributable to geographic sampling differences between the GCMs and radiosonde observations. So far, there is no well-accepted explanation to reconcile the discrepancy.

[4] Global data assimilation systems like the NCAR-NCEP [*Kalnay et al.*, 1996] and ECMWF ERA40 [*Uppala et al.*, 2005] reanalyses combine diverse data and model forecasts to produce comprehensive and self-consistent products with global coverage that are frequently used in climate studies. However, before reanalyses can be used for either diagnostic studies or model evaluation, the fidelity of their products must be tested against observations. In this study, we use a 20 year record of satellite radiance measurements from HIRS to evaluate the interannual co-variability of tropical mean humidity and temperature in both operational reanalyses and the GFDL Atmospheric Model 2 (AM2) simulations.

2. Model and Dataset Description

[5] In this study, we focus on interannual variability of tropical (30°S–30°N) mean humidity and temperature. Both the NCEP and ECMWF ERA40 reanalysis are used in this study. The new GFDL global atmosphere model [*Geophysical Fluid Dynamics Laboratory Global Atmospheric Model Development Team*, 2004], AM2, is also used for comparison purpose. We run AM2 with monthly observed SST from 1979 to 2000. Satellite measurements used in this study are from HIRS aboard NOAA series of satellites from November 1978 to December 2000. We use HIRS tropical monthly means of clear-sky radiances obtained from an updated version of the TOVS Radiance Pathfinder Project [*Bates et al.*, 2001]. Three HIRS channels are used here: 14 μm (channel 5, sensitive to temperature around 500 mb), 7.3 μm (channel 11, sensitive to relative humidity around 600 mb) and 6.7 μm (channel 12, sensitive to relative humidity around 400 mb).

[6] In order to homogenize HIRS measurements from different satellites, two problems have to be addressed: inter-calibration of the HIRS instruments on the different satellites and absolute calibration. Since we are interested in the variability, absolute calibration is not performed. Given that we only examine the tropical monthly mean clear-sky radiances, we compute the inter-satellite offsets by minimizing the differences of overlapped tropical monthly mean radiances between satellites. We have also tried to do the adjustments by minimizing the differences of overlapped regions instead of the whole tropics between two satellites. The adjustments from these two approaches yield no significant differences in the resulting product. One

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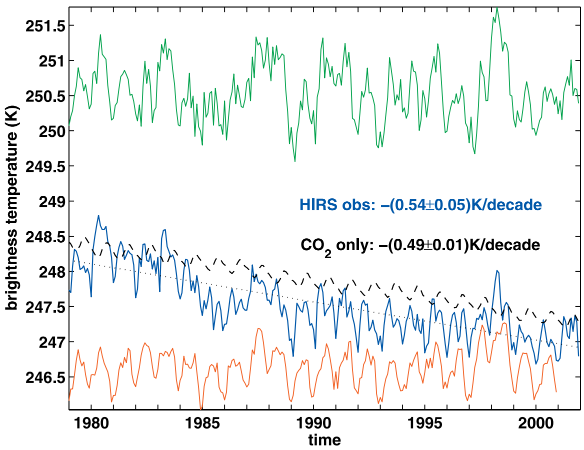

Figure 1. The blue line is the homogenized tropical mean HIRS 14 μm radiances. The dotted line is the linear trend derived from the blue line. The dash line is the synthetic HIRS 14 μm radiances assuming constant tropical temperature and humidity profiles and realistic tropical CO_2 mixing ratio. The linear trends derived from the blue line and the dash line are labeled. The red line is the homogenized synthetic tropical mean 14 μm radiances based on AM2 simulation. The green line is NCEP 400 mb tropical mean temperature (for display purpose, it is displaced by −5K).

exception is the offset between NOAA-7 and NOAA-9 because they were not overlapped with each other. Here we apply a curve fitting to the NOAA-7 HIRS time series from September to December 1984 and then extrapolate this curve to January 1985. Similar fitting is also applied to January-April 1985 (NOAA-9 observations) and then the curve is extrapolated back to December 1984. Then adjustment for NOAA-7 vs. NOAA-9 is obtained by minimizing the radiance differences of December 1984 and January 1985.

[7] The homogenized time series of HIRS 14 μm radiance is shown in Figure 1 (the blue line). It agrees well with NCEP 400 mb temperature (the green line in Figure 1) in terms of interannual variations. Moreover, this homogenized time series has a cooling trend of −0.54 k/decade (±0.05 K/decade for 95% significance). This cooling trend is due to the increasing CO_2 which makes the peak of the weighting function higher. When we use a set of typical tropical temperature and humidity profiles [*Anderson et al.*, 1986] and observed tropical CO_2 concentrations from Mauna Loa to generate synthetic 14 μm radiances based on the spectral response function of HIRS 14μm channel on a single satellite (NOAA-6), we can obtain a cooling trend (−0.49 K ± 0.01 K/decade for 95% significance, the dotted line in Figure 1) consistent with the one derived from the homogenized HIRS time series. The correlation between NCEP 400 mb temperature anomaly and HIRS 14 μm anomaly with CO_2 cooling trend removed is 0.65. This gives us further confidence on the homogenized HIRS time series.

[8] In order to make fair comparisons between the HIRS observations and AM2 simulations, 3-hourly instantaneous model output are fed into the HIRS Fast Forward radiance transfer model [*Soden et al.*, 2000] to compute synthetic HIRS radiances. Then these radiances are further sampled to the same time and location as the observed HIRS clear-sky radiances. Tropical monthly mean of synthetic radiances are derived from the sub-sampled radiances and then homogenized in the same way as done to the HIRS datasets. By these procedures, we minimize the sampling disparity between the GCM and sun-synchronous satellites.

[9] The homogenized tropical monthly mean of synthetic 14 μm radiances based on the AM2 output is shown as the red curve in Figure 1. To a large extent, it agrees with the HIRS and NCEP time series: the correlation between the AM2 curve and NCEP curve in Figure 1 is 0.73. For comparisons between the HIRS and reanalysis dataset, 6-hourly reanalysis outputs are processed in the same way to obtain homogenized monthly mean of synthetic radiances. Since we are interested in interannual variability, all time series are first detrended by linear regression and deseasonalized by removing climatology of the seasonal cycle. Then a low pass-filter is used to further remove signals with frequencies higher than one year. All results presented below are based on the interannual anomalies (hereafter, anomalies) derived in this way.

3. Vertical Structure of Temperature-Humidity Covariances in Reanalyses and AM2 Simulations

[10] Figure 2 shows $\frac{d}{dT_a}\frac{q_a}{\bar{q}}$, the fraction change of specific humidity with respect to temperature (hereafter, the fraction change). Following *Sun and Held* [1996, hereinafter referred to as SH96], T_a and q_a are the tropical mean values of the interannual variability of temperature and specific humidity, respectively. $\bar{q}$ is the tropical mean value of the annual average of specific humidity. The fraction change is estimated by linear regression of fractional anomalies ($q_a/\bar{q}$) on temperature anomalies (T_a). As it can be seen from Figure 2, the fraction change derived from the AM2 simulation closely resembles the curve of constant relative humidity (hereafter constant-RH). This is consistent with

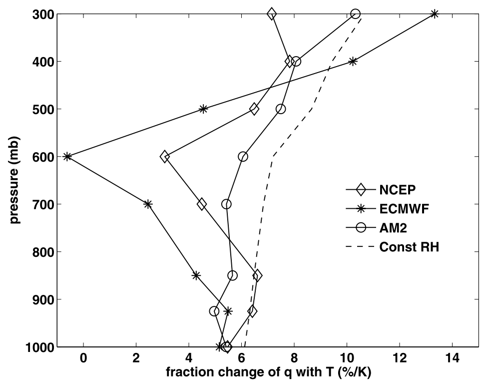

Figure 2. The fraction change of tropical mean specific humidity with temperature at different pressure levels (refer to context for the definition of the fraction change). The solid line with open circles is from AM2. The line with diamonds is from NCEP reanalysis and the line with stars from ECMWF reanalysis. The dash line is derived assuming constant relative humidity at all pressure levels. This figure is an analogue to *Sun and Held* [1996, Figure 5].

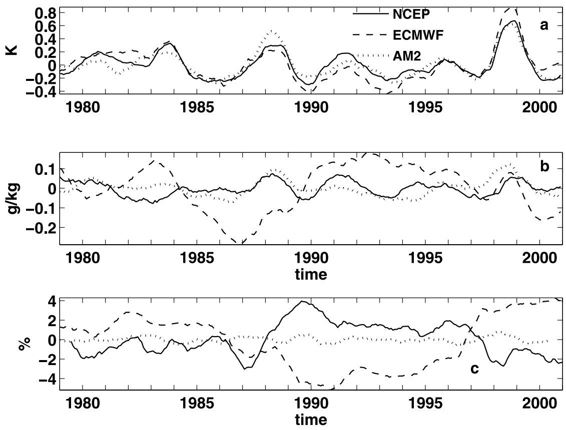

Figure 3. (a) The interannual anomalies of tropical mean temperature at 600 mb from NCEP (the solid line), ECMWF (the dash line) and AM2 (the dotted line). (b) Same as (a) except for specific humidity at 600 mb. (c) Same as (a) except for relative humidity at 250 mb, NCEP-DOE reanalysis data is used for this plot.

what has been shown in SH96 even though the GCM used here differs substantially from that used by SH96.

[11] The fraction changes from two reanalysis datasets are clearly different from that of AM2. Moreover, although two reanalyses show similar tendency in the vertical structure of the fraction changes, the disagreement between two reanalyses is as prominent as the disagreement between reanalyses and AM2 model. At 1000 mb, the fraction changes from AM2, NCEP and ECMWF are close to each other. Then they quickly diverge as the altitude increases. From 900 mb to 500 mb, the fraction changes of ECMWF are systematically smaller than those of NCEP and AM2. The largest discrepancies is at 600 mb where the fraction changes of AM2, NCEP and ECMWF are about 6%/K, 3%/K and -0.6%/K, respectively. This means that the tropical mean temperature and humidity anomalies at 600 mb are almost uncorrelated in ECMWF but highly correlated in AM2. Indeed, the correlation coefficient between q_a and T_a is -0.04 for ECMWF and 0.87 for AM2. Above 500 mb, the situation is the opposite: the fraction changes of ECMWF are larger than those of NCEP and AM2. Moreover, the fraction changes of ECMWF and NCEP above 500 mb are at different sides of the constant-RH curve. This implies that, if the ECMWF and NCEP tropical mean upper tropospheric temperature anomalies are consistent with each other, the tropical mean upper tropospheric relative humidity (UTH) anomalies from ECMWF and NCEP are opposite to each other. This is confirmed in Figure 3c that shows the ECMWF and NCEP relative humidity anomalies at 250 mb are indeed negatively correlated.

[12] We also examine the fraction changes of ECMWF and NCEP using a longer time series from 1958 to 2001 and they are highly consistent with the corresponding changes in Figure 2. The inconsistency between NCEP and ECMWF shown in Figure 2 is prominent and has also been found in studies of the column integrated water vapor [*Allan et al.*, 2004; *Trenberth et al.*, 2005]. As shown by *Bengtsson et al.* [2004], such deficiencies in the interannual variability are also found in other fields. This difference could be partly due to the differences in the methods used to assimilate HIRS observations by NCEP and ECMWF. The ERA40 reanalysis directly assimilated HIRS radiances at both temperature-sensitive and humidity-sensitive channels [*Hernandez et al.*, 2004]. For the NCEP reanalysis, HIRS radiances were not directly assimilated. Instead, only temperature retrievals from temperature-sensitive channels were assimilated into NCEP and HIRS humidity channels were not used at all [*Kistler et al.*, 2001]. Therefore, NCEP heavily rely on radiosonde datasets for humidity input. This is confirmed by the resemblance of the NCEP fraction changes (Figure 2) to the fraction changes derived from radiosonde shown in Figure 5 of SH96. ECMWF assimilated HIRS radiances at humidity channels and, compared to NCEP's curve of fraction changes, its curve is more deviated from that of the constant-RH hypothesis in the lower and middle troposphere. As shown in Figure 3a, NCEP and ECMWF are highly consistent with each other for the temperature anomalies at 600 mb. But for the humidity anomalies shown in Figure 3b, NCEP and ECMWF are clearly different in both the phase and the magnitude. It suggests that the difference between NCEP and ECMWF seen in Figure 2 be primarily due to the difference in their humidity anomalies. It also suggests that the influence of various factors (such as inter-calibration and contamination of volcanic aerosols) on assimilating HIRS radiances has to be correctly understood before such assimilation could have positive impact on interannual variation of moisture in the reanalyses.

4. Temperature-Humidity Variations From HIRS Radiances

[13] Limited by data availability, here we only use 6-hourly output from the NCEP-DOE analysis [*Kanamitsu*

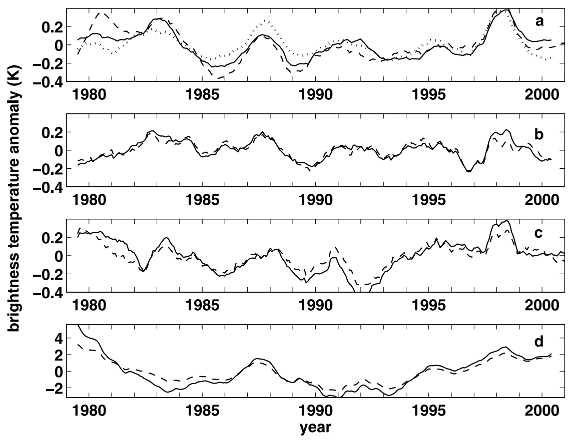

Figure 4. (a) The interannual anomalies of HIRS 14 μm tropical mean radiances (the dash line), synthetic 14 μm radiances from NCEP (the solid line) and AM2 (the dotted line). (b) The interannual anomalies of AM2 synthetic tropical mean 7.3 μm (the solid line) and 6.7 μm (the dash line) radiances. (c) Same as (b) except for HIRS radiances. (d) Same as (b) except for NCEP-based synthetic radiances. Note the order-of-magnitude difference of y-axis between (d) and (b)/(c).

Table 1. Correlation Coefficients Between Interannual Anomalies of Radiances at HIRS Mid-Tropospheric Channels[a]

	HIRS	AM2	NCEP
14 μm vs. 7.3 μm	0.75	0.74	0.44
14 μm vs. 6.7 μm	0.62	0.51	0.55
7.3 μm vs. 6.7 μm	0.92	0.92	0.98

[a]All correlations here are more than 99.9% significant.

et al., 2002]. In terms of the interannual anomalies of temperature and humidity, the difference between the NCEP-DOE and NCEP-NCAR reanalysis is minor: both the amplitude and the phase of the anomalies are consistent with each other.

[14] The interannual anomalies of three mid-tropospheric channels, 14 μm, 7.3 μm and 6.7 μm, are shown in Figure 4 for HIRS, AM2 and NCEP. The cross-channel correlation coefficients for each dataset are presented in Table 1. For all three datasets, the correlations between two humidity channels (7.3 μm and 6.7 μm) are very high, highlighting the vertical coherence of moisture changes in the free troposphere. Note also that the NCEP correlation between the 14 μm and 7.3 μm radiances is much lower compared to those from HIRS and AM2. For the anomalies in 14 μm radiances, HIRS, AM2 and NCEP agree with each other in both the amplitude and the phase (Figure 4a) except 1979–1982 which might be partially due to the significant degrading of TIROS-N data quality and the decrease of TIROS-N valid number of samplings after 1980. Fingerprints of ENSO events are clear in the 14 μm anomalies of all three datasets. For the two humidity channels, the amplitudes of the anomalies derived from HIRS and AM2 agree with each other but are an order-of-magnitude smaller than those derived from NCEP (Figures 4b–4d).

[15] Agreement between interannual anomalies of observed 6.7 μm radiances by HIRS and simulated from another GCM (HadAM3) simulation has been reported before [*Allan et al.*, 2003]. The large difference between NCEP and HIRS/AM2 is primarily due to the large interannual anomalies of relative humidity above 500 mb in NCEP. As shown in Figure 3c, the standard deviation of the relative humidity anomalies at 250 mb is 0.3% for AM2 and 1.7% for NCEP. Such difference in amplitude is persistent for anomalies above 500 mb. To support this explanation, we examine radiance anomalies in a near-surface humidity channel (8.2 μm, HIRS channel 10), which is less affected by humidity above 500 mb (see auxiliary material[1]). It turns out that the amplitude of NCEP anomalies of 8.2 μm radiances is comparable to those from AM2 and HIRS and the NCEP relative humidity anomalies in the lower troposphere are comparable to the corresponding AM2 anomalies.

[16] Noticing that the amplitude of ECMWF 250 mb relative humidity anomaly in Figure 3c is at least as large as that of NCEP, it is likely that synthetic anomalies at the humidity channels based on ECMWF output could not match observed HIRS anomalies in amplitude as well. This fact, as well as the negative correlations between the ECMWF and NCEP UTH, emphasizes the deficiencies in the representation of humidity variations in both reanalysis datasets.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL023375.

5. Discussion and Conclusion

[17] Here we show the inconsistency between AM2 model, NCEP and ECMWF reanalyses in the tropical averaged humidity-temperature relation on the interannual timescale, an important relation for correctly estimating the strength of water vapor feedback. Inconsistencies are also disclosed by the much larger amplitude of 6.7 μm radiance anomalies in NCEP compared to HIRS and AM2, the negative correlations of the UTH anomalies between ECMWF and NCEP and the discrepancy in the correlation coefficients between radiance anomalies at a mid-tropospheric temperature channel (14 μm) and a humidity channel (7.3 μm). When compared to HIRS observations, NCEP is found to have unrealistically large interannual variablity in both the upper (6.7 μm) and middle (7.3 μm) water vapor radiance channels. In contrast, the water vapor radiances simulated from the GFDL AM2 model output are shown to be in good agreement with those observed by HIRS.

[18] The problems outlined require correction before either reanalysis dataset could be considered suitable for studying long-term trends or interannual variability of humidity and closely related quantities. While the HIRS radiances are insufficient to resolve the vertical structure of moisture variability, the anomalies in humidity integrated over deep layers of the free troposphere are clearly more consistent with the GCM simulations than with the NCEP reanalyses.

[19] However, there remains no definitive observational dataset for quantifying the vertical structure of humidity-temperature relationships over the tropics. Radiosonde datasets suffer from spatial inhomogeneity and calibration while HIRS observation cannot provide retrievals with desired vertical resolutions. With the ongoing AIRS mission and IASI and CrIS in the near future, tropospheric temperature and humidity profiles could be retrieved with high vertical resolution ($1 \sim 2$km) with globally uniform coverage. GPS occultation, with its high precision measurement and uniquely robust retrieval, could also contribute to this problem. With these observations, hopefully such predicament could be alleviated in the near future.

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