Structural evolution of the Madden-Julian Oscillation from COSMIC radio occultation data

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[1] The atmospheric temperature and specific humidity profiles derived from 4 years of Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) radio occultation (RO) measurements during the boreal winter (November thru April in 2006–2010) were employed to study the large-scale vertical structure of the Madden-Julian Oscillation (MJO). In a composited MJO cycle, both RO temperature and moisture anomalies propagate eastward along with the enhanced MJO convection over the Indo-Pacific region. In the same region, the RO temperature anomaly is positively correlated with the convection (Tropical Rainfall Measuring Mission (TRMM) rainfall) anomaly in the middle and upper troposphere (800 hPa–200 hPa) and negatively correlated in the lower troposphere and at the tropopause. A positive RO moisture anomaly has a westward tilt below 300 hPa and is well associated with the convection anomaly. RO bending angle and refractivity anomalies show vertical structure similar to that of temperature MJO anomaly above ~300 hPa and to that of the moisture anomaly below that. These salient MJO features agree well with those revealed by global reanalysis data and meteorological satellite observations, such as the Atmospheric Infrared Sounder (AIRS), even though RO anomalies exhibit sharper structure at the tropopause region due to the higher vertical resolution of the RO. Investigation of the cold-point tropopause anomaly indicates that the enhanced convection is preceded by cooling of the tropopause and followed by lowering of the tropopause height. The MJO moisture structures during two boreal winters, November 2007–April 2008 (La Niña) and November 2009–April 2010 (El Niño), are individually presented to demonstrate the El Niño-Southern Oscillation (ENSO) effect on the MJO structure.


1. Introduction

[2] The Madden-Julian oscillation (MJO) is a dominant atmospheric oscillation pattern in the tropics with a period between 30 and 90 days. Known as a large-scale coupled patterns in atmospheric circulation and deep convection, with slowly eastward moving center of deep convection and precipitation mainly occurring in the Indian and Western Pacific oceans, the MJO has a significant influence on atmospheric circulations of various spatial and temporal scales (see Lau and Waliser [2005] and Zhang [2005] for a review). Despite decades of research since its original discovery [Madden and Julian, 1971], the mechanisms of formation of the MJO are still under debates. An accurate representation of the MJO feature in general circulation models (GCMs) remains a major challenge for modelers. The MJO has been considered one of the most significant challenges in tropical atmospheric dynamics [Raymond, 2001], and is still hindering our understanding of tropical physics and dynamics.

[3] One of the biggest obstacles for MJO studies is the lack of accurate observations capturing the structure and evolution of the MJO, especially in cloudy tropical regions. A number of studies have investigated the structural evolution of the MJO using radiosonde data, global reanalysis products, and satellite observations, including the temperature and moisture profiles obtained from the Atmospheric Infrared Sounders (AIRS) aboard the Earth Observation System (EOS) Aqua satellite [Lin and Johnson, 1996; Sperber, 2003; Myers and Waliser, 2003; Kiladis et al., 2005; Tian et al., 2006, 2010; Virts and Wallace, 2010; Riley et al., 2011]. Although these studies revealed some important features of the MJO, their results are subject to large uncertainties due to limited information. For example, radiosonde observations are sparse over the oceans (usually only available over tropical islands and along coast lines). The reanalysis outputs over tropical
oceans are mainly model-driven and may contain large errors in the parameterization of the cloud-radiation interaction, deep convection, and boundary layer processes [Dee et al., 2011]. For meteorological satellite data, the vertical resolution based on the radiance measurements is low (~2 km) due to the broad weighting functions (i.e., AIRS), particularly in the lower troposphere where it is most crucial for the MJO study [Lau and Wu, 2010]. Furthermore, the vertical structure of the MJO demonstrated by AIRS might be affected by its reduced sampling in thick cloud regions, which occurs commonly during MJO strong deep convection and precipitation phases [Susskind et al., 2003]. High vertical resolution observations that can sense the thermodynamic structure of the MJO below opaque clouds will tremendously improve our understanding of the MJO.

[4] In this study, we use GPS (Global Positioning System) radio occultation (RO) data to quantify the structural evolution of the MJO. The GPS RO technique scans the Earth’s atmosphere in a limb mode. With a GPS receiver onboard the LEO (Low-Earth Orbiting) satellite, this technique is able to detect the bending of RO signals emitted by GPS satellites and traversing the atmosphere. With the information about the relative motion of the GPS and LEO satellites, the bending angle profile of the radio waves can be used to derive refractivity, pressure, temperature, and water vapor profiles in the neutral atmosphere. Previous studies have proven that the RO data have high vertical resolution (0.1 km near surface to 1 km at tropopause), high temperature accuracy (<1 K), reasonable good moisture accuracy (~0.5 g/kg when comparing to ECMWF water vapor profiles) [see Ho et al., 2010a], and are all-weather observations (nearly unaffected by aerosols, clouds, or precipitation) [Ho et al., 2009, 2010a; Anthes, 2011]. The horizontal resolution of RO data is approximately 300 km [Kursinski et al., 1997], which is typical for limb sounding. Tian et al. [2012] used the GPS RO temperature data in the upper troposphere and lower stratosphere (UTLS) to examine the fine spatiotemporal patterns and vertical structure of the global intraseasonal temperature variability related to the MJO. In this study, we use RO retrievals from the surface to the 40 km, including atmospheric temperature, moisture, bending angle and refractivity profiles, from the COSMIC (Constellation Observation System for the Meteorology, Ionosphere, and Climate) mission to detect the structural evolution of the MJO during the boreal winter from 2006 to 2010. Launched in April 2006, the COSMIC mission has provided up to 2,500 RO profiles daily, which is of the MJO [Ho et al., 2009]. With the open-loop signal tracking technique, COSMIC allows accurate retrieval of the bending angle, refractivity in the lower troposphere, and can resolve structures associated with the atmospheric boundary layer [Sokolovskiy et al., 2006]. It has been demonstrated that COSMIC-derived total column water vapor (TCWV) values are highly consistent with those from ground-based GPS observations (i.e., International Global Navigation Satellite Systems (GNSS) Service (IGS)) [Wang et al., 2007] with the mean global difference between IGS and COSMIC TCWV about 0.2 mm and standard deviation of 2.7 mm [Ho et al., 2010b]. Studies have shown that COSMIC-derived water vapor products were very useful to identify the transition of La Niña conditions in 2008 to moderate El Niño conditions by the end of 2009 [Mears et al., 2010].

[5] Section 2 describes the data and analysis method for detecting the evolution of the MJO. The vertical MJO structure in terms of RO-derived temperature, specific humidity, bending angle, and refractivity are presented in Sections 3.1 and 3.2. The MJO-induced anomaly of the tropical tropopause detected by COSMIC RO is summarized in section 3.3. The boreal winter of 2007 (November 2007–April 2008) is a La Niña year, and 2009 (November 2009–April 2010) is a typical El Niño year. To investigate possible El Niño–Southern Oscillation (ENSO) effects on the MJO structure, the vertical structures of the MJO signals for different ENSO phases are compared in section 3.4. Section 4 concludes the study.

2. Data and Methodology

[6] In this study we use COSMIC data processed by the COSMIC Data Analysis and Archive Center (CDAAC). Processing of the GPS RO signals includes several steps: retrieval of bending angle (BA), refractivity (N), pressure (P), temperature (T) and water vapor (partial pressure of water vapor, q). Retrieval of BA does not use any a priori information [Kursinski et al., 1997]. Retrieval of N is not affected by a priori information in the troposphere and lower stratosphere [Kursinski et al., 1997]. However, next step, derivation of P, T, q from N where N = 77.6P/T + 3.73 × 10^6 e/T^2 [Bean and Dutton, 1968] is an under-determined problem in the moist troposphere and thus requires a priori information. This step uses one-dimensional variational data assimilation approach (1D-var) where N is the observable, and atmospheric model state (P, T, q) is the a priori [Healy and Eyre, 2000; von Engeln and Nedoluha, 2005]. In this study, 1D-var real-time processed data from CDAAC are used where the temperature and moisture analyses from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model interpolated to the COSMIC sounding times and locations are used as the first guess in the 1D-var algorithm (http://cdaac-www.cosmic.ucar.edu/cdaac/doc/documents/1dvar.pdf). In 1D-var, the adjustment of the atmospheric state depends on the observation and a priori errors (which can be projected in the observational space for comparison). The larger the a priori error of a state variable is, the more that variable is adjusted by the observation. In the lower troposphere, assimilation of the GPS RO observation adjusts water vapor to a larger extent and temperature to a much lesser extent. This is opposite in the upper troposphere and stratosphere, where due to small amount and thus errors of water vapor, the GPS RO observation basically adjusts temperature. Ho et al. [2007] has shown that because RO refractivity is more sensitive to water vapor variation in the lower troposphere than to the temperature, the information from COSMIC refractivity is mainly used to derive water vapor. The COSMIC water vapor retrieval errors are mainly from the uncertainty of temperature a priori where 1 K of temperature error results in less than 0.25 g/kg of water vapor error in the troposphere. Ho et al. [2010a] compared the global water vapor profiles between ECMWF analyses and COSMIC RO observations during a period between July to November 2006 that COSMIC data were not included in the ECMWF analysis. Results show that COSMIC and ECMWF water vapor profiles agree within 0.05 g/kg above 2 km and 0.2 g/kg below 2 km. This supports
the importance and usefulness of COSMIC RO observations in depicting global water vapor variations.

[7] COSMIC bending angle, refractivity, temperature, and humidity profiles over the tropics in boreal winters from November to April during 2006–2010 are used to examine the structure of the MJO during this period. About 500 COSMIC RO vertical profiles are available in the tropics (30°S–30°N) per day. All RO profiles are interpolated to 70 pressure levels (with pressure steps of 20 hPa between 1000 hPa and 300 hPa, 10 hPa between 300 hPa and 30 hPa, 5 hPa between 30 hPa, and 10 hPa, and 7, 5, 3 hPa specifically) before a further processing.

[8] The Tropical Rainfall Measuring Mission (TRMM) 3B42 rainfall product [Huffman et al., 2007] for the same period is used as a proxy for convective intensity. TRMM data have a 3-h temporal resolution and a 0.25° × 0.25° spatial resolution. Its spatial coverage extends from 50 degrees south to 50 degrees north latitude.

[9] To diagnose the MJO signals, we use an approach similar to that described in Tian et al. [2010]. All RO data are first averaged in the three-dimensional 1-day × 20°-longitude × 5°-latitude bins. The intraseasonal anomalies of the binned data are then generated by removing the climatological seasonal cycle and filtering by a 30- to 90-day bandpass filter. To illustrate the usefulness of the RO-derived parameters for identifying the MJO signals, we present the Hovmöller diagram of the unfiltered RO-specific humidity anomalies at 500 hPa averaged over 10°S–10°N (shading) for a one-year period in Figure 1. Eastward propagating systems are revealed mainly over the western Indo-Pacific region (60°–180°E) most of the time. The dominant period of the oscillation is about 40 days, which is typical for the MJO. Westward propagating systems are more common over the East Pacific, Atlantic, and African regions. To highlight the intraseasonal anomalies, we denote the filtered moisture anomalies and filtered TRMM rainfall anomalies by red and black contours respectively in Figure 1. Large anomaly values (>0.6 g/kg for specific humidity and >3 mm/day for rainfall) are observed in the western Indo-Pacific with clear eastward propagation most of the time. The propagation speed is about 5 m/s. Also prominent in these regions are the positive correlation between filtered moisture anomalies at 500 hPa and enhanced deep convection indicated by positive rainfall anomalies.

[10] To ascertain the structure of thermodynamic fields associated with the MJO, a compositing technique is used here based on the daily Wheeler-Hendon MJO index (WH index). The WH index is calculated from the first two principal components of empirical orthogonal functions (EOFs) of near-equatorially averaged outgoing long-wave radiation (OLR) and zonal wind fields at 200 hPa and 850 hPa [Wheeler and Hendon, 2004]. By use of the WH index, the MJO is decomposed conventionally into eight phases describing the coherent large-scale eastward propagation of MJO convection from the western Indian Ocean to the central Pacific. In this study, only strong MJO events with the WH index amplitude larger than 1 are considered. A composite MJO cycle is then calculated by averaging the intraseasonal anomalies for each phase of the MJO.

3. Results
3.1. Vertical Structure of the MJO Signals in Temperature and Humidity

[11] Figure 2 presents the composite MJO temperature and specific humidity anomalies averaged over 10°S–10°N along with the TRMM rainfall anomaly (overlaid black lines) for a full MJO cycle. All anomalies clearly show eastward propagation from the Indian Ocean to the central Pacific. The warm temperature anomaly with peak amplitude of ~0.6 K in the middle and upper troposphere (800 hPa–200 hPa) over the Indian and western Pacific oceans (50°E–170°W) is collocated with the maximum rainfall anomaly. This warm temperature anomaly is accompanied by cold anomalies near the tropical tropopause layer (~150 hPa–70 hPa) and by less pronounced anomalies below 800 hPa. The temperature anomaly near the tropopause exhibits an eastward-tilted structure, which is consistent with the forced upward propagating gravity wave response to the eastward-moving convective heating source below [Kiladis et al., 2005]. In the Western Hemisphere, though the MJO convection is weak, the amplitude of temperature anomalies is comparable to that in the Eastern Hemisphere.

[12] As for the MJO moisture structure in the Indian and western Pacific oceans, positive moisture anomalies propagate
eastward along with the strong rainfall anomalies, with peaks of ~0.6 g/kg over the middle and lower troposphere. The vertical structure of the moisture anomalies tilts westward, which is similar to previous studies [Sperber, 2003; Myers and Waliser, 2003; Kiladis et al., 2005; Tian et al., 2006, 2010]. As a result, the low-level moistening precedes the MJO convection, and is followed by rapid moistening of the entire troposphere and then by low-level drying of the boundary layer. This westward tilt of MJO moisture anomalies is associated with the westward tilt in the diabatic heating field, which, in turn, is the result of superposition of stratiform precipitation lagging deep convective heating [Kiladis et al., 2005] and the westward tilt in the radiative heating [Jiang et al., 2011]. Significant moisture anomalies found over the eastern Pacific region, accompanied by weak MJO convection, are located mainly below 500 hPa and have an eastward tilt, especially for MJO phase 1 and 2.

These vertical moist thermodynamic structures of the MJO revealed from RO data are generally similar to those from the AIRS observations and ERA-interim [see Tian et al., 2010, Figures 3 and 4]. One noticeable difference between results of RO and AIRS is found in MJO temperature anomalies near the tropopause where RO data show sharper thermal structures. This difference can be explained by the higher vertical resolution of RO data. Another difference between them is the low-level (below ~800 hPa) temperature precondition of the MJO, which is well presented in the AIRS data, becomes much weak in the RO temperature anomalies. Possible reason for this is the information of the RO temperature retrievals in the lower troposphere is mainly from the a priori NCEP GFS (as mentioned in Section 2), which has difficulty to adequately reproduce the real atmospheric variability.

3.2. Vertical Structure of the MJO Signals in Bending Angle and Refractivity

To avoid the influence of a priori information, we further examine the MJO structure using RO bending angle and refractivity. Figure 3 gives the vertical structure of

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**Figure 2.** Vertical structures of (a) RO temperature and (b) specific humidity MJO anomalies (shading) averaged over 10°S–10°N for a composite cycle (8 phases). The overlaid solid black lines are TRMM MJO rainfall anomalies (scale at right) for the same period of COSMIC RO data.
composed fractional bending angle and fractional refractivity anomalies associated with the MJO. Around the region of positive rainfall anomalies, positive fractional bending angle and refractivity anomalies are between 700 hPa and 300 hPa and negative fractional anomalies are near the surface. Above 300 hPa (~9 km), the eastward-tilted anomalies with alternating signs extend into the lower stratosphere (as expected, these alternating anomalies are out of phase with the temperature anomalies (Figure 2)). Compared to the fractional refractivity anomalies, fractional bending angle anomalies reveal finer structures with a larger magnitude, which can be explained by the integral Abel transform used to retrieve refractivity from bending angle [Kursinski et al., 1997]. The salient MJO features seen in Figure 2, such as the westward-tilted structure over the Indian Ocean and the western Pacific regions propagating eastward along with the enhanced convection, and the significant stationary anomalies over the eastern Pacific region, are also prominent in both bending angle and refractivity. The eastward tilt of the anomalies can be observed in the Western Hemisphere, though less pronounced than the westward tilt in the Eastern Hemisphere. [15] In general, MJO vertical structures detected by fractional bending angle and refractivity agree well with those detected by RO temperature structure in the upper troposphere and stratosphere (above ~ 300 hPa) and are more similar to the moisture structure below that level. This is to be expected (as discussed in section 2) and provides additional evidence that the MJO structures derived from RO temperature and moisture depend to a larger extent on RO observations and to a lesser extent on the a priori used in the 1D-var algorithm. However, the slight difference of MJO structure near the surface between moisture and fractional refractivity might be associated with the effect of a priori information.

Figure 3. Similar to Figure 2, except for the vertical structures of (a) equatorial-mean RO fractional bending angle and (b) fractional refractivity MJO anomalies (shading).
The tropical tropopause is the interface between two very different dynamical regimes: troposphere and stratosphere. It acts as a “gate to the stratosphere” for atmospheric trace gases, including water vapor and short-lived constituents [Fueglistaler et al., 2009]. Several previous studies examined the relationship of the intraseasonal variation of the tropical tropopause with tropical convection using global reanalysis data [Zhou and Holton, 2002; Ryu et al., 2008], and showed that the enhanced convection cools the cold-point tropopause (CPT) [Zhou and Holton, 2002] and raises the lapse-rate tropopause [Ryu et al., 2008]. These studies further suggested that the tropopause variability is associated with Kelvin waves excited by convective heating. Most recent study further confirmed the intraseasonal variability of the CPT properties is primarily controlled by Kelvin waves, with a non-negligible contribution by MJO convection using high-vertical-resolution COSMIC RO data [Kim and Son, 2012, hereinafter KM12]. Different from the monthly standard deviation and frequency wave number decomposition method used in KM12, we use the WH index method to re-examine the variation of the tropical tropopause temperature and height associated with the MJO from RO data, and also focus on the CPT in this study because of its relevance to the dehydration of air entering the stratosphere. The CPT properties are first detected from each RO temperature profile, and then binned into 3-dimensional grid as mentioned in

Figure 4. Spatial structures of the CPT (a) temperature and (b) height MJO anomalies for the entire MJO cycle (8 phases). The superimposed solid and dashed lines denote the TRMM rainfall anomalies of 1.5 mm/day and –1.5 mm/day separately.

### 3.3. Evolution of the MJO Signals at the Tropical Tropopause

The tropical tropopause is the interface between two very different dynamical regimes: troposphere and stratosphere. It acts as a “gate to the stratosphere” for atmospheric trace gases, including water vapor and short-lived constituents [Fueglistaler et al., 2009]. Several previous studies examined the relationship of the intraseasonal variation of the tropical tropopause with tropical convection using global reanalysis data [Zhou and Holton, 2002; Ryu et al., 2008], and showed that the enhanced convection cools the cold-point tropopause (CPT) [Zhou and Holton, 2002] and raises the lapse-rate tropopause [Ryu et al., 2008]. These studies further suggested that the tropopause variability is associated with Kelvin waves excited by convective heating. Most recent study further confirmed the intraseasonal variability of the CPT properties is primarily controlled by Kelvin waves, with a non-negligible contribution by MJO convection using high-vertical-resolution COSMIC RO data [Kim and Son, 2012, hereinafter KM12]. Different from the monthly standard deviation and frequency wave number decomposition method used in KM12, we use the WH index method to re-examine the variation of the tropical tropopause temperature and height associated with the MJO from RO data, and also focus on the CPT in this study because of its relevance to the dehydration of air entering the stratosphere. The CPT properties are first detected from each RO temperature profile, and then binned into 3-dimensional grid as mentioned in
section 2. The CPT anomalies associated with the MJO are calculated by removing the seasonal cycle, filtering through a 30–90 day filter and compositing based on the MJO phases identified by the WH index.

[17] Figure 4 presents the horizontal structure of the CPT temperature and height anomalies associated with the MJO. The superimposed contour lines denote the TRMM rainfall anomaly of 0.1 mm/day. Generally the negative (positive) anomalies of CPT height and temperature move eastward slowly with the enhanced (suppressed) convection over the Indian Ocean and western Pacific regions for MJO phases 2–6. The associated variation of the CPT height and temperature anomalies can reach 200 m and 1.2 K near the equator respectively. The poleward extension of negative CPT temperature anomalies to the west of the convective center reflects the equatorial Rossby wave response to the enhanced convection, while the equatorially confined negative anomalies to the east of MJO convection reflect the response of the vertically propagating equatorial Kelvin waves to the enhanced convection in the western Pacific [Gill, 1980]. This spatial structure of the CPT anomalies and its association with the MJO convection cannot be easily captured if using monthly standard deviation to define the intraseasonal variability of the CPT (see Figures 10 and 11 of KM12).

[18] The evolution of the equatorially averaged (10°S–10°N) tropical CPT temperature and height anomalies with the MJO phase is shown in Figure 5. It can be seen that the enhanced (suppressed) convection tends to locally cool (warm) the tropopause over the Indian and western Pacific oceans significantly, which is consistent with Figure 4. These large CPT temperature perturbations are associated with the Kelvin wave propagating upward [Ryu et al., 2008]. It is also worth noting that negative CPT temperature anomalies precede positive rainfall anomalies associated with enhanced convection by several days throughout the entire life cycle of the MJO. Such time (phase) lag between CPT temperature and MJO convection results from the eastward tilted structure of temperature anomalies near the CPT (as shown in Figure 6) driven by MJO convection. On account of the fact that the top of the convection (~150–200 hPa) is typically below the CPT, the temperature anomalies at the CPT are consequently located to the east of convective center. This result is consistent with previous findings [Zhou and Holton, 2002; Kim and Son, 2012], which used correlation analysis based on the ERA-Interim data. As for the relationship between CPT height anomalies and deep convection, our results obtained from RO show that enhanced convection lowers the CPT height. Similar features can be seen in Ryu et al. [2008, Figure 2] related to convective heating and the tropical lapse-rate tropopause height deduced from the OLR data and the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis, though this feature was not discussed or emphasized. Over other regions (140°W–50°E), the negative correlation between the tropopause height and temperature anomalies can be observed.

[19] In order to explain the association of the negative CPT height anomaly with the enhanced convection, we zoom in the CPT region (250–50 hPa) of Figure 2a, and add the dotted line to indicate the location of CPT and the dotted-dashed line to denote the CPT height perturbation by presenting this in Figure 6. In response to the convective heating, there are wavy temperature anomalies near the tropopause, tilting eastward, with the zonal wave number of 1 and vertical wavelength of ~6 km. These characteristics are consistent with vertically propagating Kelvin wave. The tropopause undulates as the phase of Kelvin wave progresses downward. The tropopause descends (rises) when cold Kelvin wave perturbation is immediately below (above) the tropopause [Ryu et al., 2008]. Figure 6 clearly indicates that directly above the enhanced convective center, the cold Kelvin wave perturbation is below the CPT, which results in the descending of the CPT height.

3.4. Vertical Structures of MJO Signals for Different ENSO Phases

[20] The MJO exhibits inter-annual variability, and extensive studies have been performed to define the interaction
between MJO and ENSO [Slingo et al., 1999; Kessler, 2000; Hendon et al., 2007; Moon et al., 2010]. However, until now no conclusive connection between them has been established. The 4-yr period used in this study covers opposite phases of ENSO, during which the boreal winter of 2009 (November 2009–April 2010) is a typical El Niño year and 2007 (November 2007–April 2008) is a La Niña year based on the well-established Niño3.4 index [Trenberth, 1997]. We use these two boreal winters from 4 years of COSMIC RO data to examine how the inter-annual variability of the MJO structure is associated with ENSO.

Figure 6. As in Figure 2a, but only focusing on the CPT region (250 hPa–50 hPa), plus two more curves indicating the location of CPT (dotted line) and CPT height perturbation (dot-dash line, scale is indicated on the right side).
moisture field differs between the two winters. One more slightly difference between them is the slowly eastward-moving anomalies move slightly further east in the El Niño year than in the La Niña year, which is consistent with the difference of the deep convective areas over the Indian Ocean and central Pacific region between El Niño and La Niña [Moon et al., 2010].

Figure 8 depicts the evolution of the equatorial-mean (10°S–10°N) CPT temperature and height anomalies (shadings) along with the MJO convection anomalies (contours) during a MJO life cycle for different ENSO years. The results show that the MJO convection decreases the CPT temperature and height in both La Niña and El Niño years. The positive correlation between the CPT temperature and height anomalies exists mainly over the Indian Ocean and western Pacific region in La Niña and over the whole East Hemisphere in El Niño. A more pronounced eastward propagation of the CPT temperature anomalies in La Niña (Figure 8a) and the CPT height anomalies in El Niño (Figure 8d) can be seen. The eastward propagation speed of the anomalies tends to be larger in El Niño than in La Niña. We need a longer period of RO data to investigate whether this difference is typical for different ENSO phases.

4. Conclusions and Discussions

[23] COSMIC RO data, including temperature, moisture, refractivity, and bending angle, are used to examine the evolution of MJO structure in detail. Unprecedented value of COSMIC RO data for MJO study lies in (i) COSMIC RO data provide more uniform temporal and spatial coverage with higher vertical resolution than polar orbiting satellites and in situ data; (ii) COSMIC RO data are not affected by clouds and allow accurate retrieval of the atmospheric parameters within and under clouds as opposed to most satellite remote sensing data.

Figure 7. Vertical structures of specific humidity anomalies (shading) averaged over 10°S–10°N for a composite MJO cycle (8 phases) from the COSMIC RO data in (a) November 2007 thru April 2008 (La Niña) and (b) November 2009 thru April 2010 (El Niño). The overlaid solid black lines are TRMM rainfall anomalies (scale at right) for the same period of COSMIC RO data.
Four years of COSMIC RO data during the boreal winter seasons reveal that MJO vertical structures identified by various RO retrieved parameters are highly correlated with tropical deep convection. Deep convection tends to cool the lower troposphere, warm the middle and upper troposphere, and cool the tropopause in the Indian and western Pacific oceans. This trimodal structure is similar to that found in AIRS observation and global reanalysis data [Tian et al., 2006, 2010]. The main difference of MJO vertical structure between RO and other data sets is over the tropopause region. RO data yield sharper temperature anomaly structures than that from other data sets, which can be attributed to a higher vertical resolution of RO data. The low-level precondition of the MJO is missing in the RO temperature MJO anomalies. This is mainly due to the information of the low-level RO temperature to a large extent from the a priori, which has poor representation of the real atmospheric variability. Further investigation of the MJO vertical structure using the RO fractional refractivity and bending angle leads to similar results to those from the RO temperature above ~300 hPa and to the RO moisture MJO anomaly below that; however, much finer structures and even more pronounced eastward-tilted anomalies in refractivity and bending angle over the eastern Pacific are identified.

With high vertical resolution and high accuracy of RO data near the tropopause, an unprecedented representation of the MJO structure in terms of CPT temperature and height anomalies is presented. Our results clearly demonstrate that the deep convection cools and lowers the CPT. The interaction between deep convection and large-scale equatorial Kelvin wave yields significant equatorial-trapped anomalies of the CPT. The off-equatorial anomalies are related to the Rossby wave response to the enhanced convection [Gill, 1980]. Furthermore, the intensive tropical convection tends to be preceded by negative CPT temperature anomalies and well associated with negative CPT height anomalies.

The effect of ENSO on the MJO structure is explored based on two boreal winter data in 2007/2008 and 2009/2010, which are typical warm and cold ENSO years, respectively. The MJO anomalies are more salient in the La Niña year but move slightly further east in the El Niño year. Comparison of equatorial-mean CPT anomalies associated with the MJO for different ENSO phases also shows significant differences in inactive regions of deep convection. Only two ENSO events are investigated in this study based on available RO data. The RO data from a longer period are needed to confirm whether the differences found in this study are typical for different ENSO phases. Such study will be performed in the future.

Figure 8. (a–d) Evolution of the equatorial-mean (10°S–10°N) CPT (left) temperature and (right) height anomalies (shading) along the TRMM rainfall anomalies (black contour with interval of 2 mm/day) associated with the MJO convection for different ENSO phases: (top) La Niña and (bottom) El Niño.
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