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# The diurnal cycle of convection, clouds, and water vapor in the tropical upper troposphere

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**Abstract.** Hourly observations of the 6.7 μm water vapor radiances from geostationary satellites are used to document the diurnal cycle in upper tropospheric water vapor and its relationship to cloud cover and convection. A coherent diurnal cycle in tropical water vapor is observed which lags the variations in cloud cover by approximately 2 hours. The variations in upper tropospheric cloud and water vapor occur (roughly) in phase with changes in deep convection over land, but nearly 12 hours out of phase with those over ocean. This feature is shown to be associated with differences in the vertical structure of land and ocean convection and offers a useful test of convective parameterizations in atmospheric models.

## Introduction

The presence of large diurnal variations in convection over the tropics is well documented. The amplitude of the diurnal cycle is typically largest over land areas, but important variations are also observed over oceans. Precipitation, for example, generally peaks in the early evening over tropical land regions and in the early morning over oceans. Such land/ocean phase differences have been the topic of considerable research and debate. Many of the most widely studied diurnal variations, such as precipitation (e.g., Gray and Jacobson, 1977; Janowiak et al., 1994), cloud cover (e.g., Fu et al., 1990), and outgoing longwave radiation (e.g., Hartmann and Recker, 1986), are directly associated with the atmospheric hydrologic cycle. Given its obvious role in linking these processes, it is surprising that there are few published investigations of the diurnal cycle of water vapor. Although the variability of water vapor on longer time scales has been widely studied, there has been relatively little effort to document its diurnal variation.

Geostationary satellites provide high temporal sampling of the infrared radiation at wavelengths sensitive to atmospheric water vapor. As shown by Soden and Bretherton (1993), the 6.7 μm channel is primarily sensitive to the relative humidity averaged over a deep layer, centered in the upper troposphere (typically 200-500 hPa). The ability to accurately infer the amount and variability of upper tropospheric moisture from geostationary satellite observations has been well established (e.g., Schmetz et al., 1988; Soden and Bretherton, 1993; Moody et al., 1999). However, this resource has rarely been utilized for studying the diurnal cycle. Indeed, only one previous study has even attempted to document the diurnal cycle of water vapor (Udelhofen and Hartmann,1992 - hereafter referred to as UH92). UH92 used four days of GOES 6.7 μm measurements to examine the diurnal variations in upper tropospheric relative humidity (UTH). To better document these variations and understand the physical processes which govern them, this study uses nearly 3 months of hourly GOES data to examine the diurnal relationships between convection, cloudiness and water vapor in the tropics.

## Data and Method

The UTH is derived from hourly GOES 6.7 μm radiances following the method of Soden and Bretherton (1993) and averaged onto a 1$^{o}$ latitude-longitude grid. Since clouds strongly attenuate the upwelling radiance at 6.7 μm, estimation of UTH is only possible from cloud-free pixels. Pixels are classified as cloudy when brightness temperature difference between the 11 and 6.7 μm channels ($T_{11}$-$T_{6.7}$) is less then 25 K (Soden, 1998). Although the selection of this threshold is somewhat arbitrary, the results presented here are not sensitive to reasonable changes in its value. Given the vertical distribution of the 6.7 μm weighting function, the fraction of cloud-screened pixels provides a crude, but useful, measure of upper tropospheric cloud cover.

Under most situations the observed radiance in the 11 μm "window" channel is larger (warmer) than that in the more strongly absorbing 6.7 μm "water vapor" channel. However as shown by Schmetz et al. (1997), in situations of deep convection where cloud tops reach the tropopause, $T_{6.7}$ becomes larger than $T_{11}$ due to the emission at 6.7 μm from stratospheric water vapor which absorbs radiation from the cloud top and emits it at warmer, stratospheric temperatures. Since this only occurs for clouds which reach the tropopause level, the number of pixels for which $T_{6.7} > T_{11}$ provides a useful proxy for deep atmospheric convection.

## Diurnal Relationships

The UTH, percentage of cloud contaminated pixels (CLD), and percentage of deep convective (DC) pixels in each grid box were computed from hourly GOES imagery for the period of June - August, 1987. A mean diurnal cycle was constructed by averaging these fields at hourly intervals from each day of the 3-month period. The resulting composite in each grid box was then decomposed spectrally using a Fourier transform to isolate the diurnal harmonic. The phase and amplitude of this harmonic is plotted in Figure 1 for DC (top), CLD (middle), and UTH (bottom). The phase corresponds to the (local) time of maxima and can be determined from the orientation of the arrows with respect to a clock. Arrows pointing upward indicate a peak at 00 local standard time (LST), downward indicate a peak at 12 LST, toward the right indicate a peak at 06 LST, and toward the left a peak at 18 LST.

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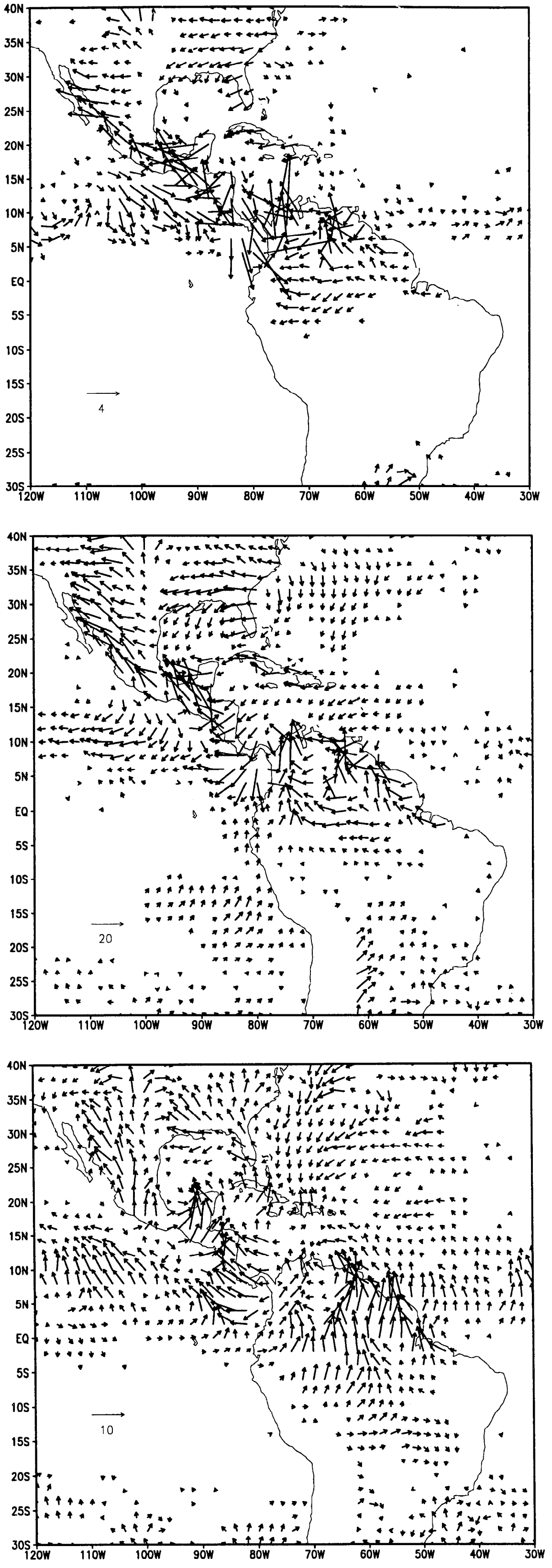

**Figure 1.** The amplitude and phase of the diurnal harmonic in DC (top), CLD (middle), and UTH (bottom). All units are in %. The length of the arrow depicts the amplitude of the harmonic (see key on inset). For clarity, results are only shown where the amplitude exceeds 0.5% for DC, 2% for CLD, and 1% for UTH.

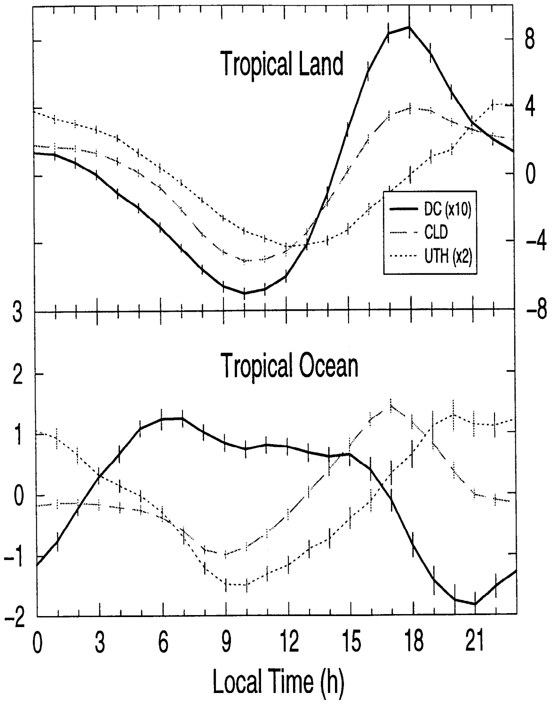

**Figure 2.** The diurnal anomalies in DC, CLD, and UTH for spatial averages (30N-30S, 120W-30W) over tropical land regions (top) and tropical ocean regions (bottom). Anomalies for DC and UTH have been scaled by 10 and 2, respectively. All units are in %. The standard errors for each variables and each hour are shown as vertical bars.

Large diurnal variations in UTH (> 10%) are observed over convectively active regions. The UTH typically peaks in the late evening (~2200-2400 LST), with an exception occurring off the eastern coast of the United States where the UTH tends to peak near 1200 LST. The spatial patterns of diurnal variability in CLD and UTH tend to be more diffuse than for DC, owing to the outflow of moisture and condensate away from the centers of convection in the upper troposphere. Note the presence of a distinct phase shift for DC, CLD, and UTH as one moves away from the Rocky mountains towards the central plains, highlighting the eastward propagation of convective complexes over this region during summer.

In many regions a distinct lag is evident in the phase-relationships between DC, CLD, and UTH. For example, over the eastern Pacific portion of the ITCZ convective activity tends to peak in the mid-morning (~0900-1100 LST), consistent with observational studies of oceanic precipitation (Gray and Jacobson, 1977; Janowiak et al., 1994). However, the upper level cloudiness tends to peak in the early evening (~1800 LST) well after the convection has peaked. Likewise, the UTH reaches its maxima in the late evening (~2200 LST), a few hours after the cloud cover does. In contrast, the phase lags between DC and CLD (or DC and UTH) over land regions tend to be much smaller (e.g, Brazil, eastern U.S.).

To provide a better understanding of the nature of these relationships, Figure 2 shows the time-averaged diurnal anomalies of the tropical-mean DC, CLD, and UTH. Tropical-mean refers to a spatially-weighted average from 30N-30S for longitudes within the GOES-7 viewing domain (120W-30W) and are computed separately from land (Fig. 2, top) and ocean grid boxes (Fig. 2, bottom). The standard errors of the time-averaged anomalies (vertical bars in Figure 2) are typically an order of magnitude smaller than the amplitude of the diurnal cycle for DC, CLD and UTH. The amplitude of the diurnal cycle in UTH (2-4%) is also roughly a factor of 4 larger than the uncertainties introduced in the retrieval due to diurnal changes in temperature at these levels (typically < 0.5 K; Wallace and Patton, 1970). Sensitivity studies using 6-hourly ECMWF analysis fields suggest that the impact of diurnal variations in temperature on the retrieved tropical-mean UTH is less than 0.25%.

The diurnal anomalies in DC, CLD, and UTH are systematically larger over land than over ocean. Over land, the variations in DC and CLD are nearly in phase with maxima in late afternoon ~1800 LST and a minima just before local noon (~1000 LST) consistent with observed variations in clouds (e.g., UH92; Fu et al., 1990) and OLR (Hartmann and Recker, 1986). Interestingly, the diurnal cycle of UTH lags the variations in DC/CLD by ~2 hours. A similar phase-lag between in CLD and UTH is observed over the tropical oceans.

What is the cause of the 2-3 hour lag between CLD and UTH? One possibility is that it results from a moistening of the environmental air due to the evaporation of cirrus clouds (Soden, 1998). However, an alternative explanation was offered by UH92 who noted an ~8 hour lag between UTH and CLD (i.e., nearly out of phase) and suggested that the variations in UTH are simply an artifact of the clear-sky sampling limitation. That is, if there were no variations in relative humidity, then variations in the retrieved clear-sky UTH could result solely from changes in cloud masking. However, this explanation requires the CLD and UTH variations to be (nearly) out of phase; i.e., maximum UTH would occur at minimum CLD. Instead, the UTH and CLD anomalies in Figure 2 are (nearly) in phase and therefore of the wrong sign to result from a clear-sky sampling bias. It is possible, however, that the 2 hr lag between CLD and UTH is attributable this cloud-masking effect. For example, if UTH and CLD were in phase, then as cirrus shields evaporate more pixels will become cloud-free and, assuming they are systematically more humid than the surrounding environment, could introduce an apparent lag in the UTH field.

As noted above, the phase of the UTH diurnal cycle in Figure 2 differs (by about 6 hours) from that presented by UH92 despite similar diurnal cycles of CLD in both studies. For example, the UTH from UH92 peaks at 0600 with a minima at 1800, whereas the UTH in Figure 2 peaks at 1900 (ocean) - 2200 (land), with a minima at 1000 (ocean) - 1300 (land). Sensitivity studies using a different cloud clearance threshold ($T_{11}$-$T_{6.7}$ < 35 K instead of 25 K) resulted in very similar phase relations, indicating that the current analysis is not sensitive to reasonable changes in cloud clearance. Another possibility is that the smaller sample size of UH92 (4 days) compared to the present study (~80 days) contributes to the discrepancy. To explore this possibility an ensemble of 4-day diurnal anomalies were computed from the 3-month period and compared to each other. The phase of UTH cycle between the various 4-day composites differed by up to 5 hours, suggesting that the smaller sample size of UH92 could account for some of the discrepancy.

While the diurnal cycles of UTH and CLD are similar over land and ocean the diurnal cycles of DC are not (Figure 2). Deep convection peaks in the late afternoon (~1800 LST) over land as opposed to late-morning (~0900 LST) over oceans. Consequently, the anomalies of CLD and UTH over oceans are nearly 12 hours out of phase with those of DC, in stark contrast to the in-phase relationship observed over land. Why are variations in UTH (and CLD) out of phase with DC over ocean? One possible explanation is that convection over the tropical oceans is less intense than over land, resulting in a greater fraction of convective outflow at lower levels. Since the threshold for labeling pixels as DC ($T_{11} < T_{6.7}$) requires having convective towers reach tropopause levels, it really measures only the *deepest* convection and therefore may not be representative of all convection in the tropics. Indeed observational studies (e.g., Hartmann and Recker, 1986; Hendon and Woodberry, 1993) have noted the presence of mid-tropospheric convective clouds (~400 hPa) whose diurnal variations tend to be out of phase with those at higher levels (~100 hPa). To investigate this possibility, observations of $T_{11}$ were binned in 5 K intervals and the percentage of pixels in each 5 K bin was computed for each hour and for each grid box. The percentages of pixels in each 5 K bin were then composited to construct a mean diurnal cycle and spatially averaged over the same domains as in Figure 2. The histogram in $T_{11}$ for the tropical-land (Fig.3, top) reveals a coherent vertical structure with peak cloudiness occurring in the early evening ~1900

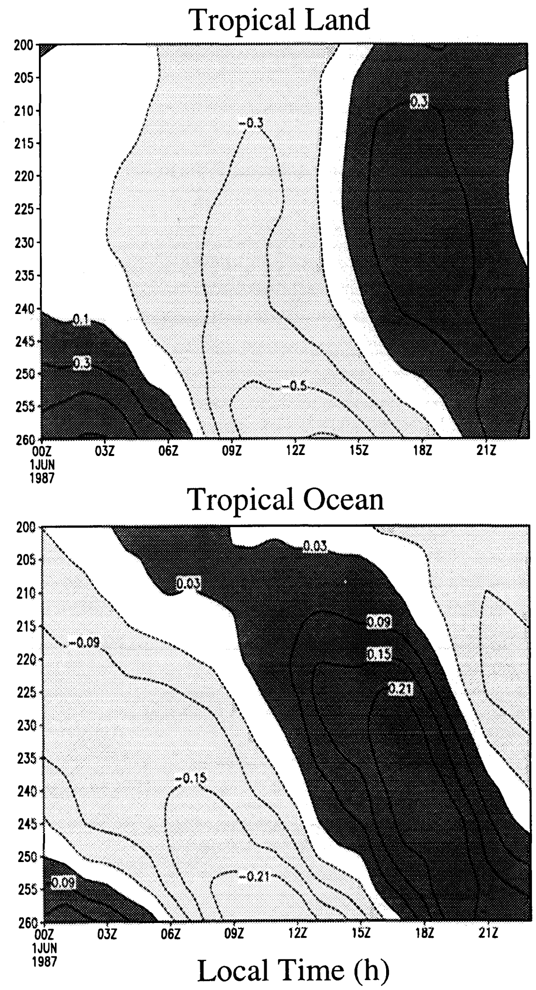

**Figure 3.** A histogram of the percentage of pixels for which $T_{11}$ occurred within each 5 K interval for tropical-land regions (top) and tropical-ocean regions (bottom). Contour intervals are 0.2 (top) and 0.06 (bottom).

LST for a broad range of cloud top heights (205 K < $T_{11}$ < 250 K). The oceanic clouds, on the other hand, exhibit a distinct vertical phase lag. The coldest and highest ocean clouds ($T_{11}$ < 205 K) peak near 0700 LST consistent with the DC index. However, at roughly this same time, warmer cloudy pixels (225 K < $T_{11}$ < 250 K) experience a diurnal minima.

The peak in DC (and high clouds) over the oceans in early morning is consistent with many observations of oceanic precipitation (Gray and Jacobson, 1977; Janowiak et al., 1994), whereas the maxima in oceanic UTH coincides with peaks in the less intense, mid-level clouds (210 K < $T_{11}$< 250 K). This implies that oceanic precipitation is primarily associated with the most intense convection (i.e., $T_{11}$ < 205 K), whereas UTH is more strongly influenced by convection which detrains at lower levels in the troposphere. This interpretation is consistent with conceptual models of tropical convection which recognize that detrainment of moisture occurs throughout the free troposphere (e.g., Betts, 1990) instead of only at the upper most levels (e.g. Lindzen, 1990).

## Summary

This study used hourly GOES 6.7 μm observations to describe the diurnal changes in convection, clouds, and water vapor in the tropical upper troposphere. The key results are:

(i) The presence of significant diurnal variations in UTH (> 10%) over both land and ocean.

(ii) The presence of a coherent diurnal relation between CLD and UTH, in which UTH lags CLD by ~2 hours, consistent with the formation of cirrus anvils and their subsequent evaporation. However, the clear-sky sampling limitation of UTH may also contribute to this apparent lag.

(iii) A fundamental difference in the diurnal relationships between DC and UTH over tropical ocean versus tropical land regions. Variations in upper tropospheric clouds and water vapor occur in phase with DC variations over land, but out of phase with those over ocean. This difference is shown to be associated with a vertical phase lag of tropical convection and highlights the importance of convective detrainment at all levels of the upper troposphere, not just the tropopause, for determining changes in upper tropospheric water vapor.

The contrasting diurnal relationships of convection and water vapor between land and ocean regions offers a useful test of convective parameterizations in atmospheric models.

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