Three-Dimensional Water Vapor and Cloud Variations Associated with the Madden–Julian Oscillation during Northern Hemisphere Winter

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ABSTRACT

The Madden–Julian oscillation (MJO) is the dominant form of intraseasonal variability in the Tropics. In previous studies, intraseasonal variability has usually been characterized in terms of wind or convection anomalies, while the structure of MJO-related moisture variations has been greatly unexplored. This work focuses on the behavior of moisture and related hydrological fields associated with MJO events during Northern Hemisphere winter. Five-day averaged (1979–99) Television Infrared Observational Satellite (TIROS) Operational Vertical Sounder (TOVS) moisture soundings from the NASA Pathfinder data were used, providing global coverage at specific pressure levels. The TOVS moisture, as well as the International Satellite Cloud Climatology Project (ISCCP) cloud fraction anomaly data, were composited based on MJO events selected via an index constructed from Xie–Arkin bandpassed pentad rainfall data. Analysis of the three-dimensional structure and evolution of precipitation, water vapor, and clouds over the life cycle of the MJO shows a rich set of relationships between the variables.

The composite evolution of moisture shows markedly different vertical structures as a function of longitude. There is a clear westward tilt with the height of the moisture maximum associated with MJO disturbances propagating eastward across the Indian Ocean. These disturbances evolve into nearly vertically uniform moist anomalies as they reach the western Pacific. Near-surface (<850 mb) water vapor leads precipitation by 1–2 pentads, as the upper troposphere is moistened following intense convection. In the eastern Pacific, the moisture variations then become confined to the lower levels (<~700 mb), with upper-level water vapor nearly out of phase. ISCCP total cloud fraction is highly correlated with humidity, and also leads observed precipitation. There is a longitudinal displacement between the maxima in rainfall and the maxima in cloud fraction, with higher cloudiness at the (western) trailing edges of the rainfall maxima. The cloud-top heights also show consistent changes over the course of the composite MJO life cycle, with an increasing (decreasing) strength of middle (high) cloud variations as the disturbances propagate eastward to the western Pacific.

Averaged over all phases of the MJO, dry anomalies dominate over moist anomalies that occur in the active phase of the disturbance. The bias toward dry anomalies is strongest between 15°N and 15°S in the Western Hemisphere and suggests a low-frequency rectification of intraseasonal variability onto the mean background moisture state of the atmosphere.

1. Introduction

Moisture has been implicated as playing an important role in the Madden–Julian oscillation (MJO) through the interaction of dynamics with convection. However, the exact interplay of the hydrological cycle with tropical dynamics, within intraseasonal disturbances in particular, remains unclear. To date, much of the previous observational characterization of the MJO has been carried out based on the upper-level wind and outgoing longwave radiation (OLR) fields (e.g., Madden and Julian 1971; Weickmann 1983; Wang and Rui 1990; Hendon and Liebmann 1994; Hendon and Salby 1994; Salby and Hendon 1994; Madden and Julian 1994). Typically, patterns of variability in tropical water vapor associated with the MJO have been discussed secondarily (e.g., Fink and Speth 1997; Maloney and Hartmann 1998). However, there is a continued emphasis on the understanding that convection and dynamics are highly coupled for the MJO (e.g., Hayashi and Sumi 1986; Lau et al. 1989; Neelin and Yu 1994; Yanai et al. 2000). Moreover, the role of the moisture budget over the life cycle of intraseasonal disturbances has only been modestly discussed in the literature, apart from surface evaporation and precipitation (e.g., Bantzer and Wallace 1996; Jones et al. 1998; Shinoda et al. 1998; Yanai et al. 2000). Since many current theoretical and modeling approaches to the MJO rely on its characterization as a moist disturbance, it seems appropriate to document patterns of large-scale intraseasonal moisture and cloud variability.
in a way that parallels and complements earlier work focusing on other fields.

Further, recent insights into the vertical structure of water vapor anomalies composited from radiosonde data (Kemball-Cook and Weare 2001) suggest there is considerable vertical structure in the intraseasonal signature of moisture that previous studies using vertically integrated measures of humidity did not capture. However, that study did not provide a broad link to the horizontal structure, as it included only selected radiosonde stations. In this study, we will document the three-dimensional evolution of moisture associated with the MJO in a global fashion that highlights the linkage between horizontal and vertical structure.

Despite this accumulation of knowledge, few general circulation models (GCMs) display a sufficiently strong intraseasonal signal. Modeling studies have continued to demonstrate poor simulation of key details of the MJO. Results from the Atmospheric Model Intercomparison Project (AMIP) MJO subproject showed that the modeled variance was often 3–10 times lower than found in observations (Slingo et al. 1997). While it has been suggested that some of the difficulties in simulation of the MJO lie in the models’ convective and/or cloud parameterizations (e.g., Slingo and Madden 1991; Wang and Schlesinger 1999; Maloney and Hartmann 2001), there are few diagnostic studies to serve as benchmarks for diagnosing moisture and cloud variability associated with MJO events. The need for such a characterization is an important one that extends even to mechanistic, theoretical models of the MJO, and not just GCMs. The recharge hypothesis of Blade and Hartmann (1993) and the radiation–convection coupling model of Raymond (2001) would also benefit from improved knowledge about the structure of moisture variability.

To help address this need, this paper focuses on characterization of the three-dimensional variability in water vapor and clouds associated with the MJO. Emphasis is placed on revealing the vertical structure of the observations and the relationship between moisture, precipitation, and clouds during various stages of evolution of the MJO. The following section discusses the data used in this study. In section 3, the methodology and compositing strategy is detailed. In section 4, the results of the analyses are described, with emphasis placed on those features not found in previous studies. Further discussion and a summary are presented in section 5.

2. Data

The data analyzed include moisture from the Television Infrared Observational Satellite (TIROS) Operational Vertical Sounder (TOVS), clouds from the International Satellite Cloud Climatology Project (ISCCP D1), and precipitation from the Climate Prediction Center’s Merged Analysis of Precipitation (CMAP). The National Aeronautics and Space Administration’s (NASA’s) TOVS Pathfinder-A dataset contains 21+ yr of polar-orbiting satellites (December 1978–December 1999), providing global measurements of water vapor observed by TOVS platform (Susskind et al. 1997). The available information has been processed to 5-day means at a spatial resolution of 1° × 1°. The chosen temporal averaging represents a compromise between the sampling bias of polar-orbiting satellites, which visit some areas of the Tropics only at certain times of day, and the necessity of differentiating various phases of the MJO as finely as possible. The vertical resolution of the sounder allows for retrieval of specific humidity and temperature at multiple levels. The analyses presented here were performed on retrievals from the 300-, 500-, 700-, 850-mb, and surface levels. The NASA Goddard Earth Observing System (GEOS) 6-h forecast is used to provide background field guesses as a part of the retrieval. While the details of the profiles cannot be considered wholly independent of the GEOS cloud and convection schemes, the separate infrared channels do provide real radiance information sensitive to water vapor at different vertical levels.

Apart from the radiosonde-based study of Kemball-Cook and Weare (2001), there has been little focus on vertical structure in studies of intraseasonal moisture variability. The use of the vertical structure information contained in the TOVS data helps set this study apart from many of the previous, more cursory assessments of intraseasonal moisture variability that generally relied on total precipitable water for evaluating the hydrological signal of the MJO. Whereas previous studies have analyzed intraseasonal behavior in microwave-derived water vapor data (e.g., Maloney and Hartmann 1998), TOVS was chosen for this study specifically for its ability to show more vertical structure and because the Special Sensor Microwave Imager (SSMI) cannot provide retrievals over land. Because the TOVS Pathfinder-A retrieval procedure relies in part on infrared instrumentation, these soundings are not technically valid under very deep convective clouds, which are usually observed during intense episodes of MJO-related tropical convection. Errors are expected to be largest near the surface as a result. Also, while diurnal variations in convection may be small over the ocean (e.g., see Yang and Slingo 2001), they may still feed back onto water vapor, which would result in an exacerbation of the sampling bias from a polar-orbiting satellite that may visit a particular tropical location only about once daily in some cases. It is to be emphasized above all that retrieving humidity profiles via an infrared sensor is very difficult even under optimal conditions. While the infrared channels do provide enough useful information to warrant their use, the errors from TOVS due to sampling bias and retrieval problems can be sizable.

These limitations may result in a biased analysis of the underlying variability; however, we did find that the TOVS specific humidities compare favorably to other estimates of water vapor, such as radiosonde data and
the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis moisture. For instance, while ECMWF mean values are typically 10%–20% higher than TOVS in the Tropics, the standard deviations of the departures from the annual cycle differ by only about 5%–10% between TOVS and ECMWF, with TOVS generally showing slightly higher standard deviations. In addition, the spatial scales found in maps of the standard deviation of anomalies are similar for the reanalysis and satellite data. The standard deviations of TOVS intraseasonal (35–95 day) specific humidity anomalies are approximately 25%–30% lower than for the ECMWF analysis in the lower troposphere (≥700 mb). Nonetheless, the amplitude of the intraseasonal moisture signal in TOVS has a typical trough-to-peak specific humidity amplitude of nearly 1 g kg⁻¹ at 700 mb over much of the Indian and western Pacific, and large individual events can have fluctuations 2–3 times this size. Also, the disparity of intraseasonal variability between TOVS and ECMWF decreases with height, and there are very clear wave-propagating signals at all vertical levels in both products. However, given that the ECMWF in fact assimilates some of the same radiance data as used in TOVS, the reasonable agreement between the two may not be much of a stringent test of the reliability of TOVS.

Another comparison of the extent of moisture variability can be made to the data of Zhang (1996) and Brown and Zhang (1997). The former included a pentad record of surface specific humidity from roughly 2 yr of Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) buoy data that displayed a typical intraseasonal amplitude of a little less than ±0.5 g kg⁻¹. The latter paper showed daily midtropospheric (550–850-mb average) moisture measured using radiosondes over the warm pool during TOGA COARE, for a duration of 120 days. The absolute range of those fluctuations is nearly 4 g kg⁻¹, but it should be noted that the variability they observed is not obviously related to the MJO, and their data contain quite substantial variability on subpentad timescales. Furthermore, qualitative examination indicates that the intraseasonal component of their data is on the order of 1 g kg⁻¹, which is similar to what is found from TOVS. Still, this is a further indication that the TOVS data could underestimate moisture variability.

We also performed our own comparison using TOGA COARE intensive flux array (IFA) data from the 120-day period spanning November 1992–February 1993. Figure 1 shows the comparison between the two sources of data over the same location during that time. The IFA data represents the moisture from an array of ra-
The TOVS data were averaged over a collocated 2-day values at 29 vertical levels from 1000 to 300 mb. The TOVS data were averaged over a collocated 2° × 2° square in order to make an appropriate comparison. Both sets of data have had their respective means over the 120-day time period removed at each vertical level. This procedure removes a small mean bias between TOVS and the IFA data (see Table 1), and makes the variability of each panel more readily visible. Figure 1 demonstrates that TOVS data may underestimate the actual moisture variability, but not greatly. The underlying intraseasonal cycle is readily apparent in both data sources.

In all, we take the above comparisons to indicate that the TOVS record captures the essential features of the moisture signal associated with the MJO, but may underestimate the amplitude due to the instrumental bias mentioned above. In addition to its high horizontal resolution and global coverage, TOVS appears reliable enough to be used for the composite analyses that will be presented below. A further comparison of composites of TOVS data with composites of radiosonde data will be presented in section 4.

ISCCP data has been interpolated to 2.5° × 2.5° resolution and averaged to 5-day means for the period spanning July 1983–February 1994 (Rossow and Schiffer 1991). Individual pixel counts from 3-hourly slices were accumulated for cloudy conditions, and divided by the total pixels observed overall to produce cloud fractions over the course of each pentad. This was done for both total cloud fraction, and infrared cloud fraction, which was grouped by cloud-top height into seven height bins. The infrared cloud bins are further grouped into high (upper three bins), middle (next two bins), and low clouds (bottom two bins). An adjustment to the ISCCP data is made following Weare (1999) to account for cloud overlap associated with the satellites’ top-down views. This affects the raw data as little as possible to account for nonzero overlap, while still retaining self-consistency. Data from both polar-orbiting and geostationary satellites are incorporated, and the ISCCP data affords good global coverage. Due to a lack of geostationary data over the Indian Ocean, there is a significant overall bias (5%–15% in cloud fraction) in the mean climatology there due to the particular equatorial crossing time of the polar-orbiting satellites used at those longitudes. However, this study concerns only anomalous cloud fractions, and after removal of the annual cycle from the data, the systematic deviations in that sector are not distinguishable.

The CMAP (Xie and Arkin 1997) precipitation data for the period 1979–99 is used here as a proxy for MJO hydrological activity. Propagating intraseasonal (35–95-day filtering) signals in rainfall are quite strong (4 mm day−1 trough-to-peak amplitude in the eastern Indian Ocean), and clearly propagating. Propagation occurs roughly to the date line, and then fairly abruptly drops off, similar to findings for OLR (e.g., Salby and Hendon 1994). However, the spatial scale of the precipitation anomalies is considerably smaller than that found in fields such as OLR and velocity potential. For this reason, we conduct our indexing and compositing of clouds and water vapor over the course of the MJO life cycle in terms of the patterns found in rainfall. This is also a desirable choice since it links the indexing to a direct hydrological source.

3. Methodology

Only Northern Hemisphere (NH) wintertime data were considered (November–April), as this is the season in which the MJO is least affected by interaction with the Asian monsoon and because these are the months during which the MJO most strongly exhibits its canonical equatorially propagating form (e.g., Wang and Rui 1990). Relative humidities were calculated from the TOVS temperature and specific humidity values, at the nominal pressure values (300, 500, 700, or 850 mb) from the TOVS soundings. For the surface retrieval values, the surface pressure was taken from the National Centers for Environmental Prediction (NCEP) reanalysis surface pressure field in order to compute a TOVS-based surface relative humidity value. The above procedure produced a 1° × 1°, pentad-averaged dataset of relative and specific humidity at five vertical levels, spanning 20 complete winters.

The primary motivation of this paper is to characterize the typical coevolution of the moisture, rainfall, and cloud fields. To accomplish this, wintertime MJO events were selected and composited by using an MJO index formed from the leading extended EOF (EEOF; see Weare and Nasstrom 1982 for examples of this technique) of bandpassed rainfall data. This was done by time filtering the CMAP rainfall using a Lanczos windowing function with half-power at 35 and 95 days to retain intraseasonal variability (this band was also used by Salby and Hendon 1994). The filtered rainfall data was then averaged from 10°N to 10°S to form a time-longitude dataset that compactly captures the equatorially propagating MJO events in northern winter. Next an EEOF with a sliding window of 75 days (15 consecutive pentads) of equatorially averaged precipitation was performed to yield leading patterns and time series.

<table>
<thead>
<tr>
<th>Vertical level</th>
<th>TOGA COARE IFA</th>
<th>TOVS</th>
</tr>
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<tbody>
<tr>
<td>Near-surface</td>
<td>18.09 (1000 mb)</td>
<td>17.70 (surface)</td>
</tr>
<tr>
<td>850 mb</td>
<td>11.88</td>
<td>12.00</td>
</tr>
<tr>
<td>700 mb</td>
<td>7.33</td>
<td>6.96</td>
</tr>
<tr>
<td>500 mb</td>
<td>3.42</td>
<td>2.67</td>
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<tr>
<td>300 mb</td>
<td>0.62</td>
<td>0.48</td>
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The time series of the first two patterns are in quadrature with each other (maximum correlation at 2–3-pentad lag is 0.9), and together the first two modes account for 39% of the variance of the intraseasonally filtered data. The eastward-propagating signature of the EOF1 and the accompanying time series are shown in Fig. 2. Note that although the time series may appear continuous from winter to winter, this is only an artifact of the plotting, since after time filtering the rainfall data, the summertime component is discarded prior to conducting the EEOF.

Using the time series of this leading EOF as an indication of MJO hydrological activity, composites of MJO-related moisture were formed, indexed to the precipitation. The maximum in the EEOF intensity is such that a peak in the EOF1 time series corresponds to a rainfall maximum of a propagating MJO event at roughly 90°E at lag zero of the EEOF. It is useful to note that even though no wavenumber filtering was performed, this method still produces a rainfall signature that has large zonal scale and an eastward propagation. As with EOFs of OLR, there is a clear signal confined almost entirely to the Eastern Hemisphere, and there is noticeable disruption of the MJO rainfall signature in the vicinity of the Maritime Continent. In all, 46 events were identified for compositing using the EOF1 of rainfall by using a greater than $1$ standard deviation threshold on the EOF time series. Using this precipitation-based indexing scheme to identify the times of maximum hydrological activity associated with the MJO, cloud fraction and moisture data were then composited to form a 15-pentad-long evolution sequence at each vertical level and, in the case of clouds, for each cloud-top height bin.

It should be noted that although the moisture data has had its annual cycle removed prior to compositing, no attempt has been made to remove the interannual variability from the moisture data. While the interannual cycle has been removed from the rainfall data prior to the use of the EEOF for selection of the MJO events, care should be taken when interpreting the resulting composites in regions with large interannual variability (e.g., the eastern Pacific). We cannot rule out the possibility of contamination of those results from interannual variations without further investigation.

4. Results

a. Comparison of TOVS composites to composites of selected radiosonde data

Radiosonde data were examined at a few tropical stations to further validate the extent of the variability found in the TOVS moisture. While earlier comparisons with TOGA COARE IFA data showed reasonable agreement, we wanted to additionally examine whether composites of the data compared well with other sources of moisture information. Figure 3 shows the structure of the intraseasonal cycle of specific humidity at three stations (Seychelles, Cocos Island, and Tarawa) from radiosonde data. The method for producing these composites is identical to that used for the TOVS data, with the indexing based on CMAP rainfall. In addition, it should be noted that the radiosonde data are not band-passed before compositing. The timing of the peaks in specific humidity correspond well to those found for those same locations using the TOVS data. The magnitude and general vertical structure of the intraseasonal variability from the radiosondes also appears very similar to that from TOVS. However, there are some very large surface variations in moisture that are not well represented in the TOVS data. The near-surface variability is lower in TOVS, which has an overall dry bias at the surface level, similar to what was found in com-
Comparison with ECMWF. These errors are likely due to the difficulty that TOVS has in performing a proper retrieval there. In general, however, this comparison provides more evidence that TOVS captures the essential features of the moisture signal associated with the MJO. Furthermore, the vertical structure and amplitude of the composite anomalies based on the TOVS data are also similar to that found in Kemball-Cook and Weare (2001), in which data from several radiosonde stations were composited and grouped together.
b. Spatial variability of variance in water vapor and rainfall

Before forming composites, it is instructive to assess the spatial pattern of variance in the moisture data, since it is not readily obvious where intraseasonal water vapor variability most stands out from other forms of variability. Figure 4 shows the ratio of intraseasonal (here, 35–95 days) and interannual (>1 yr) variance of TOVS water vapor at 500 mb. The intraseasonal standard deviation is at least as large as the interannual standard deviation over much of the Tropics. The dominance of intraseasonal variability over interannual variability is most pronounced in the eastern Indian and Atlantic Oceans, and parts of the tropical Pacific Ocean and the South Pacific convergence zone (SPCZ). There is also considerable interannual signal in water vapor over northern Africa, too. In contrast, in the eastern Pacific, where ENSO-related variability is large, interannual variance of water vapor dominates intraseasonal (i.e., MJO) variance by a similar factor of 1.5–2. The spatial pattern in the ratio of intraseasonal to interannual variance is similar though most levels of the troposphere, with intraseasonal variability focused more exclusively in the western Pacific, Indian Ocean, and Australia at levels lower than 500 mb. At the surface, the patterns of intraseasonal moisture variance are also similar, with enhanced variability relative to the interannual fluctuations less biased toward the Southern Hemisphere than at the upper levels.

By contrast, the spatial pattern of rainfall (Fig. 5) shows higher gradients between tropical areas of lower variability and higher variability. The areas of dominance of intraseasonal variability are well defined in the Indian Ocean, western Pacific, and over the SPCZ. The ratio of intraseasonal to interannual standard deviation in rainfall is at least a factor of 2 over the Indian Ocean, whereas the area over which the ratio is above 1.5 for water vapor is small. The ratio of standard deviations of rainfall reaches as high as 3 over the warm pool and Maritime Continent. It should be noted that intraseasonal variance is not by virtue necessarily an indicator of MJO activity. In particular, it may be expected that the patterns of moisture and cloud propagation in the equatorial Indian and western Pacific will have considerably different structures compared to the areas of high moisture variability corresponding to the ITCZ and SPCZ, since the MJO is predominantly confined to a narrow equatorial band during the winter. Also, bandpassed intraseasonal signals by themselves are not constrained to have large spatial scale (i.e., wavenumber 1–2) as the MJO does. Variability accounted for by a simple intraseasonal bandpass can also contain both eastward- and westward-propagating signals. Since water vapor variability is strongly tied to advection while rainfall is not, it is not surprising that the spatial scale of standard deviations should differ in Fig. 4 versus Fig. 5. Where there are sharper climatological gradients in moisture, the variability of water vapor can be expected to be...
c. Life cycle evolution of composite MJO humidity variations

Maps showing the spatial evolution of the composite life cycle of humidity are displayed in Figs. 6–10. It should be noted that while the precipitation index was initially time filtered, the moisture data have not been bandpassed prior to compositing. Hereafter, when we refer to plots of humidity, the reader should be aware that these figures represent composites of anomaly humidity values, where the anomaly is constructed by removing the mean annual cycle at each location. Thus, any resulting intraseasonal cycles in the composites are not forced to exist by virtue of time filtering. In fact, there is a strong eastward-propagating signature in both specific and relative humidity with a period of roughly 50 days, as observed by agreement of the −30/+20-day panels and −20/+30-day panels in each figure. Only the surface level is displayed in the case of relative humidity (Fig. 10), as the pattern of evolution for relative humidity was found to be nearly identical to that of specific humidity at all vertical levels other than the surface. While temperature variations that might drive differences between the two fields are expected to be small in the Tropics, the general agreement indicates that for the purposes of hydrological analysis, temperature variations are in phase with the moisture variations to a large degree.

Although the composite evolution is clearly dominated by wavenumber-1–2 structures, there is considerable smaller-scale variability as well, especially in comparison to composites of velocity potential and even OLR. Note that the scale for composite specific humidity anomalies at 300 mb (Fig. 9) is different than for the lower levels (Figs. 6–8). In each figure, composite data are shown for lags separated by two pentads, and running from lag = −30 to +30 days.
Based on the selection of 46 MJO events, only composite mean values that are statistically different from zero are displayed.

It should be emphasized that the composite amplitude of variations in a given field is smaller than the variations that can be associated with a given MJO event. Due to the pentad nature of the data, averaging of different phases together may occur, since the indexing of MJO event selection involves some uncertainty (e.g., some MJO events might have a period of roughly 40 days and others may have periods of roughly 60 days). Because of this uncertainty, as well as the fact that we cannot expect the spatial evolution of each event to be identical, there is statistical cancellation of some ex-
The surface level (both relative and specific) anomaly humidity composites show considerable asymmetry relative to the equator compared to upper levels. This asymmetry is most prominent in the vicinity of the Maritime Continent and also projects strongly in the energetic east Asian jet exit region (e.g., lag = 0 days; Fig. 6). Despite the fact that these composites are for the winter months only, the anomalous moisture variability...
over the life cycle in that area still weakly resembles a pattern that might be more expected during monsoon conditions, particularly from lag $-10$ to $+10$ days. The effect becomes less pronounced with height (cf. Figs. 7–9).

A significant symmetric off-equatorial response is prominently visible over the Indian Ocean during some phases (e.g., $+10$–$30$ days; Figs. 7–9). Similar features have been discussed based on OLR and wind in Salby and Hendon (1994), and were interpreted as the signatures of an equatorial Rossby wave response. It is in the eastern Indian region, in particular, where the areas of strongest off-equatorial composite moisture anomalies are found with the same sign and similar spatial scales. Isolated areas of lower humidity air are very noticeable there at all vertical levels from lag $+10$ to
lag +30 days, while corresponding areas with a symmetric high moisture anomaly response are only moderately noticeable at some vertical levels (e.g., 700 mb; Fig. 7) at lag −10 days. The meridional separation of these coherent areas of dry anomalies appears to decrease with height. At the surface and 700 mb (e.g., see Figs. 6 and 7; +20 days), they are located at approximately 15°N and 20°S. In contrast, at 300 mb (Fig. 9) they are centered at latitudes of roughly 5°–7° at the same lag. There is also a slight westward tilt with height of these anomalous regions. In addition, the preference for alignment of these coherent structures is for a major elliptical axis oriented southwest–northeast in the Northern Hemisphere and southeast–northwest in the Southern Hemisphere. The feature in the Southern Hemisphere shows a consistent zonal displacement,
which also varies with height, to the east of the Northern Hemisphere feature. For instance, at 500 mb, +20 days in Fig. 8, the NH feature is near 95°E and the SH feature is near 105°E.

Outside of the Indian Ocean, signs of a symmetric off-equatorial response in the composite anomaly moisture are less prevalent. One important exception is the roughly symmetric and simultaneous moistening of the ITCZ and SPCZ at lag = +20 days at 500 mb (Fig. 8), and a weak symmetric pattern at 850 mb (not shown) in the eastern Pacific.

At lag = 0 days there is a strong projection of the anomalous moisture variability onto the ITCZ at mid- and upper levels, but not at the surface, where the in-
fluence of the east Asian jet is instead more apparent. It is interesting that only positive anomalies are obvious in conjunction with the ITCZ region, with no corresponding negative anomaly projection in the opposite phases of the MJO cycle. There are, however, some less marked signs of negative moisture anomalies along the region of the SPCZ at 300 and 500 mb at lags \(-10\) and \(+30\) days (Figs. 8 and 9). The latitudes of this feature are roughly similar at 700, 500, and 300 mb. In contrast to the general agreement in patterns between specific and relative humidity anomalies, the surface relative humidity composite does depart in pattern from that shown in specific humidity along the SPCZ, with very little discernable signal in surface relative humidity (cf. Figs. 6 and 10). At lag \(-10\) days, the composite moisture anomalies along the ITCZ region more resemble a wavenumber-2 structure than at lag \(= 0\) days, when there is heightened moisture along the entire course of the Pacific basin near the equator. This apparent change in zonal scale is most noticeable at the upper levels (e.g., Figs. 8 and 9).

d. Equatorially averaged composite moisture analysis

The composite life cycle of equatorially averaged (10°N–10°S) specific humidity is shown in Fig. 11. The time axis runs from lag \(-35\) to \(+35\) days, and data from 300, 850 mb, and the surface are shown. Note that the scale for specific humidity at 300 mb is different from that for the lower levels. The trough-to-peak amplitudes of the 850-mb specific humidity variations are roughly 0.8 g kg\(^{-1}\) over much of the Indian Ocean and western Pacific. Surface specific humidity variations are somewhat weaker. Relative humidity (not shown) varies by as much as 7% over the course of the composite life cycle of the MJO at upper levels, and the amplitude is smaller at lower levels. The propagation of moisture at 700 mb (not shown) is substantially like that for the 850-mb level, while the 500-mb behavior (not shown) strongly resembles the 300-mb level.

One of the most striking features of this analysis is the prevalence of negative moisture anomalies over positive anomalies in the Western Hemisphere at many vertical levels. While it is not surprising that there is little MJO-related variation in humidity in the eastern Pacific compared to the Indian–western Pacific, it is not immediately intuitive why there should be such widespread dry anomalies over the course of the cycle for the selected strong events. In particular, the 300- and 500-mb levels, and, to a lesser extent, the surface show dry anomalies over the entire life cycle in the eastern Pacific.

![Fig. 11. Equatorially averaged (10°N–10°S) life cycle of composite specific humidity anomalies at selected vertical levels from 46 MJO events: (top) 300 mb, (middle) 850 mb, (bottom) surface. Units are g kg\(^{-1}\). Note different scale for (top). Contour intervals are 0.02 g kg\(^{-1}\) for (top) and 0.2 g kg\(^{-1}\) for (middle) and (bottom). Data for (top) and (bottom) are averaged from Figs. 9 and 6, respectively.](http://journals.ametsoc.org/doi/abs/10.1175/1520-0442(2003)016<0929:TDWVAC>2.0.CO;2?cookieSet=1)
The 850- and 700-mb levels show a strong bias toward dryness, but do contain some positive anomalies over those longitudes. One potential explanation for this pattern is that strong MJO activity has a rectification onto the mean water vapor state of the near-equatorial atmosphere. This would imply that positive low-frequency moisture anomalies occur during weaker MJO events and/or during times of low overall intraseasonal activity. This is consistent with the idea that if the MJO is more active and there is more vigorous convective activity in isolated, propagating regions, then there will be a larger spatial area of the Tropics that is controlled by compensating subsidence and drying. It could also be that the dry anomalies in the eastern Pacific result from having less consistent moistening from trade cumulus clouds.

Another potential explanation is that the composite procedure is biased because we did not remove interannual signals from the data. In particular, if this were true then we might suspect this to explain part of the composite signature observed in regions such as the eastern Pacific, where the interannual variability is large. A cursory examination of this issue was conducted by removing of MJO events from the composites that occurred in extreme El Niño/La Niña years to see if the rectification effect could be explained partly by the interannual signals remaining in the data. Although several permutations of event selections were tried, the rectification effect did not disappear or greatly lessen. If it is indeed true that MJO events are linked to the background moisture state of the Eastern Hemisphere, this would have implications for theoretical models linearized on mean wintertime moisture fields. Further investigation of this interesting avenue, including a more detailed scrutinization of the relationship to interannual variability, will be pursued in a separate study.

A clear indication of a moisture signal extends eastward well past the date line at the lower levels (≥850 mb). This differs markedly from the lack of a significant Western Hemisphere signal in OLR that has been shown in other studies. Additionally, over equatorial Africa there are still significant variations in moisture that appear to directly precede propagation of disturbances across the Indian Ocean. Again, these appear to be more strongly biased toward the drying phase. These moisture anomalies are present despite the fact that intraseasonal variations in rainfall over Africa (Fig. 5) are quite small. The 850-mb moisture propagation diagram appears to show a considerably faster phase speed in the Western Hemisphere than in the Eastern Hemisphere. There is also a much less pronounced change in phase speed east of the Maritime Continent at the upper levels (300 and 500 mb), which gives way to the aforementioned Western Hemispheric drying east of the date line.

There is also an area of apparent westward propagation near the date line at levels above the surface. However, this feature is not very robust, and the speed of westward movement and longitudes of this feature seem to differ when comparing the upper (e.g., 300 mb) and lower levels (e.g., 850 mb). A careful scrutiny of individual MJO events, as opposed to the composite cycle, also reveals that the initiation of westward propagation in the central Pacific does not occur in every MJO event. Given that these composites have been generated from a 10°N–10°S average designed to exclude as much of the off-equatorial intraseasonal variability as possible, it is not clear that these areas of apparent westward propagation could be contaminated with Rossby wave signatures. It is tempting to attribute this propagation to low-level advective moisture convergence ahead of the area of maximal MJO-related convection (as suggested in Maloney and Hartmann 1998), but the feature exists at all levels above the boundary layer and not at the surface. In addition, the surface relative humidity (not shown) exhibits this feature more prominently than surface specific humidity. The role of near-surface temperature changes that are not synchronously phased with moisture variations cannot be ruled out without further study.

e. Vertical profile of equatorially averaged moisture during the MJO life cycle

There is considerable vertical structure in the composite equatorial longitude–height cross section of specific humidity. Figure 12 shows the cross section of specific humidity, averaged between 10°N and 10°S, and composited based on the rainfall index. Plots for times lag of −15, 0, and +15 days are shown. The lowest vertical level corresponds to the surface and, hence, fluctuates in pressure from place to place. For convenience of plotting, this was taken as 1000 mb, although the actual pressures near the equator are usually slightly smaller. The masked white areas correspond to Africa and South America. Significant vertical tilt can be seen as the disturbances develop, particularly over the Indian Ocean and the extreme western Pacific. It should not be concluded from these observations alone that this evolution of the vertical structure represents tilting convective systems, since progressively penetrative moistening from below could also explain these structures. There is less apparent tilt once the MJO events pass the Maritime Continent. In the central Pacific, the anomalies become nearly uniform with height at the peak and trough of the moisture cycle. During the transitions from a dry central Pacific to a moist central Pacific, there is a period of low-level moistening that precedes the arrival of upper-level moistening. To the west, behind the area of the active disturbance, the transition from the moist phase to the dry phase first appears over Africa and then at lower levels of the western Indian (Fig. 12, middle). Three pentads later, the dryness is pervasive over virtually the whole Indian Ocean. During the passage of MJO events from the Indian Ocean to the date line, the 700- and 850-mb levels display the largest amplitude variations. Figure 11 also shows that the near-
equatorial surface specific humidity cycle has lower amplitude than at 850 mb. However, examination of the spatial evolution of the specific humidity over the whole Tropics shows that outside the area of 10°N–10°S, the surface humidity variations are actually as large or larger than those at 850 mb (not shown).

Another distinct feature of the MJO-related moisture variability is a rapid extension of a tongue of moisture to the eastern Pacific in the mature stages of the composite events. This appears to first grow as a surface trapped feature (Fig. 12, top) even as the main cluster of MJO-related humidity elevations is still located over...
the Indian Ocean. It is possible that this low-level moisture anomaly results from enhanced local surface evaporation. However, while a roughly 0.6 g kg\textsuperscript{-1} moistening for a layer from 1000 to 700 mb over 15 days only requires about +3.5 W m\textsuperscript{-2} of anomalous evaporative flux, the phase of the MJO cycle spanning the Fig. 12 (middle and bottom) corresponds to the suppressed phase for surface latent heat flux (e.g., see Jones et al. 1998). Thus, the observed low-level changes in water vapor content in the eastern Pacific are likely to be explained largely by advection. Also, given the large vertical gradient in the mean moisture across the boundary layer in the eastern Pacific, it is possible that small variations in local dynamics, as a result of the propagating MJO, can quickly make a large difference in the anomalous moisture there. Another alternative view of this phenomenon might be that the MJO begins to exhibit a less intense wavenumber-2 component upon reaching the mature phases of its development. For instance, it can be noted that the vertical scale of the simultaneous eastern Pacific and Indian Ocean fluctuations at lag \( = -15 \) days have quite different vertical scales. This is not unexpected, in that convection in the eastern Pacific is often shallow and more vertical modes than simply mode 1 appear to be important there. However, it is interesting that the baroclinic scale in the eastern Pacific appears to vary with phase.

**f. Timing between precipitation and moisture anomalies**

Figure 13 shows the phase relationship between moisture and precipitation at selected vertical levels (300 and 850 mb) and longitudes (90\textdegree E, 150\textdegree E, 90\textdegree W). A roughly 50-day cycle in both quantities is most common over the Indian and western Pacific. The precipitation cycles shown here come from data that, like the moisture data, has only had its annual cycle removed. The moisture data was averaged over 10\textsuperscript{8} squares centered at the equator for three regions chosen to be representative of the Indian Ocean (90\textdegree E), western Pacific (150\textdegree E), and the far eastern Pacific (90\textdegree W). One main feature of the phasing between precipitation and moisture is that the build up of surface level moisture leads precipitation by at least a pentad at longitudes corresponding to high MJO activity. This is similar to the result found in Kembell-Cook and Weare (2001) from radiosonde data. Near 90\textdegree E, there is a cascade of events starting with a peak in lower-tropospheric humidity (lag = \(-15\) days), followed by a peak in precipitation (lag = \(-10\) days), and later followed by a peak in the upper-level (300 mb) moisture. This is consistent with the propagation of convective disturbances that tilt with height, as viewed in Fig. 12. In the Indian Ocean, the moisture cycle at upper levels is not quite symmetric. During the dry phase of the MJO, the minimum in upper-level moisture occurs at the same time as the minimum in rainfall, whereas there is some evidence that upper-tropospheric moisture

lags rainfall during the moist phase. The relationship of low-level moisture leading precipitation is even more pronounced in the western Pacific (Fig. 13, middle). The upper-level moisture cycle is more symmetric at 150\textdegree E. There is still some indication that upper-level humidity may slightly lag rainfall there, but the composite moisture cycle in the western Pacific is generally vertically uniform in structure, and nearly in phase with rainfall.

In the eastern Pacific, the timing relationship is slightly more complicated (Fig. 13, bottom). As in Fig. 12, there is more vertical structure near 90\textdegree W than at locations farther west. The precipitation in the eastern Pacific has approximately a factor of 10 less variability than at the other two locations. The moisture variability there is also smaller, but not by a full order of magnitude. The surface humidity and precipitation show signs of a shorter period, and the low-level moisture anomalies
lead precipitation at 90°W by about 15 days, even longer than for the more convectively active regions farther west. Most strikingly, the upper- and lower-tropospheric moisture variations are roughly out of phase over most of the life cycle. Additionally, the surface (not shown) and 850-mb moisture appear to have very nearly the same timing during the dry phases of the cycle there, at a time when the moisture anomalies are largest over Africa/Indian Ocean. By the time the disturbances have reached the eastern Pacific, the surface and 850-mb moisture are no longer as tightly coupled.

g. Timing between precipitation and total cloud fraction anomalies

Examination of the lags between total cloud fraction and precipitation shows a number of interesting features (Fig. 14). The equatorially averaged (10°N–10°S) composite cloud fraction evolution has been obtained using the same methods as for TOVS moisture. The ISCCP data covers the years 1983–94 and contained 26 (of the original 46) MJO events as defined using the precipitation-based index. As with the moisture composites, the cloud composites have not been bandpassed and only the annual cycle has been removed. There is a strong eastward-propagating signature in total cloud fraction with a period of roughly 50 days. No change in phase speed with longitude is readily discernable at least as far as the date line, where the disturbances begin to show considerably less overall variability. The peak-to-trough amplitude of total cloud fraction over the MJO life cycle exceeds 30% cloudiness in the central Indian Ocean and is still as high as 15% near the date line. There appears to be an asymmetry of the 50-day cycle in the Indian Ocean, where the transition from the moist phase to the dry phase is much quicker than the transition from dry to moist. This asymmetry does not appear to exist in the western and central Pacific. Some weak signs of westward propagation are present in the cloud data, but not at the same longitudes as in the case of moisture. Near-equatorial total cloud fraction exhibits this feature between roughly 110° and 155°W.

Plotted along with the total cloud fraction cycle in Fig. 14 is the composite rainfall, also averaged over 10°N–10°S, which was composited using the EOF-based event indexing derived from the same data. Unlike the index itself, the composited rainfall data is unfiltered apart from removal of the annual cycle. The composite shown in this figure includes only the 26 events for which both rainfall and ISCCP data were available. The total cloud fraction peaks at nearly the same time as precipitation during the active phase in both the Indian and western Pacific. Examination of the timing between clouds, precipitation, and low-level moisture over the Indian Ocean (90°E) and western Pacific (150°E), shows that cloud fraction and precipitation lag near-surface humidity in a similar fashion (Fig. 14, bottom). The abscissas of the three curves have been scaled so that they can all be plotted on the same axis. In both the active and suppressed phase of the MJO at these locations, the moisture consistently leads the cloud fraction.

The most interesting feature of the relationship between cloud fraction and rainfall is that there is a longitudinal displacement between the peaks and troughs of rainfall and cloud fraction at the same phase of the
MJO. In the Indian Ocean, the centers of greatest variation and greatest cloudiness variation over the life cycle are separated by roughly 20°–25° of longitude. In the western Pacific, there is a 10°–15° displacement. There is higher cloudiness at the (western) trailing edges of actively precipitating MJO regions. This is despite having lower precipitation there compared to areas farther east. Conversely, at the (eastern) leading edges of the heavily precipitating regions, the overall cloud amounts do increase, but not as much as in areas farther west. This suggests that the precipitation efficiency and associated cloud processes are fundamentally different near the leading and trailing edges of the two most active regions of MJO activity. One hypothesis to explain this is that stratiform precipitation and cirrus clouds are considerably more prevalent at the western edges of these two areas. This could be consistent with large variations in cloudiness, but smaller variations in precipitation compared to areas with heavier convective precipitation. However, it cannot be ruled out that this separation of cloud and rainfall peaks is an artifact of the inadequacies in rainfall rate determination from satellites during these heavily clouded scenes. In any case, it is worth highlighting that this result indicates that cloud and rainfall activity are not one and the same in terms of their relation to the MJO.

**h. Equatorially averaged ISCCP cloud fraction by cloud-top height**

It is instructive to segregate the ISCCP data by cloud-top height in order to examine whether there is a change in cloud type over the course of propagation of the MJO. Figure 15 shows the time–longitude evolution of ISCCP cloud fraction anomalies by (infrared) cloud-top height bins. There do appear to be cloud-type changes that occur for propagating MJO disturbances after crossing the region of the Maritime Continent. In the Indian Ocean, the amplitude of the peak-to-trough variations in middle clouds and high clouds are roughly similar in amplitude, with the middle clouds displaying slightly greater variability. The intraseasonal variations in middle clouds in the western Pacific are nearly twice as large as the variations in high clouds there.

Overall, the high and middle clouds have very similar patterns of evolution. The largest variations in cloud fraction for all cloud types occur almost entirely west of the date line, as in OLR. The low cloud amounts do not vary as significantly or spatially coherently as the middle and high clouds. The data shown are for an equatorial average spanning 10°N–10°S. Varying the meridional averaging window in order to more properly exclude or include the role of low clouds in the ITCZ...
does not fundamentally change the lack of variance and spatial coherence of low clouds. Additional time filtering of the composites to force an intraseasonal cycle will decrease the noisiness of the evolution diagrams, but also fails to change any of the significant features. A robust feature of this diagram includes the asymmetry of the intraseasonal cycle transitions between dry/moist phases over the Indian Ocean that was noted in total cloud fraction. This behavior also exists for all the cloud types, and by comparison there is relative symmetry of the MJO cycle for high and middle clouds in the western Pacific. Similar to the equatorially averaged propagation diagrams for specific relative humidity, an overall dominance of negative anomalies is indicated in the Western Hemisphere for all cloud types. This is consistent with a lack of moisture availability. In fact, there is a prevalence of negative anomalies over positive anomalies even in the Eastern Hemisphere due to the asymmetry of the composite intraseasonal cycle. Whereas the dry anomalies were strongest at the upper levels in moisture, the Western Hemisphere negative anomalies in cloud cover are most obvious for the low clouds at top heights. However, the low cloud amount values are the most vulnerable to bias owing to inaccuracies in the cloud overlap calculation. Since the overall range of low cloud variations appears surprisingly small, this makes it likely that conclusions drawn from the low cloud data are least robust.

It should also be noted that while nonnegligible MJO-related variations in cloud and moisture are observed over Africa, no corresponding anomalies occur in precipitation. There are also some consistent middle cloud anomalies at roughly lags -20 and +25 days over South America. While these regions may not show significant MJO-related precipitation anomalies, it may be the case that observed anomalies of cloud or moisture associated with the MJO at those locations could still be useful in predictive models.

5. Summary and discussion

This study was intended to complement previous works on the life cycle of the MJO, which have characterized the details of the dry dynamics in conjunction with variations in OLR. We have presented results that show the patterns of variability associated with moisture over the course of the MJO life cycle with an emphasis on its vertical structure and relationship to cloudiness and rainfall. The composite MJO life cycle evolution of the TOVS moisture is different in many ways from the type of evolution seen in fields with less relevance to the hydrological cycle, such as wind and OLR. In particular, the use of water vapor data that is not heavily model influenced and yet contains vertical structure information provides a step forward, as a rich set of both spatial and vertical structures are present and consistent in the data.

Spatial maps of the standard deviation of rainfall and moisture in both the intraseasonal and interannual bands have been shown and compared. Despite the simplicity of such an analysis, the dominance of intraseasonal variations over interannual variations in wintertime has been demonstrated to hold for a large portion of the Tropics. The spatial extent of intraseasonal moisture variations differs somewhat from that for rainfall variations, which may not be surprising given the role that moisture advection is likely playing in the life cycle of the MJO. Where there are sharper climatological gradients in moisture, the variability of water vapor can be expected to be higher than would be produced if moisture variations were governed solely by moisture removal by precipitation and surface evaporation. This particular aspect will be examined in future research.

The distinct evolution of the MJO is easily identified in composites of relative and specific humidity from selected MJO events, even when that data has only had the annual cycle removed, and no bandpass filtering has been applied. A rich vertical and horizontal structure emerges with projection onto variability of the ITCZ, SPCZ, east Asian jet, and other known features of the mean wintertime tropical circulation. The Indian Ocean region, not unexpectedly, shows considerable signal over the course of the MJO cycle. However, the three-dimensional pattern of evolution of MJO-related moisture throughout the Tropics presented here is novel. Many specific features of that evolution structure will bear further investigation. For instance, different regimes of the MJO can readily be identified from the equatorial vertical cross section of the moisture composite life cycle. The MJO exhibits transitions between a vertically tilted structure in the Indian Ocean, a regime with nearly vertically uniform moisture signal in the western Pacific, and a phase with quasi-two-level behavior of water vapor in the eastern Pacific. In the latter case, the surface and 850-mb moisture are nearly out of phase with the upper-level tropospheric humidity. It can be hypothesized that these different hydrological regimes arise due to a number of factors, such as a longitudinally varying background state or vertical heating profile, leading to subsequently different spectra of anomalous clouds and cloud types. However, considerable work remains to confirm this link between hydrology and dynamics directly in the observations.

One of the more interesting findings of this research is the apparent large-scale drying of the near-equatorial (15°N–15°S) Tropics, particularly in the Western Hemisphere, in conjunction with strong MJO events. There is a dry bias in clouds and moisture over the course of the entire MJO cycle, and this bias extends even to the western Pacific, with more time spent under conditions of negative anomalies than positive anomalies for both quantities. This feature of the data analysis strongly suggests a low-frequency rectification of intraseasonal variability onto the mean, background moisture state of the Tropics. It seems likely that such a phenomenon has implications on the propagation of future MJO events.
following those that have been composited, and further study of this aspect of the variability found in the data is expected.

The timing of MJO-related moisture variability with changes in rainfall and clouds have also been presented. The precise sequencing of events between the hydrological fields provides empirical insight into the processes that govern MJO events in Northern Hemisphere winter. For instance, upper-level moistening appears to follow the passage of MJO events, but the relationship is not uniform with longitude. It appears from this work that the process by which the upper troposphere is periodically moistened during the MJO cycle is very dependent on location in the Tropics. Further work is necessary to understand the variability of upper-tropospheric moistening from one MJO event to the next, or, for instance, to understand how varying background conditions may affect the structure of the three-dimensional evolution of moisture during the MJO. However, the complex vertical structure of the moisture presented here suggests, at the very least, that the commonly used benchmarks (e.g., spectral power of 30–90-day variations in velocity potential, proper phase speed, etc.) for measuring model performance with respect to intraseasonal oscillations are unlikely to serve as a stringent test of whether or not a model properly characterizes the MJO. Also, the variability of clouds and rainfall with respect to moisture shows that the quantities are very strongly tied. The finding of negative low-level cloud fraction anomalies in the equatorial eastern Pacific during all phases of strong events cannot only serve as an additional diagnostic check for climate modelers, but also has implications concerning the mechanism by which the MJO impacts the boundary layer height and moisture so distinctly there. However, it should be noted that clouds and rainfall cannot be used as surrogates for one another. There is a well-defined longitudinal shift between the quantities, and there appear to be differences in cloud types between precipitating areas of developing events and regions of more mature MJO activity.

We feel that the current study adds a useful component to the characterization of the MJO as a moist convective disturbance. Even though the composite amplitude of relative humidity variations in conjunction with the MJO are found to be only on the order of ±5% (similar for both TOVS and the ECMWF reanalysis), the variations associated with any given event are on the order of ±15%, and can be larger still in isolated cases. Further research is warranted to examine the extent of event-to-event variability of the hydrological activity of the MJO. Moreover, it appears that even relatively small changes in moisture are often coincident with significant MJO-related convective and cloud variability, though which is the cause and which is the effect is not obvious. Given that there is currently great concern that state-of-the-art numerical models do not properly simulate water vapor variability, the proper documentation of MJO moisture variability, in conjunction with cloudiness and rainfall, should provide a launching point for further inquiry into model deficiencies. We hope this paves the way for advances in the mechanistic and theoretical understanding of the hydrological cycle of tropical intraseasonal oscillations.

Many questions are raised by the details of the analyses presented here. Below are listed a few of the potential avenues for future research:

1) *The rectification of the MJO onto the mean moisture state of atmosphere.* We have observed a consistent domination of negative cloud and moisture anomalies over positive anomalies for the entire Tropics, but especially in the near-equatorial (15°N–15°S) Western Hemisphere in conjunction with MJO events of strong activity. The processes that control this widespread drying should be investigated. Is it simply that the convectively active conditions of the MJO life cycle make up a smaller fraction of time and space within the life cycle than the suppressed conditions, or is there something else contributing to this rectification? The extent to which the passage of a strong MJO event may favorably or unfavorably precondition the background state for future events is unclear. As well, it would be interesting to know how much variability in this effect exist between years with strong and/or weak intraseasonal variations.

2) *Horizontal moisture budget on the intraseasonal timescale.* It has been suggested that the source of dry air that fills the off-equatorial Rossby gyres at upper levels is extratropical in nature. It would be instructive to know more clearly the times and locations of moisture transport in and out of the Tropics over the MJO life cycle, and to understand the importance of this transport on the MJO’s dynamics itself. As well, there are signs of apparent intraseasonal westward propagation in moisture near the date line at times. By examining the relationship between observed precipitation and vertically integrated moisture convergence computed from TOVS and reanalysis wind product, it should be possible to better understand some of these features. It should be noted that the vertical resolution of moisture afforded by the TOVS data will greatly improve the general picture of transports derived previously using column-integrated water vapor. Specifically, this should facilitate the following:

- better understanding of the phase relationship between rainfall and clouds;
- examination of the complex relationship between moisture and rainfall at low levels in the eastern Pacific;
- determining whether the Rossby gyres themselves play a role in maintaining the tilt of the MJO systems. How does this vary from event to event?
3) **Synergy with the ITCZ.** It has been noted that the MJO provides an important occasional source of tropical moisture to extratropical North American coastal regions in Northern Hemisphere winter. Extreme precipitation events have been implicated as a result of MJO activity in the central Pacific (Higgins and Shi 2001), bringing moisture along the route of the ITCZ and even farther northward. How much variability exists between events in the extratropical reach of MJO-related hydrological anomalies?

In addition to serving as a starting place for investigation of the topics listed above, we expect this assessment to be valuable for diagnostic evaluation of model performance with respect to the MJO.

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