Observations of Temperature, Wind, Cirrus, and Trace Gases in the Tropical Tropopause Transition Layer during the MJO*

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ABSTRACT

Satellite observations of temperature, optically thin cirrus clouds, and trace gases derived from the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and the Microwave Limb Sounder (MLS) are analyzed in combination with Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim) wind and humidity fields in the tropical tropopause transition layer (TTL), using the Madden–Julian oscillation (MJO) as a carrier signal. MJO-related deep convection induces planetary-scale Kelvin and Rossby waves in the stably stratified TTL. Regions of ascent in these waves are associated with anomalously low temperatures, high radiative heating rates, enhanced cirrus occurrence, and high carbon monoxide and low ozone concentrations. Low water vapor mixing ratio anomalies lag the low temperature anomalies by about 1–2 weeks. The anomalies in all fields propagate eastward, circumnavigating the tropical belt over a roughly 40-day interval. Equatorial cross sections reveal that the anomalies tilt eastward with height in the TTL and propagate downward from the lower stratosphere into the upper troposphere.

As MJO-related convection moves into the western Pacific and dissipates, a fast-moving Kelvin wave flanked by Rossby waves propagates eastward across South America and Africa into the western Indian Ocean. The region of equatorial westerly wind anomalies behind the Kelvin wave front lengthens until it encompasses most of the tropics at the 150-hPa level, giving rise to equatorially symmetric, anomalously low zonal-mean temperature and water vapor mixing ratio and enhanced cirrus above about 100 hPa.

1. Introduction

In the tropics, the troposphere and stratosphere are linked by the tropical tropopause transition layer (TTL), which lies above the tops of most deep convective clouds (Alcala and Dessler 2002) and above the altitude of zero net radiative heating (Folkins et al. 1999; Corti et al. 2005). The climatological-mean TTL is characterized by mean upward mass flux that links the tropospheric Hadley circulation with the stratospheric Brewer–Dobson circulation (Corti et al. 2005), and the upper limit of the TTL can be described as the level at which the upward mass flux has dropped off to values characteristic of the stratospheric Brewer–Dobson circulation (Fu et al. 2007). Temperatures near the tropical cold point, around 90 hPa, are lower than those observed at similar altitudes in the midlatitudes and those at the midlatitude tropopause (Fueglistaler et al. 2009a). The lowest temperatures and the greatest prevalence of TTL cirrus clouds tend to be observed over the areas of frequent deep convection over the equatorial landmasses of Africa, South America, and the Maritime Continent (Fueglistaler et al. 2009a; Virts and Wallace 2010). The TTL is modulated on a variety of temporal scales by stratospheric phenomena, such as the annual cycle in the strength of the upwelling in the Brewer–Dobson circulation (Yulaeva et al. 1994) and the descending zonal wind regimes in the quasi-biennial oscillation (Randel et al. 2000), and by the interannual El Niño–Southern Oscillation (ENSO; Randel et al. 2000; Gettelman et al. 2001; Kiladis et al. 2001).

Tropical atmospheric variability at intraseasonal time scales (i.e., with periods in the 30–80-day range) is dominated by the Madden–Julian oscillation (MJO;
Madden and Julian 1971, 1972). The active phase of the MJO begins with the development of a region of enhanced convection with low-level convergence over the equatorial Indian Ocean. The convective envelope propagates eastward across the Maritime Continent into the western Pacific warm pool and dissipates over the central Pacific (Rui and Wang 1990; Madden and Julian 1994; Hendon and Salby 1994; Zhang 2005). The tropospheric heating produced by the MJO convection induces planetary-scale perturbations extending upward into the TTL that are not confined to the equatorial Indian and Pacific Ocean regions but rather propagate throughout the tropical belt (Hendon and Salby 1994).

The zonally symmetric component of the MJO has been investigated using observations of length of day and the related entity atmospheric angular momentum. The maxima in both length of day and atmospheric angular momentum coincide with the time when the maximum MJO-related convection has reached the western and central Pacific and is just starting to weaken (Madden 1987; Weickmann et al. 1997). The maximum equatorward eddy flux of westerly momentum is observed approximately \( \frac{1}{8} \) of a cycle earlier (Grise and Thompson 2012). The zonal-mean structure of the MJO has not yet been analyzed in depth.

In recent years, a series of satellites, described in section 2, has provided unprecedented sampling of temperature, clouds, and trace gas concentrations in the TTL. In this study, we examine the covariability of these atmospheric fields using the MJO as a carrier signal. We first review the basic structure of the MJO-induced planetary-wave pattern and then investigate the relationships among the MJO-related anomalies at a single level (100 hPa) in the TTL and in longitude–height cross sections above the equator, using both reanalysis fields and a variety of satellite observations (section 3). Zonally averaged MJO perturbations in the TTL are examined in section 4, and conclusions are presented in section 5.

2. Data and analysis techniques

a. Data sources

The six satellites in the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)–Formosa Satellite-3 (FORMOSAT-3) measure the atmospheric refraction of radio waves from GPS satellites (Anthes et al. 2008). On average, over 500 tropical temperature profiles per day are obtained from these radio occultations. COSMIC temperature profiles extend from 40 km down nearly to Earth’s surface. The profiles are provided with 100-m vertical resolution, although the actual resolution is a function of height and is about 1 km in the TTL (Kursinski et al. 1997). The National Center for Atmospheric Research (NCAR) has made available COSMIC profiles corrected for the effects of water vapor on the GPS signal. We make use of these corrected profiles even though the water vapor effect is small in the relatively dry and cold TTL and lower stratosphere (Kursinski et al. 1996; Anthes et al. 2008).

The Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and Aura are polar-orbiting satellites in National Aeronautics and Space Administration (NASA)’s Afternoon constellation (or “A train”); Aura flies just minutes behind CALIPSO in the constellation. CALIPSO carries a two-wavelength polarization lidar that is capable of detecting cloud layers with optical depths of 0.01 or less. Cloud-layer data are available at 5-km along-track resolution and 60-m vertical resolution for the altitudes of interest (Winker et al. 2007). The lidar signal can become completely attenuated in optically thick clouds (Winker et al. 2007); following Fu et al. (2007), we assign such opaque layers a cloud base at Earth’s surface.

The Microwave Limb Sounder (MLS) aboard the Aura satellite measures thermal emissions in spectral bands centered on 190 and 240 GHz. From these radiance measurements are derived vertical profiles of ozone, carbon monoxide, and water vapor mixing ratio at 1.5° intervals along the satellite’s orbital path (Read et al. 2007; Livesey et al. 2008). In this study, we analyze MLS ozone and carbon monoxide mixing ratios at 100 hPa and water vapor mixing ratios at levels between 316 and 46 hPa. The vertical resolution of the MLS water vapor profiles varies with height and is about 3 km near 100 hPa (Read et al. 2007); ozone and carbon monoxide profiles have vertical resolutions of about 3 and 4 km in the TTL, respectively (Livesey et al. 2008).

Fields of other atmospheric variables are represented in this study by the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim) (Dee et al. 2011). The 100-hPa ERA-Interim fields examined in section 3 are available four times daily at 1.5° horizontal resolution, spanning the globe. In addition, we examine daily ERA-Interim zonal and meridional winds, as well as shortwave and longwave radiative heating rates, at 1° horizontal resolution and at 14 vertical levels between 320 and 44 hPa. The sum of the shortwave and longwave heating rates is the net radiative heating rate, which is referred to as “heating rate” in this study. Ascent in the TTL and lower stratosphere induces adiabatic cooling that is balanced by radiative heating, as the air layer undergoes relaxation toward its radiative equilibrium temperature (Andrews et al. 1987; Fugetlistaler et al. 2009b; Abalos et al. 2012).
simulated vertical velocities derived from the reanalyses, these authors as well as Yang et al. (2008) have used diabatic heating rate as a proxy for vertical velocity. We will compare the vertical velocity inferred from the radiative heating rates with the reanalysis vertical velocity in the TTL.

This study also makes use of NOAA’s outgoing longwave radiation (OLR) observations, which are available at 2.5° latitude × 2.5° longitude resolution.

b. Three-dimensional indices

In this study, we analyze 4 years (13 June 2006–12 June 2010) of observations from each of the satellites listed above and about 3.5 years (1 April 2006–31 December 2009) of ERA-Interim data. As in Virts et al. (2010), a weekly TTL cirrus index is calculated on a 10° latitude × 10° longitude grid and is defined as the fraction of CALIPSO cloud profiles acquired within each grid box that identified a cloud layer with a base above 15 km. For each 10° × 10° grid box, a weekly height-dependent cloud index is also calculated as the cloud fraction within successive 200-m layers. Similarly, a zonal-mean height-dependent cloud index is calculated as cloud fractions within 5° latitude bands. These indices are referred to as “cloud fraction” in this paper. Similar spatial and temporal averaging is performed on ERA-Interim data, MLS trace gas observations, and COSMIC temperature profiles at each vertical level. On average, CALIPSO and MLS sample some portion of a 10° × 10° grid box in the equatorial belt 5 times per week, and COSMIC averages approximately 15 temperature profiles per week per 10° × 10° grid box.

After spatially and temporally averaging the data, an 80-day high-pass Lanczos filter is applied to the time series at each grid box to remove the leading harmonics of the annual cycle and the nonseasonal ENSO cycle. The Student’s t test is used to determine the statistical significance of correlation coefficients. The filtered time series analyzed in section 3 have an average of about 166 effective degrees of freedom, estimated using the formula of Leith (1973), so if a two-sided distribution is assumed, correlations stronger than 0.16 in absolute value are statistically significant at the 95% level. Zonally averaged fields, with their stronger temporal autocorrelations, average about 77 degrees of freedom, so that correlations stronger than 0.22 are significant at the 95% level. The patterns emphasized in this study exhibit correlations ranging up to 0.5 and beyond in absolute value.

c. MJO index

To quantify the evolution and strength of the MJO, we use the real-time multivariate MJO (RMM) index introduced in Wheeler and Hendon (2004). The two components of this index, RMM1 and RMM2, are the standardized time series obtained by projecting daily observations, with annual and interannual variability removed, onto principal component time series associated with the first two empirical orthogonal functions (EOFs) of a field of daily, near-equatorial OLR and zonal wind at 850 and 200 hPa. RMM1 and RMM2 are used to define the phase space illustrated in Fig. 1, which has been modified from Wheeler and Hendon (2004). An idealized evolution of the MJO appears as a counterclockwise rotation when represented on this chart.

Figure 2 shows OLR patterns obtained by regressing 80-day high-pass-filtered OLR time series onto RMM1 and RMM2; for clarity, we also show OLR patterns associated with the standardized linear combinations RMM1 − RMM2 and RMM1 + RMM2, which fall 1/3 cycle before RMM1 and RMM2, respectively. A broad area of enhanced cloudiness, indicated by anomalously low cloud-top temperatures, develops over the equatorial Indian Ocean and propagates eastward over the Maritime Continent into the western and central Pacific Ocean, followed by an area of suppressed cloudiness. OLR anomalies are also observed over Africa and the Americas, but they are not statistically significant. By construction, the remaining half of an idealized MJO cycle is associated with OLR patterns.
with signs opposite of those shown in Fig. 2. Thus, as indicated in Fig. 1, RMM1 can be thought of as an MJO-related pulsation of cloudiness and precipitation over the Maritime Continent and RMM2 as a dipole with opposing centers over the Indian Ocean and the western Pacific Ocean.

3. MJO signature in 100-hPa maps and equatorial cross sections

a. Planetary-wave signature in the temperature field

The 100-hPa temperature anomalies associated with the MJO, based on COSMIC GPS radio occultation temperature profiles, are shown in Fig. 3. Similar patterns and amplitudes are obtained by analyzing COSMIC cold-point temperatures or ERA-Interim 100-hPa temperatures $T_{100}$ (not shown). Cross sections of near-equatorial ($5^\circ S$–$5^\circ N$) COSMIC temperature correlations for the same MJO phases are shown in Fig. 4. The MJO-related temperature perturbations shown in Figs. 3 and 4 exhibit the following characteristics:

- At 100 hPa, a planetary-scale region of anomalously low temperatures propagates eastward along the equator about $30^\circ$–$45^\circ$ of longitude ahead of the enhanced MJO convection; likewise, higher temperatures are observed to the east of the areas of suppressed MJO convection. Anomalously low 100-hPa temperatures and high tropopause heights above and to the east of the convection were also observed by Madden and Julian (1972), based on radiosonde data.

- The temperature field above the warm-pool region resembles the modeled response to a heat source situated on the equator (Matsumo 1966; Webster 1972; Gill 1980). Low temperatures extend along the equator to the east of the temperature minimum and tilt eastward with height (Fig. 4)—a configuration that is consistent with the downward phase propagation and upward energy dispersion in an equatorially
trapped Kelvin wave (Holton and Lindzen 1968; Wallace and Kousky 1968; Holton 1979). Subtropical cold anomalies suggestive of Rossby waves are observed poleward of the enhanced convection and extending westward of it (Fig. 3).

- As enhanced MJO convection moves from the Maritime Continent into the western and central Pacific, a narrow belt of equatorial cold anomalies, suggestive of a fast-moving Kelvin wave front (Heckley and Gill 1984), propagates rapidly eastward from the central Pacific across South America and Africa, reaching the western Indian Ocean at the time of maximum RMM2 (Figs. 3d and 4d). This Kelvin wave complex is flanked by subtropical warm anomalies, with a maximum amplitude of approximately 20°–30°, suggestive of a Rossby wave signature.

Aspects of the structure and evolution of the MJO-related planetary-scale temperature perturbations in the upper troposphere and TTL have been previously documented based on temperature observations from the Microwave Sounding Unit (MSU; Hendon and
Salby 1994; Bantzer and Wallace 1996), the Atmospheric Infrared Sounder (AIRS; Tian et al. 2006), GPS radio occultation measurements including COSMIC (Tian et al. 2012; Zeng et al. 2012), and reanalysis datasets (Kiladis et al. 2001; Zhou and Holton 2002).

The results based on temperature have illustrated the location and basic structure of the equatorial planetary waves associated with the MJO. In the remainder of this section, we emphasize the coherent picture that emerges by examining MJO-related perturbations based on data from diverse satellite sensors and reanalyses.

### b. Analysis of other variables

In this section, we examine the anomaly patterns of circulation, clouds, and trace gases in the TTL produced by the planetary waves induced by the MJO deep convection. Because of space limitations, only fields associated with RMM2 are shown. To facilitate comparison among the various fields, the RMM2 temperature patterns from Figs. 3d and 4d are repeated in contours in each panel of all subsequent figures and are overlain with colored shading representing other atmospheric fields. For each field shown, the online
supplemental material includes an animation showing its evolution throughout the MJO cycle; the title of each frame is numbered to allow for comparison among the animations. We will occasionally refer to these animations in the text, and we encourage readers to view them to gain a fuller understanding of the MJO’s impact on the TTL.

MJO-related zonal ($u_{100}$) and meridional ($v_{100}$) wind components at 100 hPa from the ERA-Interim are shown in Fig. 5a. The 100-hPa winds converge into the region of anomalously high temperature above the Maritime Continent and diverge from the region of anomalously low temperature over the equatorial central Pacific. Westerly winds are observed from the equator out to about $20^\circ$ latitude over South America and Africa, in association with an equatorial Kelvin wave flanked by subtropical cyclonic anomalies. Anomalies of vertical velocity in pressure coordinates from ERA-Interim, shown in Fig. 5b, exhibit subsidence (i.e., positive values) at 100 hPa above the western Pacific warm pool, centered about $20^\circ$ of longitude to the east of the warm anomalies, while ascent is observed farther to the west, over the equatorial Indian Ocean. However, the remainder of the ERA-Interim vertical velocity field exhibits little or no relationship with the overlain temperature field. The RMM2 96-hPa diabatic heating rate anomaly pattern shown in Fig. 5c exhibits much closer spatial agreement with the pattern of temperature anomalies—heating in association with cold anomalies, and vice versa, on time scales of several days (section 2b). In contrast to vertical velocity, a strong correspondence is also observed between diabatic heating and independently detected fields such as TTL cirrus and trace gases, as will be shown later.

An equatorial cross section of RMM2 circulation anomalies, as represented by zonal wind and heating rates, used here as a proxy for vertical velocity, is shown in Fig. 6. The heating rates are represented as vertical vectors; because pressure is the vertical coordinate, these correlation coefficients are multiplied by a factor of $2$ so that upward-pointing vectors indicate positive heating rates, and vice versa. The circulation and temperature anomalies are indicative of anomalous warmth and divergence in the upper troposphere around the 250-hPa level centered just to the east of the date line, which has become decoupled from the decaying convection, centered near $140^\circ$E (Fig. 2d). Westerly wind anomalies and ascent are observed to the west and easterly wind anomalies and descent (i.e., radiative warming) to the east of the warm phase of the Kelvin wave, which tilts eastward with height above about 200 hPa from approximately $60^\circ$ to $150^\circ$E (Fig. 6a), above the region of suppressed
convection (Fig. 2d). The associated zonal wind signature is approximately in quadrature with the wave in the temperature field. This configuration of temperature and circulation anomalies is consistent with the idealized Kelvin wave pattern described in Holton and Lindzen (1968), Wallace and Kousky (1968), and Holton (1979).

MJO-related anomalies in clouds and water vapor concentrations in the TTL are shown in Figs. 7 and 8. TTL cirrus from CALIPSO, represented in Fig. 7a as anomalies of cloud fraction with bases above 15 km, is negatively correlated with the 100-hPa temperature anomalies. Suppressed convection is indicated by the 300-hPa cloud minimum near 85°E in Fig. 8a and the OLR maximum in Fig. 2d. A region of suppressed cirrus extends eastward and upward from the region of suppressed convection, coincident with the band of anomalously high temperatures (Fig. 8a). Enhanced cirrus is observed over the equator in the central Pacific and extends westward along approximately 10°N toward the Philippines and along 10°S toward Australia, suggestive of a Rossby wave signature, which is in agreement with previous analysis of MLS data by Eguchi and Shiotani (2004).

The strong temperature dependence of the saturation vapor pressure, as given by the Clausius–Clapeyron equation, is evidently the dominant factor in determining the distribution of mixing ratio and specific humidity, as evidenced by their positive spatial correlation with temperature in Figs. 7b and 7c. The anomaly fields are not precisely aligned, however, as indicated by the displacement between the center of the warm anomaly near 110°E above the equator and the water vapor mixing ratio anomaly approximately 20°–30° of longitude to the west of it. Hence, it is clear that variations in relative humidity are also important. Indeed, the spatial correlation between relative humidity and temperature, shown in Fig. 7d, is even stronger than the correlation between specific humidity and temperature. It is negative because ascending air is adiabatically cooled and brought to or maintained at saturation.

The relationship between temperature and water vapor in the TTL is more clearly seen in the equatorial cross section of RMM2 MLS mixing ratio anomalies in the equatorial belt shown in Fig. 8b. Above the level of main convective outflow (~250 hPa; Highwood and Hoskins 1998), the temperature and water vapor anomalies above

Mass concentration of atmospheric water vapor can be represented by the nearly equivalent entities specific humidity, which is available in the ERA-Interim output, and water vapor mixing ratio, which is measured by MLS. The RMM2 anomaly patterns of MLS water vapor mixing ratio and ERA-Interim specific humidity at 100 hPa (q100), shown in Figs. 7b and 7c, are in close agreement, even though MLS water vapor data are not input to ERA-Interim (Dee et al. 2011). Low water vapor concentrations are observed in association with the anomalously low temperatures over the central Pacific, extending westward along approximately 10°N toward the Philippines and along 10°S toward Australia, suggestive of a Rossby wave signature, which is in agreement with previous analysis of MLS data by Eguchi and Shiotani (2004).

The relationship between temperature and water vapor in the TTL is more clearly seen in the equatorial cross section of RMM2 MLS mixing ratio anomalies in the equatorial belt shown in Fig. 8b. Above the level of main convective outflow (~250 hPa; Highwood and Hoskins 1998), the temperature and water vapor anomalies above
the Indian Ocean and Maritime Continent are nearly in quadrature—the cold phase of the Kelvin wave that is propagating downward and eastward is followed ¼ cycle later by a region with anomalously low water vapor concentrations, and vice versa. As layers of air ascend and undergo adiabatic cooling in the cold phase of the Kelvin wave, water vapor condenses, forming cirrus clouds. After the layer reaches its lowest temperature, the dehydrated air can increase in water vapor concentration through the evaporation of the cirrus over time scales of several days (Dinh et al. 2012) or through vertical mixing. Hence, at a fixed location, water vapor concentration anomalies are expected to lag the temperature anomalies. The observed lag of about 1–2 weeks, also documented in MLS data by Schwartz et al. (2008), has yet to be explained.

Animations of 100-hPa water vapor anomalies during the MJO cycle, shown in the online supplemental material, illustrate the propagation of the water vapor signal eastward over equatorial South America and Africa; however, the anomalies in these areas are nearly a factor of 2 smaller in magnitude than those above the warm-pool region in the equatorial eastern Indian Ocean and the western Pacific.

Climatological-mean ozone mixing ratio increases rapidly with height from the tropical upper troposphere to the lower stratosphere (Takashima and Shiotani 2007), where ozone is formed through the photolysis of O2 molecules. Thus, ascent within the TTL and lower stratosphere brings air with lower ozone concentrations up from below (Fujiwara et al. 1998; Mote and Dunkerton 2004; Folkins et al. 2006; Randel et al. 2007).
The map of filtered MLS 100-hPa ozone mixing ratios regressed onto RMM2, shown in Fig. 9a, indicates that anomalously low ozone concentrations are observed in association with cold anomalies (i.e., air layers with a recent history of upwelling; Fig. 5c), and vice versa. The ozone anomalies are small in the equatorial belt, particularly above the Maritime Continent, but are larger in the subtropics, where climatological-mean ozone concentrations are higher at the 100-hPa level. The Rossby wave signature in subtropical ozone was also noted in MJO composites of observations of ozone columns and profiles from several satellites (Tian et al. 2007; Li et al. 2012).

In contrast, carbon monoxide is produced near Earth’s surface by processes including biomass burning and fossil fuel combustion (Holloway et al. 2000). It is well mixed in the troposphere and decreases with height in the TTL and lower stratosphere (Randel et al. 2007; Fueglistaler et al. 2009a). In the regression pattern based on RMM2, shown in Fig. 9b, anomalously high carbon monoxide mixing ratios are observed in association with low temperatures, and vice versa. Anomalies of both ozone and carbon monoxide are planetary in scale and exhibit the distinctive spatial patterns of Kelvin and Rossby waves, as discussed in section 3a.

Thus, when examining the MJO-related perturbations in Figs. 3–9, a consistent picture emerges in which convection gives rise to planetary-scale regions with air masses with contrasting properties that identify them as “tropospheric”—cold, widespread cloudiness, and anomalously high carbon monoxide and low ozone concentrations—or “stratospheric” (the reverse).

4. The zonally symmetric MJO signature

To analyze the impact of the MJO on the zonally symmetric circulation, filtered tropical-mean (equatorward of 10° latitude) time series of the reanalysis and satellite variables examined in section 3 have been correlated with various linear combinations of RMM1 and
RMM2. The strongest positive correlation for each variable (or the strongest negative correlation in the case of temperature and water vapor and ozone concentrations) is indicated in Table 1 along with the MJO phase during which it is observed.

It can be seen in Table 1 that the strongest westerlies, the highest heating rates, the lowest temperatures, the highest relative humidities, and the cloudiest conditions at 100 hPa are observed in the phase of the MJO cycle when the convection is moving from the Maritime Continent into the western Pacific. This is consistent with the timing of the maximum in tropical-mean upper-tropospheric MSU temperature and equatorial zonal wind (Bantzer and Wallace 1996), atmospheric angular momentum (Madden 1987; Weickmann et al. 1997), and the maximum in TTL planetary-wave amplitude (Grise and Thompson 2012). Comparing composites of temperature and TTL cirrus fraction at this stage of the MJO to those observed when the convection is over the eastern Indian Ocean, Virts and Wallace (2010) reported a decrease in tropical-mean 100-hPa temperature exceeding $2^\circ$C and more than a doubling of tropical-mean TTL cirrus fraction. The correlations between tropical-mean trace gas concentrations and the MJO, shown in Table 1, are not statistically significant, but the phases portray a physically consistent picture. The minimum in tropical-mean ozone is observed at a similar point in the MJO cycle as the minimum in 100-hPa temperature and the maximum in TTL cirrus fractional coverage. Both the observed and reanalysis fields of tropical-mean water vapor concentration indicate a minimum approximately \(\frac{1}{4}\) cycle after the minimum in temperature, or about 10–15 days after dehydration is observed at 100 hPa above the western Pacific, consistent with results of Wong and Dessler (2007), based on MLS data. Tropical-mean carbon monoxide fluctuations exhibit quite different timing and are believed to be related to an injection of carbon monoxide–rich air over Africa (Wong and Dessler 2007).

Zonal-mean cross sections of correlations between RMM2 and filtered COSMIC temperature, ERA-Interim zonal wind and mean meridional circulation, CALIPSO cloud fraction, and MLS water vapor mixing ratio are shown in Fig. 10. As indicated by Table 1, RMM2 represents the stage of the MJO cycle shortly after most of these variables exhibit their largest MJO-related tropical-mean amplitudes. Animations illustrating the evolution of the zonal-mean fields during a typical MJO cycle are available in the online supplemental material.

### Table 1. Phase and strength of strongest correlation between the MJO index and 80-day high-pass-filtered tropical-mean (10°S–10°N) time series of the indicated variables (\(Q\) is the radiative heating rate). Italicized correlation coefficients indicate that the values are not statistically significant at the 95% level. MJO phase diagram is in Fig. 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>MJO phase</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>COSMIC (T_{100})</td>
<td>6</td>
<td>-0.36</td>
</tr>
<tr>
<td>ERA-Interim (u_{100})</td>
<td>5</td>
<td>0.33</td>
</tr>
<tr>
<td>ERA-Interim (Q_{100})</td>
<td>5</td>
<td>0.46</td>
</tr>
<tr>
<td>ERA-Interim (RH_{100})</td>
<td>6</td>
<td>0.36</td>
</tr>
<tr>
<td>ERA-Interim (q_{100})</td>
<td>8</td>
<td>-0.22</td>
</tr>
<tr>
<td>MLS (H_2O_{100})</td>
<td>8</td>
<td>-0.28</td>
</tr>
<tr>
<td>MLS CO(_{100})</td>
<td>3</td>
<td>0.13</td>
</tr>
<tr>
<td>MLS O(_{3,100})</td>
<td>6</td>
<td>-0.36</td>
</tr>
<tr>
<td>CALIPSO TTL cirrus fraction</td>
<td>6</td>
<td>0.44</td>
</tr>
</tbody>
</table>
At the time of maximum RMM2, MJO-related convection is enhanced over the western Pacific and suppressed over the eastern Indian Ocean (Fig. 2). In the TTL, westerly winds extend from the region of divergence over the central Pacific Ocean eastward for over 240° of longitude, in association with the equatorial Kelvin wave signature. The RMM2 zonal-mean zonal wind field, shown in Fig. 10b, is accordingly dominated by westerly winds that extend from the upper troposphere up to about 100 hPa. Overlying the westerly winds in the TTL is a region of zonal-mean easterly winds in the lower stratosphere.

The RMM2 mean meridional circulation, as inferred from the diabatic heating rates in ERA-Interim, is shown in Fig. 10c. Consistent with the temperature field, the inferred vertical velocity field exhibits a phase reversal around the 100-hPa level. Below 100 hPa, the meridional winds are equatorward, converging just to the south of the equator, near the latitude of the strongest westerly wind anomalies. The radiative heating rates are indicative of
subsidence between about 200 and 100 hPa from the equator poleward out to at least 30° latitude, and the associated adiabatic warming is evident in the observations of anomalously high temperatures in that layer (Fig. 10a). Warming of the upper troposphere in association with the fast-propagating Kelvin wave front was previously observed by Bantzer and Wallace (1996), based on MSU channel-3 and -4 temperatures. Convection in the equatorial belt is suppressed at the time of maximum RMM2, as illustrated by the cloudiness anomaly centered just south of the equator in Fig. 10d, while enhanced cloudiness and associated weak cold anomalies are observed in the lower TTL over the subtropics. Latent heating associated with convection is larger in the upper troposphere than in the TTL and stratosphere, so the radiative heating rates do not give a complete picture of the diabatic circulation in the lower portion of the cross section. Above 100 hPa, the meridional winds are also equatorward, and heating rate anomalies are positive up to about 70 hPa; these mean meridional circulation anomalies extend poleward out to about 20° latitude (Fig. 10c). The heating rate and temperature anomalies suggest that the strongest zonal-mean ascent tends to be observed around 90–80 hPa, and this is corroborated by the zonally symmetric TTL cirrus anomalies in Fig. 10d that also extend poleward out to about 20° latitude. It has previously been shown that strengthening of the equatorial planetary waves produces a zonal-mean temperature tendency pattern similar to the observed temperature patterns in Fig. 10a (Grise and Thompson 2013, based on COSMIC data).

The RMM2 zonal-mean MLS water vapor anomalies in the lower TTL, shown in Fig. 10e, are consistent with the CALIPSO cloudiness anomalies in Fig. 10d—enhanced cloudiness corresponds to anomalously high water vapor concentrations, and vice versa. The cold layer between 100 and 70 hPa at the time of maximum RMM2 is marked by anomalously low water vapor mixing ratios. In the zonal-mean water vapor animation, included in the supplemental material, the water vapor anomalies over the equator appear to shift upward during the evolution of the MJO. This behavior is of questionable significance given that the effective vertical resolution of MLS water vapor profiles near 100 hPa is about 3 km (Read et al. 2007). Analogous behavior is not observed in animations of zonal-mean ERA-Interim specific humidity (not shown).

5. Conclusions

In this study, we have examined MJO-related variations in TTL temperatures, circulation, clouds, and trace gases. Our results indicate that these fields vary in a physically consistent way during the evolution of the MJO. Perturbations in the TTL are not localized near the anomalous MJO-related convection; rather, the atmospheric fields shown in Figs. 3–9 exhibit planetary-scale perturbations consistent with patterns of circulation anomalies associated with equatorial Kelvin waves and Rossby waves. Positive heating rate anomalies coincide with regions with a recent history of ascent, which is consistent with the notion of radiative relaxation. Adiabatic cooling associated with the wave-driven ascent also gives rise to planetary-scale regions of enhanced relative humidity and TTL cirrus, and vice versa. Water vapor mixing ratios decrease in layers in which TTL cirrus are enhanced, and minima lag the cold anomalies by about 1–2 weeks. MJO-related anomalies of the trace gases ozone and carbon monoxide are consistent with a vertical velocity field acting on their strong climatological-mean vertical gradients.

The zonally symmetric signature of the MJO at the time of maximum RMM2 (Fig. 10) is marked by westerly wind anomalies throughout much of the TTL and easterly anomalies in the lower stratosphere, accompanied by meridional convergence into the equatorial belt. The 100-hPa level marks an approximate transition level, with subsidence, adiabatic warming, and suppressed convection below and ascent, adiabatic cooling, and enhanced TTL cirrus coverage above. The polarity of the zonal-mean anomalies above approximately 150 hPa appears to be determined by the polarity of the planetary-wave perturbations over the central Pacific, the Americas, and Africa, and is opposite to that of the perturbations over the Maritime Continent, as can be verified by comparing Fig. 10 with Figs. 3–8. In other words, the zonal-mean RMM2 signature is dominated by the fast-moving Kelvin wave front that circumnavigates the equatorial belt. The associated mean meridional circulations in Fig. 10c can be understood as a thermally indirect response to the zonal wind forcing that sets up a temperature field in thermal wind balance with the perturbed zonal wind field.

The MJO is associated with a distinctive set of planetary-scale anomalies in the TTL, many of which have been analyzed in the previous studies cited above. What is new in this study is the use of the MJO as a carrier signal—that is, we have analyzed MJO variations based on reanalysis fields as well as a suite of independent, satellite-based observations in order to gain a comprehensive view of the large-scale relationships among temperature, circulation, clouds, and trace gas concentrations in the TTL. Gettelman et al. (2001) analyzed ENSO variations in a similar fashion. The MJO is well suited to this type of analysis because it dominates tropical variability on its characteristic time scale and has experienced enough realizations during the relatively short satellite record to permit a rigorous statistical analysis.
In addition to giving insight on the physical relationships among these atmospheric fields, as summarized above, this analysis also offers a comparison between reanalysis fields, which assimilate observations but are also to some degree model dependent, and independent observations. COSMIC bending angle profiles are assimilated into ERA-Interim, as are MLS ozone profiles, but CALIPSO and MLS water vapor and carbon monoxide mixing ratios are not (Dee et al. 2011). The close correspondence between anomalies of CALIPSO TTL cirrus fraction (Fig. 7a) and of ERA-Interim heating rate (Fig. 5c) and relative humidity (Fig. 7d), and between anomalies of MLS water vapor mixing ratio (Fig. 7b) and anomalies of ERA-Interim specific humidity (Fig. 7c), offers reassurance that the ERA-Interim representation of the TTL is correctly representing the relationships between the different variables.

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REFERENCES


