Relative Humidity Variations in the Tropical Western Pacific and Relations with Deep Convective Clouds

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Introduction

Most general circulation models (GCMs) agree that water vapor feedback due to warming caused by increasing greenhouse gases is positive (Cess et al. 1990). However, Lindzen (1990) argued that GCMs might overestimate the water vapor feedback because increased convection in a warmer climate would actually dry the upper troposphere. A number of studies have been conducted 1) to test whether the atmosphere is observed to be more humid in a warmer climate (e.g., Rind et al. 1991), and 2) to study the direct relationship between deep convections and humidity (e.g., Soden and Fu 1995).

In this study, we use 20-year (1976-1995) daily rawinsonde data at five stations in the Tropical Western Pacific (TWP) to examine the vertical relative humidity (RH) variations on diurnal, seasonal, interannual, and decadal time scale. The advantages of a 20-year daily rawinsonde dataset are that 1) the rawinsonde data can provide information on the vertical structure of water vapor variability (rather than total column value); 2) the long-term water vapor variations can be studied because of its long-time record; 3) the availability of hourly data makes it unique for analyzing water vapor variations on different time scales and investigating their interactions; and 4) for the first time, the new rawinsonde data after October 1993 include humidity reports at RH<20% and at temperatures lower than -40° C (Wade 1994). Another purpose of this study is to investigate the relationship between water vapor and deep connective clouds. Our approach is to combine rawinsonde humidity data with the International Satellite Cloud Climatology Program (ISCCP) cloud data.

Data Sources

The subset of a 20-year global daily rawinsonde dataset (Wang 1997) is employed in this study, and is available twice a day at 00 Greenwich Mean Time (GMT) and 12 GMT at five stations (Koror, Yap, Truk, Ponapei and Majuro) in the TWP. We also use 5-mb sounding data collected from the 46 priority sounding stations during the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE) (November 1992–February 1993).

The ISCCP D1 data provide the deep convective cloud amount in a grid box of 2.5° x 2.5° every 3 hours, and are available for March and April of 1994. The ISCCP DX data (30-km pixel, 3-hourly) for TOGA-COARE are utilized to show the characteristics of RH profiles for different cloud types.

RH Variations on Different Time Scales

Seasonal Variations

The RH differences between warm and colder climates (summer versus winter, El Niño versus La Niña, and daytime [00GMT] versus night time [12GMT]) are shown in Figure 1. The atmosphere is more humid in summer than in winter; the largest changes (> 30% of the mean) occur in the midtroposphere. The seasonal differences in RH agree very well (both sign and magnitude) with the GCM (Del Genio et al. 1994): 15% to 20% in the midtroposphere and 0% to 10% in the low and upper troposphere, and have the same sign as those from the Stratosphere Aerosol and Gas Experiment (SAGE-II) but larger magnitudes (Rind et al. 1991; Del Genio et al. 1994).

Interannual Variations

The interannual variations of water vapor in the tropics are primarily modulated by El Niño and La Niña events, so the contrast in RH between La Niña and El Niño events is used to represent humidity variations on the interannual time scale. We present the difference in RH between 1995 (La Niña) and 1994 (El Niño) from September to December in Figure 1. The data before 1993 are also employed to calculate mean RH profiles in DJF for La Niña (76, 85 and 89) and El Niño (77, 78, 80, 83, 87, 88 and 92) years. The

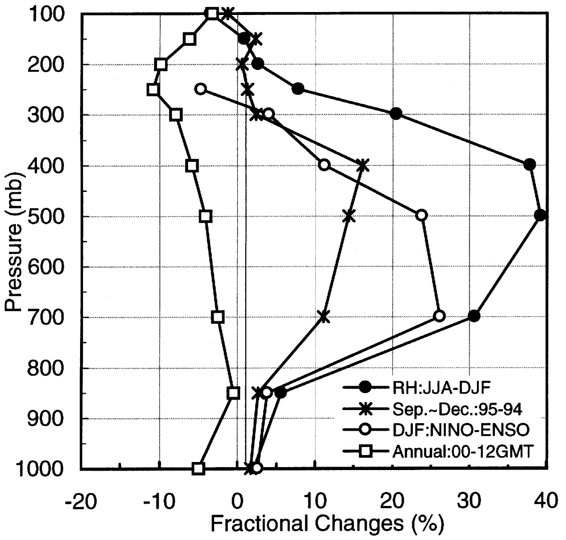

Figure 1. Fractional changes (absolute changes normalized be mean values) in RH between JJA and DJF, 1995 and 1994 from September to December, La Niña and El Niño years in DJF, and 00 GMT and 12 GMT.

data both before and after 1993 show that RHs are higher in La Niña years than in El Niño years, and the vertical structure exhibits peak amplitudes in the mid-troposphere. The interannual variability of RHs has similar vertical structure as that of seasonal cycle, but smaller magnitudes.

Diurnal Variations

On the diurnal time scale, the upper troposphere is drier during daytime (00GMT) than during night time (12GMT) (Figure 1). This is likely associated with more anvil and cirrus clouds during daytime. We found that there are more frequent occurrences of RHs (with respect to water) around 60% at 250mb and 50% above 250mb, corresponding to RH with respect to ice above 94%, indicating saturated air (e.g., clouds are formed). It suggests that the diurnal variability of RH is closely associated with local fluctuations of high clouds.

Long-Term Trend

The 20-year (1976-1995) and 13-year (1976-1988) long-term trends of temperature and humidity are calculated for both absolute and normalized monthly anomalies (Figure 2).

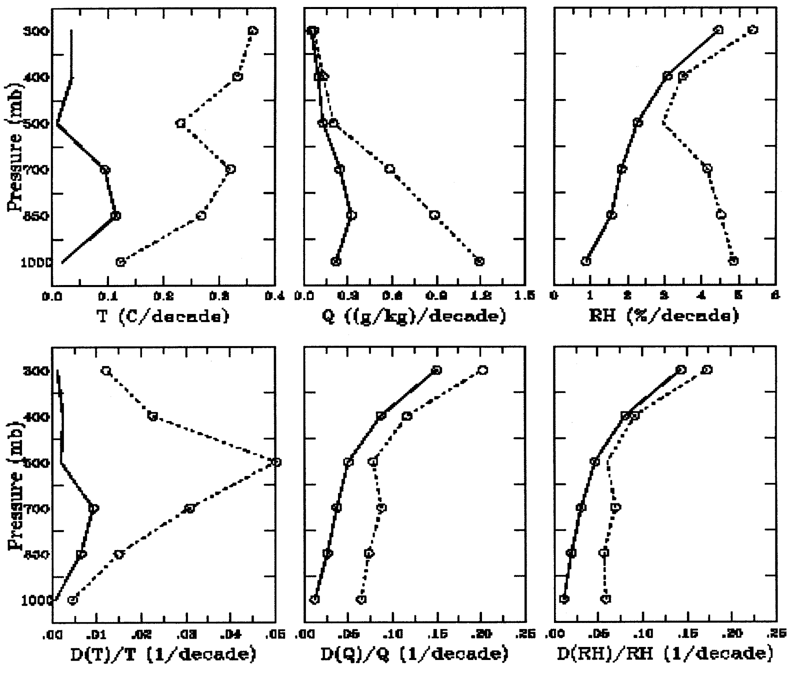

Figure 2. Vertical profiles of linear trend coefficients for temperature (T), specific humidity (Q) and RH in both absolute (upper panel) and relative (lower panel) values for 20-year (1976-1995) (solid lines) and 13-year (1976-1988) (dotted lines) trends. The circles indicate that coefficients are statistically significant

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First of all, all cases show that the atmosphere throughout the troposphere has become warmer and more humid since the mid-1970s. The specific humidity increase is large enough to produce the positive RH trends despite the warming trend. Secondly, the 13-year (76-88) trends are larger than the 20-year (76-95) trends for both temperature and humidity at all levels. This is attributed to relative coolness and dryness in the 1990s associated with the long (El Niño-Southern Oscillation) ENSO in 1991-1995 (Trenberth and Hoar 1996). Thirdly, the specific humidity trends decrease with height in absolute values but increase in relative values, which is not consistent with the assumption of equal relative perturbations of humidity vertically (Shine and Sinha 1991). The RH trends in both absolute and relative values, however, generally increase with height. Such vertical structure would amplify positive water vapor feedback due to the greater sensitivity of outgoing longwave radiation (OLR) to lower RH and its variability in the free troposphere (Spencer and Braswell 1997). The vertical structures of RH and Q long-term trends are distinct from those of seasonal and interannual RH variability that peak in the midtroposphere. It suggests that the long-term humidity trend can be considered as a sensitive indicator of long-term climate change.

Relations with Deep Convective Clouds

Temporal Correlations Between RH and Convective Cloud

In this section, we first use rawinsonde data and co-located ISCCP D1 data to study instantaneous and lag correlations between RH and deep convective (DC) cloud cover. The RH profiles are matched with the deep convection observations taken concurrently at the same location and at times 3, 6, 9, 12, 15,18, and 21 hours earlier, which forms eight categories of hours after convective events start (0, 3, …, 21). Regardless of time after DC starts, RHs increase throughout the troposphere if there are deep convective clouds, but decrease without occurrences of DC. Such changes in magnitudes peak in the middle and upper troposphere, and the increases in RHs, enhance with DC cloud fractions. The result suggests that on time average, increased tropospheric RH is associated with enhanced tropical convection. The same technique is applied to the TOGA-COARE 5-mb rawinsonde data and co-located ISCCP DX data to analyze correlations between RH and DC cloud top. The results also show higher RHs as DC clouds occur and increased RHs with higher DC tops.

Variations of RH Profiles with Cloud Types During TOGA-COARE

The RH variability in the upper troposphere during TOGA-COARE are as much as 60% of the mean and are larger than that in the lower troposphere (Figure 3). To understand the variability of upper tropospheric humidity (UTH), RH profiles are classified according to ten cloud types defined in ISCCP DX data, and their means are shown in Figure 4. As expected, the upper troposphere is more humid for middle and high cloud types than for low clouds and clear sky. Inversion layers within 700 mb to 550 mb, referred to "tropical inversions near the 0° C level" (Johnson et al. 1996), occur for DC, nimbostratus (Nb), cirrostratus (Cs), and cirrus (Ci). The inversion layer for DC and Nb is 0.78° C cooler than that for Cs and Ci. It supports the finding that the cool/moist inversion layers are a result of the direct effects of melting in the precipitation systems associated with DC and Nb (Johnson et al. 1996). The association of warm/dry inversion layers with cirriform clouds suggests that they may simply be remnant melting layers from past convections (Johnson et al. 1996).

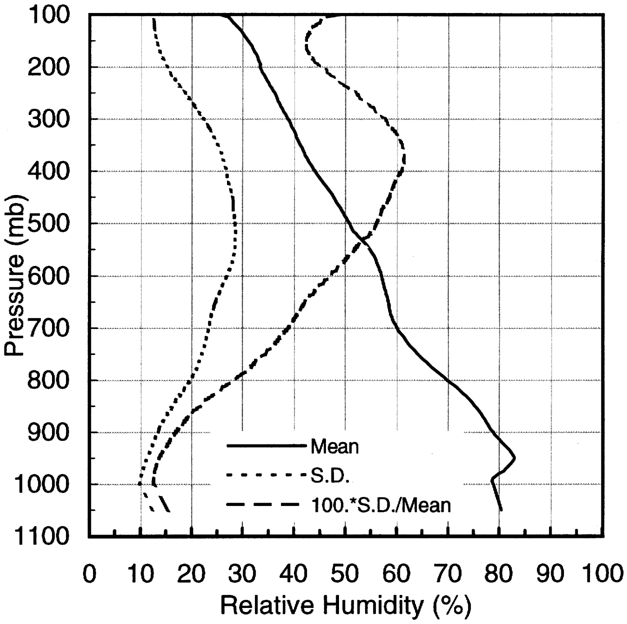

Figure 3. Vertical profiles (1000 mb to 100 mb) of mean, standard deviations (S.D.), and normalized S.D. of RH during TOGA-COARE. Values at 1050 mb represent surface values.

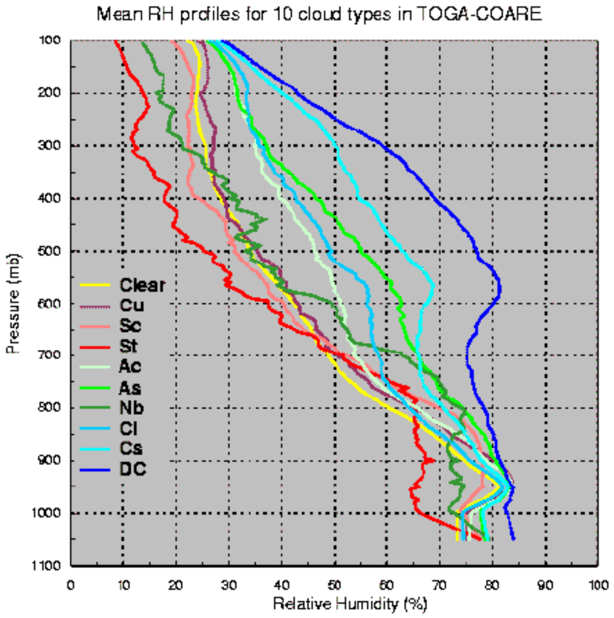

Figure 4. Vertical profiles (1000 mb to 100 mb) of mean RH (%) for ten cloud types during TOGA-COARE. Values at 1050 mb represent surface values. (For a color version of this figure, please see http://www.arm.gov/docs/documents/technical/conf_9803/wang-98.pdf .)

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