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# CONTROLS ON SUBTROPICAL UPPER TROPOSPHERIC HUMIDITY

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## 1. INTRODUCTION

The Earth's climate is particularly sensitive to the water vapor content of the subtropical free troposphere (Held and Soden 2000), and it is important to know the spatial and temporal variations of water vapor in this region as well the processes that determine this variability. Here we examine the spatial and temporal variations in upper tropospheric humidity (UTH) using 4 years of measurements from the Atmospheric Infrared Sounder (AIRS) satellite instrument on the Aqua satellite (Aumann et al. 2003). These variations in UTH are then related to different dynamical processes, in particular to Rossby wave breaking along the tropopause and to modulation of subtropical anticyclones by the Madden Julian Oscillation (MJO).

## 2. DATA

We use AIRS level-2 data retrievals (Fetzer et al. 2003) which has been binned into a $1^{o}$ by $1^{o}$ latitude-longitude grid by Gettelman et al. (2006). We consider Northern Hemisphere (NH) wintertime (December, January, and February) data for 2002/03 to 2005/06. We also examine meteorological fields from the NCEP-NCAR reanalyses (Kalnay et al. 1996) and outgoing longwave radiation (OLR) data obtained from the NOAA-Cooperative Institute for Research in Environmental Sciences (CIRES) Climate Diagnostics Center (http://www.cdc.noaa.gov/).

## 3. RESULTS

### 3.1 Water Vapor Distribution

The climatological winter-mean relative humidity (RH) from AIRS has significant zonal variations, in both the tropics and subtropics. In the tropics there is high RH in the convective regions (e.g., Indonesian region, tropical Africa, and tropial America) but there are also regions with low RH (in particular, the eastern tropical Pacific). In the subtropics there are local minima over the Indian, central Pacific, and Atlantic oceans, with very low values over the central Pacific.

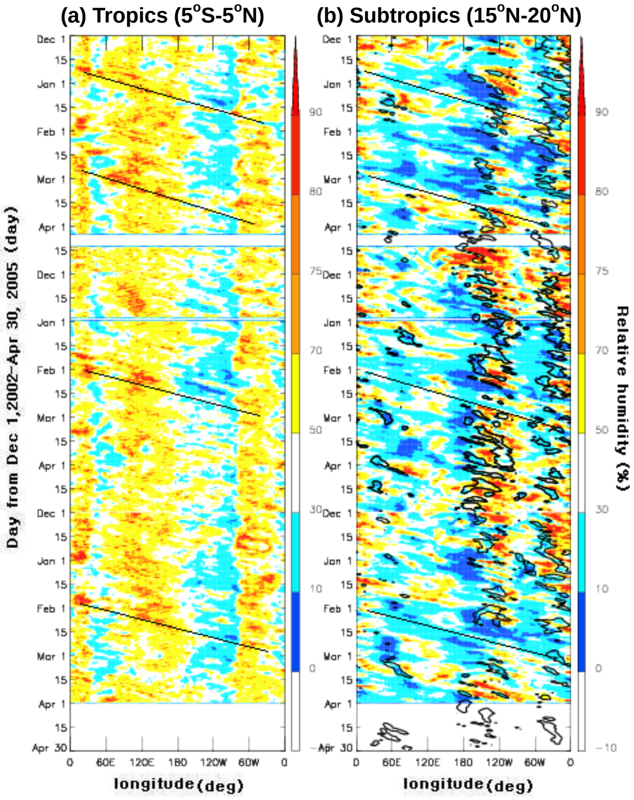
(a) Tropics (5$^{o}$S-5$^{o}$N)
(b) Subtropics (15$^{o}$N-20$^{o}$N)

**Figure 1. Hovmoller diagram of daily AIRS RH at 250 hPa averaged over (a) the tropics (5.5$^{o}$S-5.5$^{o}$N) (b) the subtropics (15.5-20.5$^{o}$N) with PV = 1.5 PVU contours for December – April in 2002/03-2004/05. Black lines illustrate the eastward movement of RH features.**

The variability about these mean values also varies with longitude, and in both the tropics and subtropics the highest (lowest) variability occurring in regions with high (low) mean values. The largest variability occur near the tropopause in regions with large mean values, e.g. eastern Pacific and Atlantic oceans, and the smallest occur in the eastern tropical Pacific, where there

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are very low mean values.

The above longitudinal variations in the mean and variance of the RH can be seen in Figure 1. This shows Hovmoller plots of 250 hPa RH for the 3 winter considered averaged over (a) 5$^{o}$ S-5$^{o}$ N and (b) 15$^{o}$-25$^{o}$ N. In the tropics there is high tropical RH around 130$^{o}$ E and 300$^{o}$ E, whereas in the subtropics there is high RH around 240$^{o}$ E and 0$^{o}$ E. Figure 1 also shows that the time scales of the variability also varies between regions. In the subtropical eastern Pacific and Atlantic oceans there is large day-to-day (synoptic) variability, with rapid transitions between dry and moist air (RH varies from greater than 20% to less than 80% within a few days). There is smaller variability in the Indian and western Pacific oceans, and here the variations occur at lower frequency. The most prominent of these low frequency variations are eastward propagating features with periods around 2 months between 60$^{o}$ E to 180$^{o}$ E, which can be seen in both the tropics and subtropics.

The different characteristics of RH in different tropical and subtropical regions suggest that several different transport processes are involved in controlling the humidity distribution. These processes are examined in the next subsections.

### *3.2 PV Intrusions*

The large synoptic variability in the eastern Pacific and Atlantic oceans is linked to Rossby wave breaking, which can lead to intrusions of air with high PV into the tropical UT (Waugh and Polvani 2000). As shown in Waugh (2005), there is low RH within and west of the high PV intrusions, and high RH east of the intrusions. The mechanism for high RH ahead of PV intrusions is a combination of location convection and poleward advection, both induced by the intrusion (Kiladis 1998).

The connection between PV intrusions and subtropical UTH can be seen in Figure 1b where PV=1.5 PVU contours are overlaid on the RH field. Intermittent regions of high PV, which correspond to PV intrusions, are common in the eastern Pacific and Atlantic oceans. The occurrence of intrusions in these two regions is consistent with the analysis of Waugh and Polvani (2000). Regions of high PV also occur over the Indian Ocean region (around 60$^{o}$ E), but are less frequent and weaker (maximum PV is smaller). In all three regions there is low RH within and west of the high PV, and high RH to the east. A composite analysis confirms this connection between PV intrusions and RH.

Figure 2 shows relative-longitude versus height cross section of composite-mean RH for all intrusions in the eastern Pacific (170$^{o}$ E-270$^{o}$ E). (The relative longitude is the longitude relative to the central longitude of each event.) There is a similar mean RH structure for intrusions in the Atlantic oceans (280$^{o}$ E-360$^{o}$ E) regions (not shown). There is a region of high RH (RH > 70%) ahead (east) of the PV intrusions and low RH (RH < 10%) behind and within the intrusions.

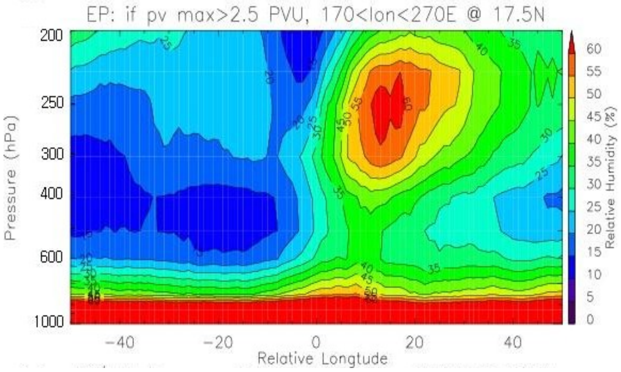

**Figure 2. Phase-shifted longitude-height cross section of composite mean RH for the northern eastern Pacific intrusion events in DJF for 2002/03-2005/06. The relative longitude is the longitude relative to the longitude where maximum PV is observed.**

These regions of high/low RH are vertically coherent, and there is high RH down to 400 hPa. High RH ahead and low RH in the intrusions is also seen in the composite for intrusions in the Indian-western Pacific region (not shown). However, consistent with weaker PV intrusions the RH ahead of the intrusions is lower and there is weaker vertical penetration, than for the eastern Pacific and Atlantic ocean events.

### *3.3 Subtropical Anticyclones and Madden-Julian Oscillation*

PV intrusions seldom occur in the western Pacific region (120$^{o}$-160$^{o}$ E), and hence are not the cause of variability in subtropical RH in this region. Instead variations in the subtropical anticyclones in this region appear to explain the variations in subtropical RH. In the Indian-western Pacific region there are upper tropospheric subtropical anticyclones stradding, but slightly west of, the equatorial convection. There is northward flow in the western edge of the northern subtropical anticyclone which transports air from the equatorial convective region into the subtropics, and generally increases the subtropical humidity. In contrast, the southward flow in the eastern edge brings drier air down from the subtropical jet. These anticyclones and the subtropical RH vary on the 1-2 month time scale. As shown in Figure 1 there is significant low frequency variability in the RH in the Indian-western Pacific region, with eastward propagating features in both the tropics and subtropics. The most likely cause of these eastward propagating features is the Madden-Julian Oscillation (MJO). The MJO-related variations in RH are examined by performing a composite analysis based on the NOAA CPC MJO indices (http://www.cpc.noaa.gov).

Figure 3 shows the composite RH (and OLR and horizontal wind) anomalies for three different MJO indices. There are coherent variations between tropical OLR and RH anomalies. When the negative OLR anomaly is centered at 80° E (Figure 3a) there are positive RH anomalies in the same region (i.e. increased RH when increased convection). There are also RH anomalies in the northern subtropics at this longitude, however these anomalies are of the opposite sign to the tropical anomalies and extend further to the east. These dry subtropical anomalies are coincident with longitudes with southward flow anomalies. Both the tropical and subtropical RH anomalies move to east with the OLR (and associated flow) anomalies. At the phase when the negative OLR anomaly is centered at 140° E (Figure 3b) the tropical and subtropical RH anomalies occur around the same longitude, again with subtropical dry anomalies where there are southward flow anomalies. In the MJO phase with enhanced convection at 40° W (Figure 3c) there is reduced convection over the Indian-western Pacific region and the OLR, flow and RH anomalies are of the opposite sign to that for the MJO index at 80° E (Figure 3a).

As well as the anomalies in Indian and western Pacific oceans there are also large RH anomalies in the subtropical eastern Pacific. When there is enhanced convection (negative OLR anomalies) at 80° E (Figure 3a) there are positive RH anomalies in the subtropics around 235° E. Similarly, there are negative RH anomalies in this regions when there is reduced convection at 80° E (Figure 3c). A possible cause for these eastern Pacific anomalies is modulation of PV intrusions by the MJO. During the phase of MJO with enhanced convection over the east Indian Ocean the subtropical jet is weaker and equatorial westerlies stronger over the central-eastern Pacific (Matthews and Kiladis 1999; Sassi et al. 2002), which are favorable conditions for Rossby wave breaking in eastern Pacific (Waugh and Polvani 2000). Thus during this phase there could be more intrusions and increased RH in the subtropical eastern Pacific, and the reverse for the opposite phase.

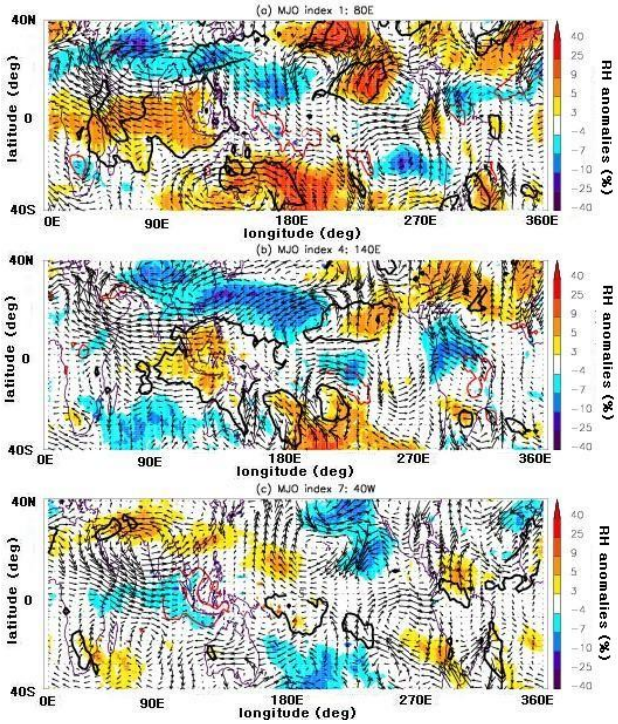

**Figure 3. The 30-80 day bandpass filtered composite RH anomalies at 250 hPa during DJF in 2002/03-2005/06 at three different MJO indices: 80E, 140E and 40W. The 30-80 day filtered OLR anomalies are overlaid. Red contours (10 W/m$^2$) represent the suppressed convections and black contours (-5 W/m$^2$) represent the enhanced convections.**

## 4. CONCLUSIONS

There are significant longitudinal variations in both the seasonal mean and variability of subtropical UTH. This is related to the different transport processes that are dominant in the different (longitudinal) regions. Over the eastern Pacific and Atlantic ocean there are intermittent high and low values that are due to intrusions of high PV air into subtropics. There is very dry air (RH less than 20%) behind and within the

Intrusions and moist (RH around 70%) air ahead of it. On the other hand, the humidity distribution over the Indian Ocean and western Pacific is more closely linked to the location and strength of subtropical anticyclones. In these regions there are eastward propagating features in the subtropical UTH that are out of phase with tropical UTH and are linked to the MJO.

## ACKNOWLEDGEMENTS

We thank Andrew Gettelman for the gridded AIRS data. This work was supported by grants from NASA and NSF. The NOAA spatially and temporally interpolated OLR were obtained from the NOAA-CIRES Climate Diagnostics Center (http://www.cdc.noaa.gov/).

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