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ANALYSIS OF MOISTURE VARIABILITY ASSOCIATED WITH THE MADDEN JULIAN OSCILLATION DURING NORTHERN HEMISPHERE WINTER

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1. INTRODUCTION

There is growing interest in characterization of tropical hydrological variability on all timescales, and the Madden-Julian Oscillation (MJO) is the dominant form of intraseasonal variability at low latitudes. MJO disturbances comprise a frequent set of events bridging the realm of weather and climate, and provide a mechanism for studying tropical variability using satellite retrieved moisture data. The focal data of this study are five-day averaged (1979-1999) TOVS moisture soundings from NASA Pathfinder data, providing global coverage at specific pressure levels. Composites based on an index formed from the first extended EOF of bandpassed Xie-Arkin (CMAP) precipitation have been formed for the TOVS moisture data and ISCCP cloud fraction. Analysis of the three-dimensional structure and evolution of rainfall, water vapor, and clouds over the MJO life cycle shows rich relationships between the variables.

Near-surface level water vapor leads precipitation by one pentad over the Indian Ocean and Western Pacific while upper level water vapor lags the peak in precipitation. The composite evolution of the MJO as tracked by specific humidity shows markedly different vertical structures as a function of longitude. There is a clear westward tilt with height of the moisture maximum associated with eastward propagating MJO disturbances, which disintegrates into a nearly vertical positive anomaly as it reaches the Western Pacific, and then becomes trapped to the lowest level in the Eastern Pacific. ISCCP cloud fraction is highly correlated with humidity, and also leads observed precipitation. However, the maxima in rainfall do not occur at the same longitude as the maxima in cloud amount, and there appears to be a shift in the dominant cloud type as the MJO systems propagate eastward.

Another important feature is a rectification of the MJO cycle onto the mean state of the atmosphere, with coherent non-zero average rainfall and moisture patterns occurring over the life cycle of strong events. Over the course of a whole winter season that contains above average MJO activity, there are also significant moistening and drying trends. While this latter effect has been checked for possible contamination from a few large ENSO events, such an artifact still needs to be more systematically ruled out.

We also examine the surface heat flux (from Jones et al. 1999, and also at this meeting in the artificial intelligence session) and moisture transport (calculated using TOVS and ECMWF winds) along with the above rainfall and three-dimensional moisture evolution in order to get an integrated view of the MJO's hydrological cycle. While there is a high correlation of these fluxes with the rainfall and water vapor, the interrelationship of all the hydrological quantities shows considerable spatial variability.

Given that even models with significant intraseasonal variability often fail to display many features listed above, this assessment will serve as a powerful yardstick for evaluating model performance with respect to the MJO. This work should provide some guidance for model development of intraseasonal simulation of the tropics.

2. DATA

The data analyzed include moisture (TOVS), clouds (ISCCP D1), and precipitation (CMAP). The

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TOVS Pathfinder-A dataset (Dec 1978–Dec 1999), provides global measurements of satellite water vapor observations (Susskind et al. 1997). The available information has been processed to 5-day means at a spatial resolution of 1˚x1˚. 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 300mb, 500mb, 700mb, 850mb and surface levels. Compositing of clouds and water vapor over the course of the MJO life cycle is conducted an index constructed from the precipitation record (see section 3).

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. TOVS was chosen for this study specifically for its ability to show more vertical structure and because SSM/I 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. 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 ECMWF reanalysis moisture. For instance, the standard deviations of TOVS intraseasonal (35-95 day) specific humidity anomalies are only about 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 at 700 mb over much of the Indian and Western Pacific (similar to what is found in Brown and Zhang 1997 from TOGA-COARE buoys). Also, the disparity of intraseasonal variability between TOVS and ECMWF decreases with height, and there are very clear propagating signals at all vertical levels in both products.

We also performed our own comparison using TOGA COARE intensive flux array (IFA) data from the 120 day period spanning November 1992-February 1993. The IFA data represents the moisture from an array of radiosondes that were combined to form an area-averaged data set, and has been averaged to five-day means from daily values at 29 vertical levels from 1000 mb to 300 mb. The TOVS data were averaged over a colocated 2˚x2˚ 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). While the TOVS data may underestimate the actual moisture variability, the underlying intraseasonal cycle is apparent when both data sources are plotted.

Table 1: The mean values of specific humidity at particular vertical levels over the intensive flux array (IFA) region during November 1992-February 1993, from TOVS and COARE data. Values in g kg^{-1}.

Vertical level	COARE-IFA	TOVS
Near-surface	18.1 (1000 mb)	17.7 (sfc)
850 mb	11.9	12.0
700 mb	7.33	6.96
500 mb	3.42	2.67
300 mb	0.62	0.48

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.

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). 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. 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

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. 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 variaiblity (e.g., the Eastern Pacific). We cannot rule out the possibility of contamination of those results from interannual variations without further investigation.

4. RESULTS

4.1 *Life Cycle Evolution of Composite MJO Humidity Variations*

Maps showing the spatial evolution were examined. It should be noted that while the precipitation index was initially time-filtered, the moisture data has not been bandpassed prior to compositing. 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. Although the composite evolution is 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.

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. 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 during certain phases.

A significant symmetric off-equatorial response is prominently visible over the Indian Ocean during some phases. 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 during much of the life cycle, while corresponding areas with a symmetric high moisture anomaly response are only moderately noticeable at some vertical levels and for shorter times during the life cycle.

There is a strong projection of the anomalous moisture variability onto the ITCZ at mid and upper levels, but not at the surface. It is interesting that only positive anomalies are obvious in conjunction with the ITCZ region. There are some less marked signs of negative moisture anomalies along the region of the South Pacific Convergence Zone (SPCZ) at 300 and 500 mb at some phases.

4.2 *Equatorially Averaged Composite Moisture Analysis*

The composite life cycle of equatorially averaged (10˚N-10˚S) specific humidity shows a 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 mb, 500 mb, and, to a lesser extent, the surface show dry anomalies over the entire life cycle in the Eastern Pacific. The 850 mb 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 event 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 Nino/La Nina 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.

Other well-defined features of the equatorially averaged composites of specific humidity are:

- 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 significant Western Hemisphere signal in OLR that has been shown in other studies.
- 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 mb 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. 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.

4.3 Vertical Profile of Equatorially Averaged Moisture During MJO Life Cycle

There is considerable vertical structure in the composite equatorial longitude-height cross-section of specific humidity. Figure 1 shows the cross-section of specific humidity, averaged between 10N-10S, and composited based on the rainfall index. Plots for time lag -15 days, 0 days, and +15 days are shown. 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 (Figure 1, middle panel). 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 mb and 850 mb levels display the largest amplitude variations.

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 (Figure 1, upper panel) 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 moistening for a layer from 1000 mb to 700 mb over 15 days only requires about +3.5 W/m^2 of anomalous evaporative flux, the phase of the MJO cycle spanning the middle and lower panels of Figure 12 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.

4.4 *Timing Between Precipitation and Moisture Anomalies*

One main feature of the phasing between precipitation and moisture is that the buildup of surface level moisture leads precipitation by at least a pentad at longitudes corresponding to high MJO activity. Near 90˚E, there is a cascade of events starting with a peak in lower tropospheric humidity, followed by a peak in precipitation a pentad 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. 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.

In the Eastern Pacific, the timing relationship is slightly more complicated. There is more vertical structure near 90˚W than at locations further 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 further west. Most strikingly, the upper and lower tropospheric moisture variations are roughly out of phase over most of the life cycle. Additionally, the surface 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.

4.5 *Timing Between Precipitation and Total Cloud Fraction Anomalies*

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 by 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˚W and 155˚W.

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 and Western Pacific shows that cloud fraction and precipitation lag near-surface humidity in a similar fashion. 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 degrees of longitude. In the Western Pacific, there is a 10-15 degree 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 further 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 further 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.

4.6 *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. 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. A robust feature resulting from this analysis is 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. An overall dominance of negative anomalies is indicated in the Western Hemisphere for all cloud types. 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 cloud top heights. However, the low cloud amount values are the most vulnerable to bias owing to inaccuracies in the cloud overlap calculation.

5. DISCUSSION

This study was intended to complement previous work 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.

The primary results of our characterization of water vapor variability associated with the Nov-Apr MJO can be summarized as follows:

• Spatial maps of the standard deviation of rainfall and moisture in both the intraseasonal and interannual bands show a dominance of intraseasonal variations over interannual variations in wintertime for a large portion of the tropics.

• 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. The three-dimensional pattern of evolution of MJO-related moisture throughout the tropics presented here is rich in structure. 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.

• 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 intreaseasonal 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 examined. 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 can not 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.

Many questions are raised by the details of this characterization. Below are listed two specific follow-on avenues of research being currently pursued in preparation for the AMS meeting:

• *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 (15N-15S) Western Hemisphere in conjunction with MJO events of strong activity. The processes, which 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.

• *Horizontal moisture budget on the intraseasonal time scale.*

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 ECMWF reanalysis wind product, it is possible to better understand some of these features. This is current being undertaken. Coupled with composites of surface evaporative heat flux, this should facilitate: (1) better understanding of the moisture budget over the life cycle of the MJO; (2) a better examination of the complex relationship between moisture and rainfall at low levels in the Eastern Pacific; (3) determination of whether the Rossby gyres themselves play a role in maintaining the tilt of the MJO systems.

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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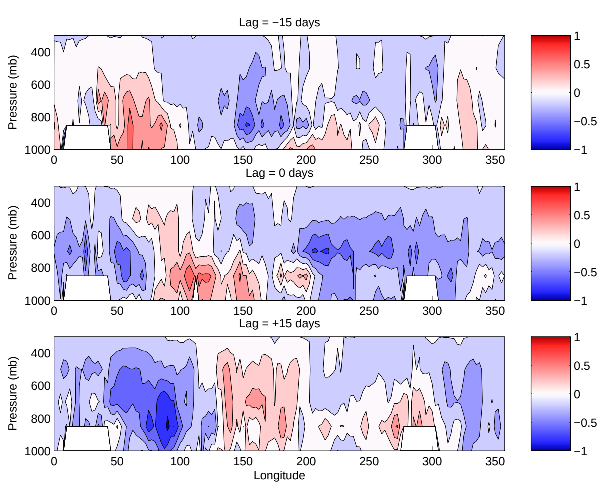

Figure 1: Vertical structure of TOVS specific humidity during evolution of MJO life cycle at three different lags. Each time-longitude cross-section is a composite of 46 MJO events. Units are g kg^{-1}. Contour interval is 0.2 g kg^{-1}. African and South American landmasses are masked out. Upper panel: -15 days lag. Middle panel: 0 days lag. Lower panel: +15 days lag.