An assessment of the tropical humidity-temperature covariance using AIRS

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[1] We investigate the horizontal and vertical structure of the covariance between water vapor and temperature in the tropical troposphere, using satellite measurements from the Atmospheric InfraRed Sounder (AIRS). Our analysis reveals large spatial gradients in the local covariance between water vapor and temperature. Positive correlations dominate the tropical lower and upper troposphere, while regions of negative correlation are common in the tropical middle troposphere. While regressions of the tropical mean water vapor and temperature profiles reveal slopes of the same order of magnitude of the Clausius-Clapeyron regime, the regression of local values can be up to an order of magnitude larger than the Clausius-Clapeyron prediction. Results from the NOAA GFDL global circulation model are also shown for comparison. **Citation:** Gambacorta, A., C. Barnet, B. Soden, and L. Strow (2008), An assessment of the tropical humidity-temperature covariance using AIRS, *Geophys. Res. Lett.*, *35*, L10814, doi:10.1029/2008GL033805.

1. Introduction

[2] The water vapor - temperature covariance has been the focus of several studies in the past [*Sun and Oort*, 1995; *Sun and Held*, 1996; *Bauer et al.*, 2002; *Huang et al.*, 2005]. These efforts have focused on tropical averages of monthly anomalies of water vapor and temperature measurements and have led to a disagreement on the strength of the water vapor dependence on local temperature variations, particularly in the middle and upper troposphere [see, e.g., *Huang et al.*, 2005, Figure 4]. They have also highlighted the inadequacy of sparse and inhomogeneous radiosonde data sets or low vertical resolution satellite retrievals, to accurately characterize this correlation.

[3] In this paper, we analyze the horizontal and vertical structure of the covariance between temperature and water vapor retrieved from the Atmospheric InfraRed Sounder (AIRS). Section 1 describes the instrument and the data used for this analysis. Results and conclusions are shown in section 2 and 3.

2. Instrument and Data Set Description

[4] Launched into orbit on May 4, 2002 on board NASA EOS Aqua platform, AIRS is a medium resolution infrared grating spectro-radiometer, designed to provide retrievals of atmospheric components, including temperature and water vapor [*Aumann et al.*, 2003]. One of the key elements of the AIRS retrieval algorithm is the radiance cloud clearing process [*Susskind et al.*, 2006], that enables an increase of the daily yield of observational data up to 80%, and eliminates the clear-sky bias typical of analysis based on clear-sky satellite measurements. The analysis shown here uses an updated version of the retrieval algorithm (version 5), which includes enhanced temperature and water vapor products (http://disc.sci.gsfc.nasa.gov/AIRS/documentation.shtml, 2007). Since we found that the version 5 quality flag configuration causes many of the homogeneous cloudy scenarios to be rejected, or only partially accepted up to a certain pressure level, for the purpose of this analysis, we accept or reject the entire retrieval profiles according to the version 4 "mid trop" quality flags, as defined by *Tobin et al.* [2006]. We found (results not shown) that this configuration almost doubles the yield of the product to an average of 25 accepted cases per month. The reader is referred to *Tobin et al.* [2006] for a detailed description of the "mid trop" rejection criteria of AIRS version 4 algorithm. It needs to be pointed out that the cloud clearing algorithm can degrade the accuracy of the retrieval especially in the presence of low gradient cloud fractions, and in the presence of low level clouds, where the atmosphere is more opaque and it is also more difficult to distinguish between cloud formation and surface properties. *Tobin et al.* [2006] have shown that under the "mid trop" rejection configuration, the tropical temperature RMS errors are about 1K or less below 200 mbar and the tropical water vapor RMS errors are about 20% or less below 400 mbar, and increase to about 30% at 300 mbar [see *Tobin et al.*, 2006, Figures 9 and 13].

[5] It has been shown that AIRS Version 5 tropospheric temperature (moisture) retrieval resolution, as determined by the full-width half-maximum of the averaging kernels, ranges between about 2.5 km (3 km) near the surface and 6 km (4 km) near the tropopause [*Maddy and Barnet*, 2008]. The data set used in this study is a 3 × 3 degree gridded subset of AIRS observations. The sub-setting procedure is performed by selecting AIRS footprints closest to locations of a fixed 3 × 3 degree resolution reference grid. This procedure allows for a quick re-processing of a 4-year period of data and does not introduce any systematic bias in our database. In the specific context of this analysis, it will be shown in the next section that the local covariance of water

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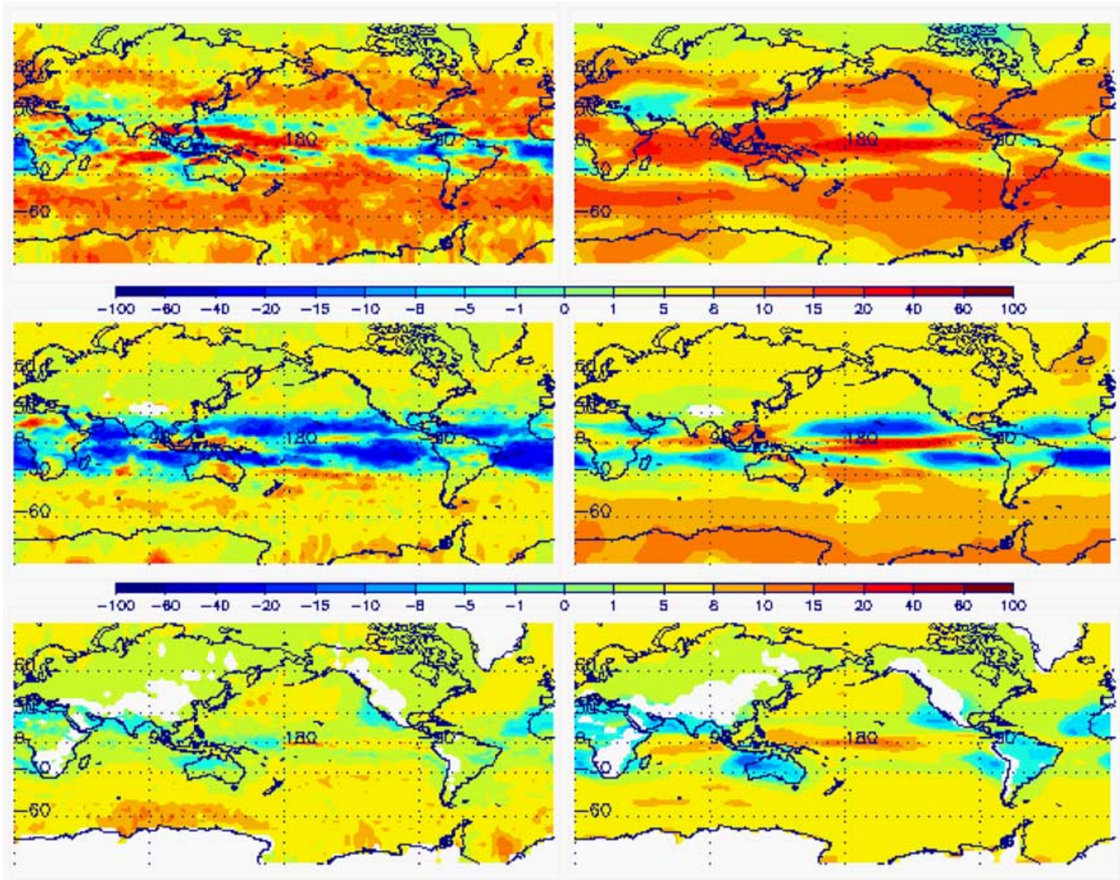

Figure 1. Fractional regression of monthly averaged specific humidity and temperature (%/K) from (left) AIRS and (right) the GFDL model. Three representative pressure levels (about 300, 600, 900 mb) are shown.

vapor on temperature varies on spatial scales larger than a 3×3 degree resolution.

3. Horizontal and Zonal Structure of Temperature and Water Vapor Covariance

[6] It has been found [*Raval and Ramanathan*, 1991] that the water vapor absorption is approximately proportional to the logarithm of the concentration of water vapor, and that the net flux at the tropopause is more sensitive to changes in water vapor at the upper troposphere than in the lower troposphere [*Held and Soden*, 2000]. For this reason, we are particularly interested in analyzing the fractional change of water vapor with temperature and its vertical structure.

[7] Following the approach of *Sun and Oort* [1995], *Sun and Held* [1996], and *Huang et al.* [2005], we define the fractional change of specific humidity, q, with respect to temperature, T, as the weighted linear regression (the weight being based on the number of monthly measurements) of the monthly seasonal anomalies of water vapor and temperature, divided by the annual mean specific humidity.

[8] The left side of Figure 1 shows the latitude-longitude dependence of temperature and water vapor fractional change from AIRS, at 3 different representative pressure levels: about 300 (top), 600 (center) and 900 mb (bottom), respectively. It is shown that at all levels in the atmosphere, the sensitivity of water vapor to temperature is strongly latitude-longitude dependent. It needs to be pointed out that regions of positive as well as negative covariance are extended over spatial scales larger than the 3×3 degree spatial resolution adopted for this analysis, implying that no spatial bias is introduced by the subsetting technique.

[9] In the boundary layer, tropical values are in general more uniform with respect to the free troposphere. A probability distribution analysis (see auxiliary material[1]) of the fractional slopes in the tropical region (30S–30N) shows a positive mode of about 5%, close to the Clausius-Clapeyron regime (7%/K).

[10] When the free troposphere is considered, the tropical fractional slopes show a broader distribution, with positive and negative values even higher than 50%/K. The highest positive correlations are found in the tropical upper troposphere, particularly in the regions of the South East Asia and Western Pacific. Extended regions of negative correlations instead, are found in the middle tropical troposphere, with the main exception of the tropical continents and the Western Pacific archipelago. The right side of Figure 1 is a comparison with the NOAA zonal model [*GFDL Global Atmospheric Model Development Team*, 2004], at roughly the same pressure levels. The comparison indicates a good agreement in terms of spatial variability and order of

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033805.

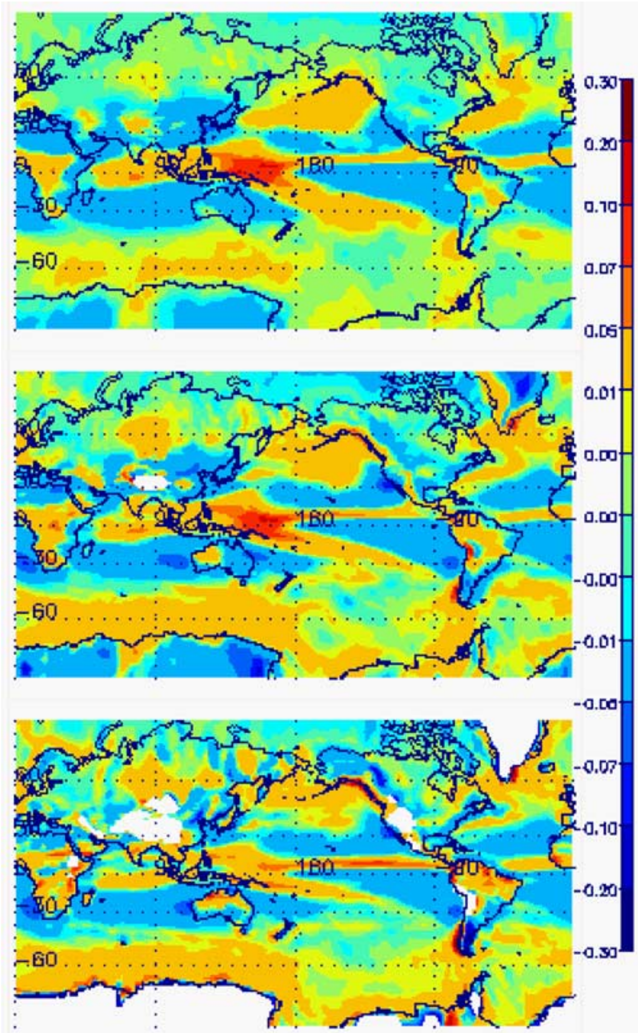

Figure 2. NCEP Vertical velocity field, omega, for the period August 2003–December 2004, at the same pressure levels as in Figure 1. Red: ascending air, blue: descending air.

magnitude of the covariance values, with a tendency of the GFDL model to under-represent the regions of negative correlations in the free tropical troposphere. The opposite is true in the lower atmosphere, particularly over land.

[11] The fact that we find negative regression slopes, and positive values that are up to one order of magnitude higher than the Clausius - Clapeyron regime, indicates the presence of other mechanisms regulating the water vapor variations at these locations, besides local temperature. A careful analysis of these figures suggests a possible connection between these mechanisms and the patterns of the tropical circulation. More specifically, the positive and negative regression regions roughly resemble the regions of the convective and subsiding branches of the tropical circulation, respectively.

[12] To evaluate the dependence of the humidity-temperature covariance on the large scale tropical circulation, Figure 2 shows the vertical velocity field, omega, at the same three representative pressure levels of Figure 1, provided by the NCEP re-analysis [*Kalnay et al.*, 1996]. A common temporal subset to AIRS and NCEP data has been used for this analysis, spanning the period August 2003–December 2004. To facilitate the comparison with Figure 1, the opposite sign of the omega field, $-dp/dt$, has been represented, so that regions in red correspond to ascending air, and regions in blue correspond to descending air. This analysis provides some evidence that the regions of strongest positive correlations between water vapor and temperature are predominantly associated with the ascending convective regions of the tropical continents and the Western Pacific Ocean, particularly in the upper troposphere. Regions of strongest negative correlations broadly resemble the descending subsiding areas of the subtropical branches of the Hadley and Walker circulation. These features are more evident in Figure 3, which represents the height-latitude cross section of the monthly averaged water vapor and temperature fractional slopes from AIRS data (Figure 3, top) and the GFDL model (Figure 3, bottom). The GFDL model results show a more uniform positive covariance region, with value up to 15%/K, over the vertical extent of the deep tropics followed by negative regions over both sides of the subtropics, with values up to −5%/k. AIRS features are not as symmetric as in the GFDL case, with a tendency toward lower positive correlation values in the deep tropics and higher negative correlation values (up to −15%/K) in the southern subtropical middle troposphere. Both AIRS and the GFDL model present regions of highest correlations in the upper troposphere of about 15%/K.

4. Covariance of Tropical Averages

[13] In Figure 4 we compute a fractional regression analysis between tropical averages of water vapor and

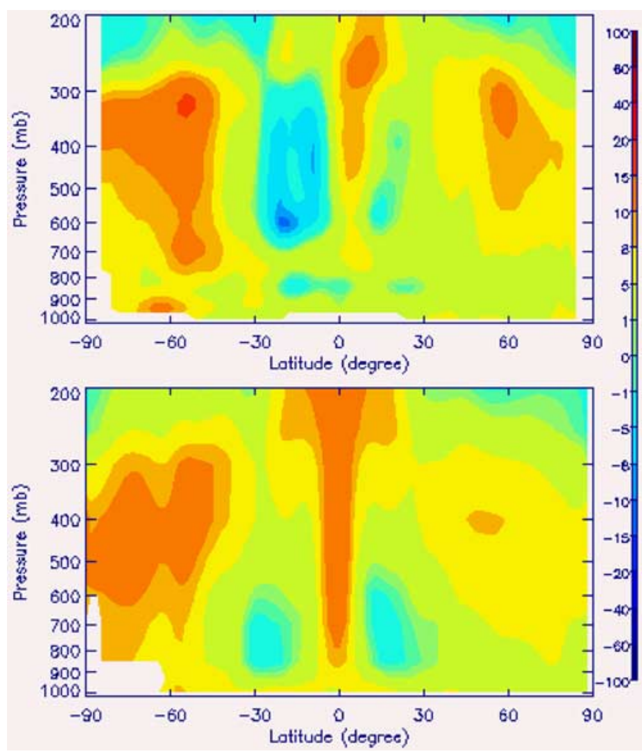

Figure 3. Height-latitude cross section of the monthly averaged water vapor and temperature fractional slopes (%/K) from (top) AIRS and (bottom) the GFDL model.

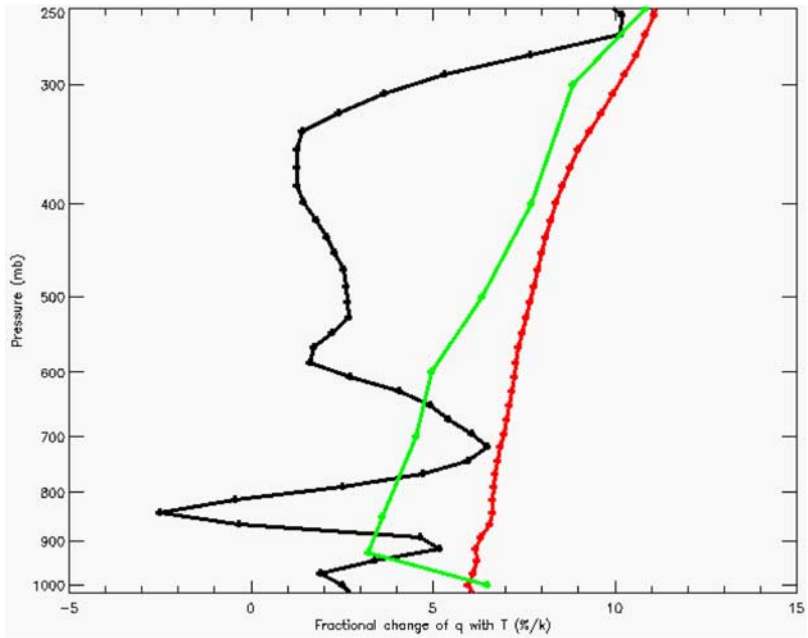

Figure 4. Black, green and red curves: AIRS, GFDL and constant relative humidity fractional regressions of monthly tropical averages of water vapor and temperature.

temperature anomalies (black is AIRS, green is GFDL), and we compare it with the fractional change of specific humidity under the assumption of constant seasonal relative humidity (red).

[14] Compared to the previous works [*Sun and Oort*, 1995; *Sun and Held*, 1996; *Bauer et al.*, 2002; *Huang et al.*, 2005] and the GFDL model, AIRS results show a more height dependent structure. In particular, a negative minimum of about −2.5%/K is found in AIRS profile, in the proximity of the boundary layer.

[15] Auxiliary material Figure S1 represents the whole time series of AIRS tropical temperature and water vapor average anomalies at 4 representative pressure levels: 300, 600, 850, 900mb. Figure S1 shows the distinctive 2006–2007 El Nino signature, corresponding to positive correlations in the upper troposphere, and negative correlations through the middle and lower troposphere, and explains the positive and negative peaks found in Figure 4. The incomplete spatial sampling of the in situ data [see, e.g., *Sun and Oort*, 1995, Figure 2] and the clear-sky only and coarser vertical resolution of the HIRS data, can possibly explain the disagreement found between the previous cited studies and AIRS. To assess the impact of the subsetting technique in AIRS computation of the tropical averages, it can be useful to repeat the analysis of Figure 4 using the full 1 × 1 degree resolution of AIRS products, once it becomes available in the future.

5. Conclusions

[16] This study highlights a complex horizontal and vertical structure of the water vapor and temperature covariance. While regressions of the tropical mean water vapor and temperature profiles reveal slopes of the same order of magnitude of the Clausius-Clapeyron regime, the regression of local values can be of the opposite sign or up to an order of magnitude larger than the Clausius-Clapeyron prediction.

[17] Local water vapor anomalies appear to be most strongly positively tied to local temperature changes in the upper troposphere. Values up to 50%/K are found here. Nonetheless, values of the same order, but of opposite sign, are also found to characterize extended regions of the free troposphere, particularly at mid altitude levels. Here, the mode of the probability distribution of the tropical fractional slopes derived from AIRS data becomes negative (about −5%/K).

[18] The fact that we find negative and positive regression values up to one order of magnitude larger than the Clausius-Clapeyron regime, suggests that other processes besides local temperature, play a more important role in determining moisture changes in the free troposphere. The horizontal and zonal distribution of the positive and negative regression regions reveal a possible connection of these sources to the transport mechanisms of the large-scale tropical circulation, with positive regions associated to convective areas and negative regions associated to areas of subsiding air motion. Several studies in the past have tried to identify the mechanisms regulating the redistribution of moisture in the free troposphere and their connection to the large scale circulation. *Sun and Lindzen* [1993] have used theoretical budget studies to show that a considerable moisture source for the large-scale subsiding flows appears to be the evaporation of the hydrometers transported to the upper troposphere by deep convective clouds. *Newell et al.* [1996] have also emphasized the role of horizontal transport, particularly from the continental areas of South America, in regulating the water vapor budget of the subsiding branch of the Eastern Pacific.

[19] Recent findings by *Vecchi et al.* [2006] of a weakening process of the tropical circulation due to anthropogenic forcing, highlight the necessity of an accurate

understanding of these moistening and drying sources. In the near future, by exploiting the combined sounding geometry of the AIRS and the IASI instrument, it will be possible to acquire four global measurements of the atmospheric state per day. Once these data become available, it will be possible to better analyze the high variability of water vapor in the tropical region, by exploiting a higher horizontal resolution and temporal scales eventually shorter than monthly averages. Central to this investigation, in particular, is the radiative role that these sources and sinks play in the overall energy budget. Future studies may focus on the characterization of the vertical and horizontal dependence of the outgoing long-wave radiation with respect to water vapor and temperature distributions, from different regions in the troposphere.

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